AN IMPACT IDENTIFICATION FRAMEWORK FOR LARGE RESERVOIRS

by

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ABSTRACT

This study is undertaken on the premise that virtually all large reservoir projects, in addition to meeting certain primary objectives, cause certain other secondary effects, which are often unanticipated during planning stages. Whether these secondary effects are deemed to have positive or negative value, their recognition during the preoperational period would be advantageous. Hence, the objective of the thesis is development of a check list framework approach for identification of physical, biological, and human or cultural effects which stem from the creation of reservoirs.

The thesis commences with a review of the secondary effects of reservoirs in various parts of the world. Both temperate and tropical environments are considered, and both concrete arch and earth fill dams. The review forms the basis for development of the impact identification framework.

A stepped matrix approach is used in the framework. Initially, the potential "objectives" of reservoir creation are identified. Meeting of these "objectives" requires certain "methods of execution", and these are identified on the second axis. The third axis identifies the "impacts" of
the various "methods of execution", and continues with an indication of the potential "multiple order consequences".

The thesis concludes as the framework approach is applied in an illustrative manner to a proposed reservoir development at Moran Canyon on the Fraser River in southwestern British Columbia. Potential impacts and consequences are discussed. Finally, an assessment is made as to the utility of the framework identification approach, and to methods by which the technique might be improved.

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Supervisor
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Man made lakes or reservoirs are usually built for some "primary" purpose, but the construction or presence of reservoirs can create "secondary" problems which may include economic loss and human suffering unless reservoir planning in its earliest stages thoroughly considers both primary and secondary aspects. (Lagler, 1969, p. vii)
1. INTRODUCTION

In this study an attempt is made to develop a useful and comprehensive impact identification framework for large reservoirs. Reservoir construction projects are generally initiated to meet certain objectives such as the reduction of flood hazard, hydroelectric generation, the supply of irrigation water, the facilitation of navigation, and the facilitation of recreation. In order to achieve these objectives operational procedures or "methods of execution" must be followed. These methods might be summarized as "the construction and operation of the reservoir system", however, they may also be listed as components such as "construction of the dam", "initial filling of the reservoir", "creation of a man-made lake", and so on. Certain impacts on the physical, biological and human environments result from each "method of execution", and these impacts have "multiple order consequences". The objective of the study is the development of a comprehensive framework upon which these secondary effects are indicated as linkages of impacts and "multiple order consequences". The framework may then serve as a check list for identification of potential secondary effects during the planning stages for proposed reservoir projects.

The rationale for the study stems from the fact that to date the planning process has not given due regard to the
comprehensive identification of impacts resulting from construction and operation of large reservoirs. Some impacts have been expected; however, other impacts, which were given no consideration in planning stages and which have come about in a completely unexpected manner, may be documented for virtually every large reservoir project. Any contribution towards ensuring preidentification of impacts which might otherwise occur unexpectedly should serve to improve the planning process.

At this point, no value judgement as to whether the impacts and their consequences are of positive or negative value is intended. Certainly, some of the secondary effects stemming from the development of large reservoirs are of positive value to man, though they are not included as objectives in initiation of the reservoir project. Others are of definite negative value, resulting in human suffering and economic loss. In either case, early recognition of impacts is likely to be beneficial; positive impacts may be enhanced, and negative impacts may be minimized or may be met with planned rather than crisis responses. Further, comprehensive identification and evaluation of impacts will serve to improve the data base upon which feasibility criteria are tested and project feasibility is established.

Although project evaluation is not intended to be a
central issue in this study, the feasibility criteria which must be met through some form of evaluation procedure should be given brief consideration. Five elements: engineering feasibility, economic feasibility, financial feasibility, political feasibility and social feasibility, must be met in order for the planning and decision making processes to determine that a program should be initiated or that a project should be constructed.

The first criterion, engineering feasibility, is met if a proposed physical superstructure is capable of bringing about the stated objective or objectives. In the case of reservoirs, these objectives are generally directed towards obtaining the direct and obvious outputs of the project such as the reduction of flood hazard or the supply of irrigation water. Potential objectives involving minimizing of negative impacts or maximizing of positive impacts may be overlooked at an engineering level, simply because lack of identification of the impacts prevents incorporation of their maximization or minimization within the engineering design. Engineering feasibility is met when it is shown that the stated objectives may be accomplished or may be obtained, but comprehensive identification of impacts is an unnecessary prerequisite to meet the criterion.
Economic feasibility is established

"... if the total benefits that result from the project exceed those which would accrue without the project by an amount in excess of the project cost" (James and Lee, 1971, p. 161).

Though there are many advocates of the benefit-cost analysis technique for establishment of economic feasibility, it is unlikely that any would fail to recognize the weakness inherent in its inability to correctly evaluate secondary and intangible factors. Many impacts and their consequences fall within the groups of secondary and intangible factors. Their recognition will serve to improve the validity of the establishment of economic feasibility, though even comprehensive identification of impacts cannot ensure absolute validity of proven economic feasibility.

The ability to meet the cost of project installation and operation, or financial feasibility, has little to do with the identification and evaluation of impacts, beyond the fact that faulty economic analysis may lead to an invalid picture of financial feasibility.

Political feasibility is established if the required political approval backs the position of the decision makers. If the general public are involved, the failure to achieve comprehensive understanding of the impacts of large reservoirs may result in the establishment of political
feasibility on the basis of incomplete evaluation.

The final criterion, social feasibility, is met if it can be shown that the population for whom the project is built will accept the outputs or opportunities created, turning them into the intended benefits. The inability to achieve social feasibility may, in itself, bring unexpected impacts after a project is completed. However, it can generally be established that the outputs of a proposed reservoir project will be accepted and utilized, but this in no way indicates comprehensive identification of the impacts resulting from the project.

After consideration of the five elements of overall project feasibility it may be concluded that an incomplete feasibility rationale generally precedes decision making on the implementation of large projects. Though each element may be satisfactorily evaluated in its own respect, there is no guarantee that all the factors which might be evaluated have in fact been included. The fault results, not from the process of considering the individual feasibility criteria, but rather from the inability to include all relevant factors. These factors which are omitted include the unexpected impacts and their consequences. Any methodology which can be developed to aid in identification of these effects should, through contributing to the feasibility assessment
of each of the elements, have some utility within the context of project planning and subsequent decision making. Some of the effects identified will be fully expected by those designing and authorizing the project, however, if successful the impact identification framework will also indicate effects which have occurred unexpectedly in past projects and which are likely to reoccur in current projects; and effects which have not occurred in the past but may in current or future projects. Systematic impact identification has the potential for improving the data base for the establishment of feasibility criteria.

The methodology of this study is essentially a pragmatic approach, based on identification of problems or consequences and recognition of their causes. A major part is composed of documentation of the impacts which have been recorded after the construction of large dams and reservoirs at sites throughout the world. This section, rather than detailing the effects of individual projects, as is most common in the literature, attempts to bring forth the effects as classes, indicating as examples, particular projects where they have been recorded. Documentation of this sort may of course, be of minimal interest to those familiar with the subject of large reservoirs, and whose main interest in this study is in the development of the impact identification framework. On the other hand, for those who are less familiar with the
study of reservoirs, the section should provide a useful background, and indicate sources of additional information which may be required in working through an impact identification framework for a proposed reservoir project. As far as the study itself is concerned, documentation of recorded impacts and their consequences is a necessary component, as it must be relied upon as a major source of the substance of the impact identification framework. A broad geographic perspective is attempted, including effects of reservoirs in both temperate and tropical regions. It is not intended that all the impacts identified will be applicable to any one reservoir project, but rather that the framework may serve as a useful check list during the planning process.

It is essential at this point to explain the context in which certain terminology is used later in the study. The term "objectives" refers to the intended primary outputs of the reservoir operation such as hydroelectric generation, the reduction of flood hazard, etc. To achieve these outputs certain operational procedures or "methods of execution" must be carried out. These methods bring about certain secondary effects or "impacts" which lead to "multiple order consequences". For the purpose of this study, "final consequences" are those at which the "objective to method of execution to impact to consequence" linkage is terminated. This termination generally occurs at the point at which the
consequence has a direct effect upon human activity, or at the consequence which immediately precedes this point. It will be noted that some of the "final consequences" will be "feedbacks" or effects on the achievement of the project's "objectives". By way of example, accomplishment of the "objective" of facilitation of recreation through the construction of a dam and creation of a reservoir, requires the "method of execution" of creation of a man-made lake. One of the "impacts" which stems from this method is seepage, which may bring the "final consequence" of improving agricultural output through the supplementation of groundwater, and which may have a "feedback" by reducing the amount of water available to meet a second "objective"—generation of hydroelectricity. Though this terminology is generally avoided in the lengthy chapter which follows, it will be useful to bear it in mind as the impacts stemming from large reservoir construction projects are documented.

Selection of the parameters for the scope of the effects to be discussed is a difficult task. Ideally, the perspective would be broad enough to show the reservoir's interrelationship with factors such as the natural environment, other projects, the economy, and human welfare generally. Such a perspective would, however, be very difficult to achieve. A somewhat arbitrary decision must initially be made as to the classes of impacts which are to be considered. For the purposes of
this study, the effects are restricted to fall within three broad, interrelated classes: physical effects, biological effects, and human or cultural effects. Physical effects include major changes in the hydrologic system, and generally less obvious changes in the atmosphere and the earth's crust. Biological effects include changes in both aquatic and terrestrial biotic communities. For example, the populations of some species may be eliminated by the construction of a large reservoir, while the emergence or growth of populations of other species may be encouraged. Human or cultural impacts stem directly from reservoir construction, and as consequences of physical and biological impacts. The interrelationships between the three impact classes are complex, and small impacts within one of the classes may have significant consequences within either of the other two classes. It should be made clear that the effects discussed are those caused by the reservoir project. No attempt is made to identify the effects which would occur without the accomplishment of the reservoir objectives, and which are prevented by the successful operation of the reservoir.

In addition to establishing the classes of effects which will be considered, it is necessary to justify the point at which termination of consequences will occur. It will be found in the following chapter that most of the impacts and consequences will ultimately have an effect on man.
Therefore, it seems reasonable to attempt the identification of a sequence of consequences to the point at which man will obviously be affected, or to the point at which remedial measures must be executed to reduce the level of the consequence. This is the basis for establishment of the "final consequence".

The study is composed of two main parts. The first is a documentation of the effects caused by the construction of large reservoir projects in various parts of the world. This section attempts to present a comprehensive cross section of effects, covering those likely to be encountered in any particular reservoir project or proposal. It is a critical basis for the second main part of the study, in which impact identification schemes are discussed and the impact identification framework for large reservoirs is presented and explained. To supplement the basic study a third part is presented in which the impact identification framework is applied in a brief case study. This leads to an opportunity for evaluation of the framework, and discussion of its utilization in the conclusion.

Before proceeding with the study, it is worthwhile to consider briefly why an investigation of this sort should be undertaken. Is the present situation with respect to reservoirs and their unexpected effects unfavourable, and can the
planning profession offer a useful service? It is felt that the answer to both questions is in the affirmative.

Current technology enables use of a high level of competence in the design and subsequent operation of large reservoir projects. From an engineering viewpoint, achievement of the stated objectives with respect to the reduction of flood hazard, hydroelectric generation, the supply of irrigation water, the facilitation of navigation and the facilitation of recreation, may not be too great a problem. However, it is infrequent that primary objectives of reservoir development projects go beyond these objectives. Consideration of secondary effects has not been carried out in a comprehensive manner in the past, and there is little in the way of methodology to ensure such analysis even today. Unless changes are made in the planning procedure it is difficult not to concur with the viewpoint of Thayer Scudder, an authority on population relocation resulting from inundation of reservoir basins, when he states,

"In years to come, I believe that resettlement and development connected with the creation of large-scale man-made lakes will continue to be carried out on a poorly timed, trial and error basis until certain basic policy changes are made; changes which view dams not just as a means for power generation and flood control, but rather as a means for an integrated river basin development designed to raise the standard of living of the total population involved, both urban and rural. The very real problem of timing can be reduced if the necessary fisheries, hydrological, ecological, social and other surveys are included within the original feasibility studies. Though these are apt to continue
over a number of years prior to site selection and the initiation of dam construction (following which a rigid schedule is essential), their scope is much too narrow. Though expansion would increase costs, these are hardly major in terms of subsequent benefits to both the people and the nation" (Scudder, 1966, p. 107).

Clearly, changes are required in reservoir planning. How should these changes come about?

This study is undertaken with the belief that the situation of reservoir planning can be improved through development of a comprehensive methodology to determine the probable effects of proposed projects.

"... A good deal of foresight is desirable to assess the changes which will occur, to prepare for them, to take advantage of those that are favourable, and to take measures against those that are not. This involves research of a multi-disciplinary kind, working up the food chain from the inorganic and physical factors, through the plant links and the animal links to man himself" (Worthington, 1966, p. 4).

The multi-disciplinary nature of the problem provides an excellent opportunity for the planning profession to contribute towards its improvement. The profession should be able to offer a basic understanding, though not necessarily high expertise, in each of the many fields of study which are involved. Further, the profession should be capable of applying its own expertise in the field of assimilating material for the analysis of alternatives, and assembling an output indicating the probable and potential consequences of any particular reservoir.
If successful, this study may contribute towards insuring the harmonious development of reservoir projects. It is undertaken with the clear understanding that even after identification of secondary effects, there are still gaps in the ability to evaluate them. Perhaps new techniques can be devised elsewhere to improve the evaluation process. It must also be stressed that the planner has not the expertise to manipulate the consequences which he predicts. To this end, the cooperation of specialists in a number of different fields is required if reservoirs are to meet primary objectives, minimize negative effects, and maximize positive effects.
2. THE EFFECTS OF LARGE RESERVOIRS

As noted in the introductory chapter, the secondary effects of reservoirs have, for the purpose of this study, been divided into three broad classes: physical, biological, and human and cultural. To present and discuss these impacts and their consequences in an orderly manner, it is necessary to focus upon one class at a time. However, in so doing, it must be born in mind that there are complex relationships of impacts and consequences within and between classes. A physical impact may lead to a biological consequence. This biological consequence in turn may lead to a feedback on one of the objective outputs of the project and to a consequence within the human and cultural class. To give recognition to all the impacts and consequences of a large reservoir project in a subjective review of the type which follows is obviously impossible. The framework which is developed in the following chapter may aid in conceptualization of these relationships. This chapter serves to provide a background for approaching the development of the impact identification framework. The background will be enhanced if the reader makes an effort to conceptualize the linkages between impacts and consequences.

The order in which the classes of effects are presented is not especially critical, though the order followed here
is considered to be the most logical. Physical effects are considered first, followed by biological and then human and cultural effects. It may be anticipated that generally physical impacts will lead to physical, biological and human and cultural consequences. This is a generalization, not a rule; it will be observed that some biological impacts and some human and cultural impacts stem directly from the methods of execution used to meet reservoir objectives.

THE PHYSICAL EFFECTS OF LARGE RESERVOIRS

HYDROLOGICAL EFFECTS

To understand the impact of a reservoir on a watercourse, it is necessary to first focus briefly on some of the hydrological factors in the evolution of an undisturbed, natural stream; that is, a stream undisturbed by man, animal, or natural events such as tectonic activity, earthquakes or glaciation. As water is precipitated to the earth, completing the hydrological cycle, it will move downwards under the influence of gravity. Low points in the landscape will accumulate water. If they are open ended the water will flow downward until it reaches a depression from which it can no longer continue to flow, be it a lake or the sea. As the water moves it is capable of three related actions: erosion, transportation of particulate and dissolved materials and
deposition. These three actions are critical in the development of a watercourse towards the lowest state of free energy. Erosion by overland flow and stream flow will remove particulate material and subsequently wear more particulate material from the soil or rock over which the watercourse flows. Depending on the size of this particulate material, it may be suspended load (held in suspension by the water motion), or bed load (moving in an irregular manner along the stream bed). The faster moving the watercourse, and the greater the volume of flow, the larger the silt load may be. The amount of silt eroded and transported in any particular water basin will depend on the degree of consolidation of earth materials, and their resistance to abrasion.

The normal pattern for watercourses is one in which the gradient increases towards the headwaters, and levels towards the confluence with the sea, lake or other river into which it flows. Thus, the load of eroded material transported by a stream may be maintained by the velocity of the stream at its headwaters, or by the quantity of water in its lower reaches. As the water slows, the load of eroded material will be deposited as silts along the banks or in a delta area at the point of outflow. This overview of the natural stream is highly simplified, but covers aspects which serve to complement the following discussion.
Siltation of reservoirs

Siltation or sedimentation, whether unexpected or planned for, often poses a problem of considerable consequence in both large and small reservoirs. Deposition of the river's suspended and bed loads may be expected to come about as the river water slows in the lake impounded behind the dam. From a purely physical point of view this phenomenon may range from inconsequential to highly significant. Several reservoirs have been rendered virtually useless through collection of sedimentary material. In Texas, New Lake Austin on the Colorado River lost 95 percent of its water capacity to sediments within thirteen years, while in Algeria the Malbra Reservoir lost 58 percent of its capacity within twenty-two years (Barning and Banson, 1969).

Before construction of most large reservoirs the silt load of the river is carefully calculated, and where necessary compared as a ratio of probable annual sediment deposition to reservoir volume. In the case of the Hoover Dam, it has been calculated that each year the Colorado River deposits 224 million tons of silt into Lake Mead (Bardach, 1964). Although this material rapidly built up to a depth of a hundred feet immediately above the dam, it is estimated that the reservoir should not fill with silts for some 500 years. Figures for the Aswan High Dam, in which approximately
twenty percent of the reservoir volume has been allotted for silt build up give a lifespan of several hundred years (Simaika, 1970). It must be remembered, however, that extensive siltation of a reservoir will reduce its storage capacity, thus lowering its potential for hydroelectric generation, flood hazard reduction and irrigation.

The process of siltation generally follows a pattern in reservoirs. During the process of filling of the reservoir, the silt load will be dropped in the zone in which the river waters slow (Leentvaar, 1966). Gradually this zone will move upstream until the headwaters of the reservoir are reached and the impounded lake level reaches its maximum. Thereafter, the current in reservoirs generally follows the old river channel towards the dam, with only moderate mixing with the lake water on either side. The coarser, heavier particles of silt are deposited near the entry of the river into the reservoir, and only small amounts of the very fine material spread out and circulate around the lake (Neel, 1963). This in itself may pose a problem where a layer of fine sedimentary material might be considered a desirable method of reducing the permeability of a reservoir bed. Here again, the Aswan High Dam may be considered as an example. It was hoped that the fine volcanic sediment carried by the Nile from Ethiopia would settle on the 300 mile long side of the reservoir composed of Nubian sandstones.
(Church, 1968; Sterling, 1971). This has not been the case; most of the silt is settling in the deeper, old river channel, apparently leaving opportunity for significant seepage losses (Sterling, 1971).

The problem of sedimentation may be reduced by various techniques in the design and operation of dams and reservoirs. Spillways located at carefully chosen heights in the dam wall may be opened during periods of water surplus, increasing the current through the reservoir and sluicing collected sediments from the reservoir bottom. However, in several cases the spillways have been located too low, and in effect have been sealed by silt before being opened (Berthier, et al., 1970; Liechti and Haeberli, 1970). In France, major modifications were necessary on both the Chambon and the Sautet dams, the former after twenty years of operation, the latter after thirty-two. In each case the reservoirs had to be drawn-down and silt removal was followed by relocation of sluicing spillways (Berthier, et al., 1970). In Switzerland, siltation threatened the operation of the Palagnedra Reservoir, requiring the development of a floating dredge capable of excavating to a depth of 50 meters for removal of silts to a point downstream from the dam. At the point of river entry into the reservoir, a gravel extraction plant was located to remove the river's bed load (Liechti and Haeberli, 1970). The cost of remedial measures to remove silt is
likely to be high in relation to design features for flushing, and is most unlikely to be included in project planning cost studies.

Some sedimentation must be expected in virtually all reservoirs. In the planning stages of any large reservoir project, due account must be paid to the process, not only for its physical effect on the operation of the project, but also for the related biological effects which it induces. These related effects are reviewed in subsequent sections.

Solution of soluble materials in the reservoir bed

Little attention has been given to soluble minerals in the beds of large reservoirs. This situation is understandable, as it seems the dissolution of minerals has never created particular problems. Nevertheless, the factor warrants passing mention, as it could bring about undesirable consequences, and might not be given consideration. In arid regions where the earth surface has had a minimal amount of leaching by precipitation and runoff, a variety of soluble salts may be expected at or near the surface. Inundation will lead to dissolution of these compounds, bringing certain ions into the reservoir waters. It is estimated that approximately twenty million tons of minerals including sulphates, calcium, sodium, potassium, and chloride dissolved into Lake Mead on
the Colorado River within the first thirteen years after Hoover Dam was closed (Neel, 1963). No harmful effects were noted in this case; however, it is quite conceivable that mineral content could render the water unfit for a variety of purposes such as domestic supply, industrial supply, or even the support of a lake fishery.

Development of a reservoir littoral area

The littoral area of large reservoirs may be divided into three distinct zones: the permanent beach, the draw-down zone, and the permanently submerged zone. Because the draw-down of a reservoir is usually far greater than the high to low water fluctuation of a natural lake, the littoral strip will be wide by comparison. The rate of formation of the shoreline of a reservoir is greatest when the reservoir is new, and slows as a dynamic equilibrium of maturity is reached.

The steepness of the reservoir shore and the resistance of the material of which it is composed are major factors determining the final physical form of the littoral area. As currents in a reservoir are minimal, except at the inflow, the major force shaping the shore will be wind created waves. Beach areas may form either from material eroded from the shore, or from river sediments carried to the shore by waves. If the underwater shore slope is steep, waves will not break
until they reach the beach, and erosion landward may be expected if the shore material has low resistance. If, by contrast, the shore slopes gently under water, waves will break before reaching the beach, and landward erosion may be slowed considerably. During periods of draw-down, an underwater bar formed by the breaking waves may be exposed.

As the littoral gradient develops, so too a lineal development takes place. Where shores are dissected by inlets and bays, there will be a tendency towards greater erosion of promontories and lesser erosion of inlets. This may be expected, as the waves will lose much of their energy on the promontories, especially if, as is usually the case, the water off these areas is quite deep relative to that in inlets. In summary, "the common basic tendency of development of the shoreline is equalization of its contour" (Zhivago and Lange, p. 580, 1969).

The draw-down zone of reservoirs is one of the principal features differentiating them from natural lakes. It may be anticipated that the draw-down zone of a reservoir shore of shallow gradient will become a very wide strip of land at low water. A 30 foot draw-down of a reservoir with shores of five percent gradient, for example, will uncover a 600 foot wide strip of shore land. Until the shore reaches a state of even slope, and a smooth line of water to land contact,
the depressions in this marginal area may become stagnant ponds. The character of this part of the littoral area may have an adverse effect on many of the activities occurring along the shore.

It may be concluded that careful planning of the littoral area of a reservoir is a prerequisite to successful multi-purpose reservoir operation. The shore cannot be considered as simply the original contour of the proposed reservoir level, but rather must be contemplated as something evolving from a long term geomorphological process. Careful attention to the draw-down zone may lead to minimization of its negative effects.

Absorption and seepage

The related processes of absorption and seepage may have quite different effects on the operation of a reservoir. The material of which the reservoir bed is composed will allow some penetration or absorption of stored water. Absorptive capacity must be met before the reservoir reaches an operational stage. However, once reached, it will no longer reduce the amount of inflowing water available for the uses for which the reservoir is intended. Seepage, by contrast, may cause considerably greater problems. It involves the
percolation of water from the reservoir to some other area, thus eliminating its availability for reservoir use. If the reservoir bed is composed in part of a permeable rock zone, or if the dam does not form an effective seal with the valley walls, some water will escape, either to an area below the dam, or an area outside the watershed. Though some seepage is expected at most dams, and is considered normal for earth fill dams, failure to forecast the extent of seepage may prevent operation of the reservoir in the planned manner.

Both absorption and seepage are being closely watched at the Aswan High Dam. It is estimated that to achieve saturation of the basin within which the reservoir is situated, 48 billion cubic meters of water will be absorbed, a volume equal to about 30 percent of the reservoir's total capacity (Abu-Wafa and Labib, 1970). If seepage was not a problem, this situation would simply amount to building up an operating balance, after which all further inflow could be relied upon to meet other requirements. Unfortunately, this is not the situation at Aswan. Although opinions as to the magnitude of the problem differ, seepage from the reservoir will significantly reduce usable water (Sterling, 1971, Abu-Wafa and Labib, 1970). Sterling attributes a loss of fifteen million cubic meters annually to seepage from the reservoir basin to other areas. Though this seepage along with other factors threatens to prevent the reservoir from filling by the early
1980's as planned, it may at some future date be highly advantageous. In the event that a number of wet years eliminate the reservoir's capacity to hold back flood waters for regulated discharge to the lower Nile, seepage from the upper 30 meter zone which is intended for flood water storage will reduce the amount of water which must be passed downstream.

Absorption and seepage must be carefully considered in planning a reservoir project. Absorption is of importance in setting the date for initial filling of a reservoir, while seepage may be a factor which prevents a reservoir project from yielding its intended benefits.

Ground water charging

Directly related to seepage of water through permeable underground rock strata is the potential for ground water charging. In this case seepage may be highly desirable to the point that it should be incorporated within the operating goals of a multi-purpose reservoir development. Through the process of ground water charging it may be possible to have water move underground through a natural aquifer to another area, where water near or at the ground surface can be put to good use. It is hoped that some of the water seeping from the Aswan High Dam reservoir will ultimately supplement the water supply in oases located many miles to the east in the Nubian desert.
Charging of underground aquifers with reservoir waters may not always bring beneficial effects. The Sennar irrigation reservoir in Sudan has charged aquifers, but

"... near the frontier (with Ethiopia) the water table, raised by the reservoir, caused the Faras basin to be flooded with salt water. The salt created an agricultural problem ... " (Lewis, 1966, p. 45).

In contrast, Roosevelt Lake, impounded behind the Grand Coulee Dam is considered to have had a highly desirable charging effect.

"... Today the original seventeen lakes in the project area have been joined by a host of new lakes. These lakes rose out of the ground as irrigation water in the area caused the water level in the soil to rise and this higher water table enlarged some of the old lakes, formed new ones, and caused still others to merge into larger bodies of water" (U.S. Department of the Interior, 1964, p. 26).

To accurately predict the potential and effect of charging underground aquifers would be a very difficult task, as it would require almost perfect knowledge of subsurface geology. The cost of remedial measures to relieve deleterious effects is high if not prohibitive, so when reservoirs are constructed there is a definite degree of uncertainty as to the ultimate effect of ground water charging and movement of water through underground aquifers.

**Evaporation from reservoirs**

Natural evaporation may cause a considerable loss of water from large reservoirs. The potential for evaporation
will be determined by a combination of temperature, humidity, and air motion. Reservoirs in windy tropical arid areas will have a very high potential for evaporation, while those in the humid tropics and in temperate areas will be less prone to substantial evaporation losses. At Lake Nasser, preconstruction estimates of evaporation were proven wrong when the dam was closed. Correct allowances had not been made for the increased potential for evaporation because of winds, and as a result losses are one and one-half times those expected, or some fifteen billion cubic meters annually (Sterling, 1971). For small reservoirs it may be possible to reduce evaporation by covering the water surface with a mono-molecular layer of a non volatile solution which will effectively seal the water from exposure to air. On large reservoirs this procedure would be rendered virtually ineffective by continuous wave action. Thus, evaporation remains a problem, especially from large reservoirs in windy arid areas, and from those with wide expanse relative to shallow depth.

Modification of Water Temperature

Creation of a reservoir brings about modification of riverine water temperature in two ways. First, it brings about a lake like situation in which a usual lake temperature pattern may be expected. Secondly, it modifies the
temperature of waters released through the dam.

Large reservoirs simulate the normal pattern of lake temperature changes. In the warm seasons the surface waters warm quickly relative to the bottom waters, and in their expanded, lower specific gravity state remain at the lake surface. Frequently a region of rapid temperature gradient, known as a thermocline, forms a distinct stratification between the lighter, warmed surface water and the heavier, cooler water at the bottom. There is minimal circulation between the two layers, though in the case of reservoirs, the current through the impounded waters which is induced by inflow and outflow may encourage mixing. In the cooler months of the year the surface water will gradually lose its heat, finally reaching the point at which its temperature (and therefore density) is equal to that of the bottom water, and the lake mixes or overturns. Overturn is an important phenomenon in large reservoirs, as it is through this process that oxygen is carried to the reservoir bottom, when the cooled, oxygenated surface water displaces warmer, less dense bottom water. The bottom waters, which may have become devoid of oxygen during the period in which the lake has been stratified, now circulate to the surface and have an opportunity to absorb atmospheric oxygen.

As the downstream movement of water is slowed or halted
in a reservoir, its opportunity to gain or lose energy from the atmosphere in the form of heat is increased. Water released from the dam may thus, depending on the season, have a higher or lower temperature than that which the natural stream would have had at the same time of the year. The pattern which must be expected is one which will "delay river temperature rise in the spring and decline in the autumn" (Neel, 1963, p. 589). One of the effects of this temperature modification is discussed in the following section.

**Downstream ice conditions**

As noted in the previous section the normal riverine pattern of temperature fluctuations is retarded by creation of a reservoir. This may have a noticeable impact on ice formation in rivers downstream from dams in temperate areas. Relatively warm reservoir waters may prevent the natural pattern of ice formation, as has been the case with rivers in the Chesapeake Bay area. This in turn has prevented the previous annual scouring of the riverbed by ice during the break up period (Cronin, 1967). On rivers in areas colder than the Chesapeake Bay area, ice may ultimately form, but because of the slow warming of reservoir water little melting will be accomplished by the underflowing river water in the spring, and break up will be slowed considerably.
Modifications of the natural pattern of ice formation of large rivers may have a considerable effect on other aspects of the environment.

Downstream erosion

As the sediments from the headwaters of a watershed are mostly trapped by large reservoirs, their loss from the river regime downstream from a dam may be expected to pose a number of problems. It seems to be generally agreed that the erosive capacity of clean water is greater than that of water carrying a heavy sediment load, perhaps because of the increase in speed of the water (Aksoy, 1970; Pretious, 1972; Simaika, 1970). Degradation of a river bed downstream from a dam is probable, and problems encountered after the initiation of operation of a reservoir include undercutting of the foundations of bridges, dykes, and other river bank facilities. Although the loss of silt and the downcutting of the river is usually a problem, the factor may be advantageous in rivers in which the silt load hampers other river uses, and sedimentary deposits require removal.

In addition to increased erosion resulting from loss of the river's sedimentary load, a far more rapid form of erosion may take place immediately below a dam. This results when the outflow structures are improperly located and they
"... induce erosion of what was formerly the alluvial side of the river ..., followed by a bank-to-bank shifting of cutting and deposition that removes sandbars of long standing and fills in established channels" (Neel, 1963, p. 589).

Allowance for downstream erosive effects must be made when dams are constructed to create reservoirs. There may be little in the way of preventative design that can be included in the construction of the dam, so costs will follow for corrective measures required downstream after the project is in operation.

**Downstream land modification**

Various changes may be brought upon the river banks, estuarine areas, and the coast of the water body which a river flows into, either from the loss of silt in a river downstream from a dam or from modification of the riverine flow pattern. The natural pattern of rivers is one in which a heavy silt load is carried downstream in the river's high water or flood period, followed by a decreasing to almost nonexistent load at other times of the year. The silt fills a variety of important functions including the building up of natural levees along the river banks, the stabilization or expansion of estuarine deltas, and the provision of beach material to be moved by currents along the shore of the receiving water body. After the dam becomes operational, sediment in the lower reaches of the river is reduced.
considerably, or may be totally eliminated. Not only is the material trapped behind the dam, but also the regulated river may lack sufficient speed and volume to bear a significant load. In the case of the Nile River today, the sediment load has been so reduced by building of the Aswan High Dam, that parts of the delta area are eroding into the Mediterranean Sea at a rate of several yards annually (Sterling, 1971). Other problems are created along the river where the annual flood has been eliminated and the river banks no longer receive an annual deposit of sediments, important both to maintain soil fertility and to stabilize the relationship between land and river. Another interesting example of land modification resulting from dam building is documented by Berthier, et al. (1970). In this case the dam regulated water flow to a low level in comparison to that in the natural river situation. Downstream, a fast, minor tributary, bearing a heavy load of sediments, merged with the river. Prior to dam construction, the volume and speed of the main river was sufficient to bear the tributary's load downstream, however with the main river's flow regulated to a reduced volume, the speed was no longer sufficient to bear the silt material. Gravel, sand, and mud bars built up at the confluence of the two watercourses.

As with many of the other physical effects of large dams and reservoirs, there is not a great deal that can be done
to prevent downstream land modification. It may be possible to flush silt through the reservoir and release sufficient water to scour the river bed, but such measures are only a partial simulation of nature, and the effects will at most be reduced. Other costly remedial measures such as stabilization of the delta areas and construction of spits to divert currents from shoreland may also be necessary.

**Downstream water deficit**

A lack of water release from a reservoir may result in inability to bear the sediment load, as has already been discussed, but this is not the only area in which water deficit is a factor. Also common is the situation where flow regulation by a dam or diversion from a reservoir can lead to drying of downstream lakes and marshes. This situation is prevalent in areas where the dammed river is a principal source of water supply to a lake in a region of minor relief. At least two areas have been affected by drying resulting from flow reduction. In southwestern Asia the levels of the Aral and Caspian Seas have been dropping in recent years. This is the result of damming the inflowing rivers for irrigation and for hydroelectric generation. Between 1961 and 1969, the Aral Sea dropped over one meter, a significant amount for an inland sea with an average depth of approximately twenty-five meters (Goldman, 1970). The Caspian Sea has
dropped 2.5 meters in the past two decades for the same reason. Ultimately these seas may be no more than salt marshes if inflow is not augmented.

In Canada the problem of water deficit resulting from dam construction is currently under investigation in the delta area of Lake Athabasca (Environment Canada, 1971a). The creation of the Williston Lake reservoir on the Peace River has altered a complex natural situation in which water from the Peace annually flooded the delta area and flowed into Lake Athabasca during the high water period. Now, with the reduced flow, most of the delta area is bypassed by the waters of the Peace, which flow directly into the Slave River as they would during the low water period (Schultz, et al., 1970). Breakdown of this complex annual flow reversal situation is leading to drying of delta lakes and conversion of delta marshes to dry land. In order to preserve the delta environment a current crisis program of remedial measures is underway, including construction of a rock-fill dam to impound enough water to inundate the delta in the spring of 1972. There is every indication that the problem which has arisen in this particular delta area was not given any attention in planning the creation of Williston reservoir.

The effect of reduction of downstream discharge cannot
be predicted with precision in the planning of a reservoir project. The matter should receive attention, though, especially in cases where downstream releases will be permanently reduced by diversion. Also worthy of consideration is the effect of gross reduction of downstream discharge during initial reservoir filling. To this end it may be advantageous to slow the filling operation in order to maintain the minimum desirable downstream flow.

**Estuarine salinity**

A third class of problems may arise from water flow reduction caused by a reservoir project. This is in the field of changes in estuarine salinity brought about through changes in dilution by the river water, and is common among rivers flowing from dams to salt water. Soon after closure of the Volta Dam at Akosombo, it was noted that lowering of water flow in the lower Volta was leading to a deeper tidal penetration (Ewer, 1966). The changing salinity gradient had an effect on various forms of life in the estuarine area. Similarly, it has been found that the loss of waters from the Nile River in the Mediterranean Sea has promoted a flow of the highly saline water of the Red Sea into the eastern Mediterranean (Sterling, 1971). This in turn is leading to changes in marine flora and fauna, and salinity of previously fresh water marsh and crop areas. Although river flow
reduction beyond a certain point is harmful, some flow modification may bring more beneficial results. It has been noted that a fast flow of fresh water will stay above heavier saline waters in estuaries, while a slower flow will retard stratification and encourage mixing (Cronin, 1971). In this manner oxygen may be carried to the estuary bottom, a zone which otherwise would be held without oxygen by the stratification of the fresh water overflow.

CLIMATIC EFFECTS

It is well known that large lakes modify the climate of the surrounding land, and it should be expected that in a similar way the land surrounding large man-made lakes will undergo a climatic modification. This modification may include an increase in rainfall, reduction of temperature extremes, and retardation of seasonal changes.

The climatic effect of Volta Lake in Ghana is being carefully watched and statistical experiments have been conducted to see if there is a significant change (De-Heer Amissah, 1969). It is to be expected that the warm monsoon air masses would have the greatest capacity for evaporation and that their accumulated moisture will precipitate on northeastern Ghana, while southern Ghana will receive a lesser amount of precipitation from the cooler north easterly
winds. To establish whether this is in fact the case will require observation over a number of years, but it is unlikely that such macro-climatic effects will be significant. Climatic changes of lesser areal extent, however, have already been established (De-Heer Amissah, 1969). At Kete-Krachi, on the shore of the new Volta Lake, monthly temperature maxima and minima are respectively lower and higher than in the period prior to reservoir construction. Humidity at this location has also risen.

Climatic effects of Kariba Lake on the Zambezi River are expected, but seem not to be well documented. It is hoped that Kariba will increase humidity sufficiently to cause an increase in precipitation, and this in turn will lead to increased agricultural productivity on the escarpments between which the river flows (Cole, 1960).

In temperate areas reservoirs may also be expected to cause climatic changes. A proposed major water project in the James Bay area of Canada would create large lakes which during the winter would be ice covered. It is postulated that the effect of these lakes will be a local lengthening of the winter, brought on by the length of time required to melt through the ice (Hare, 1972).

Climatic changes induced by large reservoirs will not
be of great magnitude. However, the importance of these changes should not be underestimated. In one case, increased humidity and extra precipitation may open up an agricultural potential, while in another the reduction in temperature extremes may promote breeding of the carriers of diseases. Forethought must be given to these and other possibilities, if positive effects are to be enhanced and negative effects met with preparation for a minimization of consequences.

EARTHQUAKES

It is now recognized that seismic activity can be correlated with the loading of the earth's crust brought on by the filling of a large reservoir. Two factors may be seen as inducing earthquakes or tremors. The sheer weight of the impounded water will cause a sinking of the earth's crust, marked by sudden movements along sheer zones. These movements are further induced by water penetration along faults and shears, which serves to lubricate movement between two rock surfaces that would otherwise be held immobile by friction. In either case, seismic activity may result. There is no evidence however, that earthquakes are caused by reservoir filling; rather their occurrence is induced at an earlier time than would have been the case in a natural situation.
Extensive damage has been caused by earthquakes associated with reservoir loading in various parts of the world. The most devastating seismic activity occurred in 1967, about 150 miles southeast of Bombay, India, near the Koyna reservoir. Some two-hundred deaths were caused in this earthquake. In Greece there has been considerable seismic activity in the vicinity of the Marathon and Kremasta dams. This has led to land slumps and slides, destruction of 480 houses and damage of over 2,000 others (Rothe, 1968). Much seismic activity is associated with the filling of Lake Kariba, with two shocks registering magnitudes of 5.8 (Gough and Gough, 1969). No significant damage is attributed to these relatively high magnitude shocks. Other records of seismic activity are available from most, if not all, large reservoirs where equipment is available for measurement.

It may be concluded that:

"... there are strong indications that impounding of reservoirs, loading of lakes and changing their levels can induce seismic activity in the immediate area, particularly if the area is geotectonically unstable. Moreover the above mentioned disturbances on the crust can trigger off earthquakes even in areas where earthquakes are rare, but where stress and strain relations in the rock are such that disturbances on the surface cause elastic rebound in depth. These delicate stress-strain conditions are usually difficult to detect in what are generally known as stable areas, and appear only when loading is already in progress." (Kall and Charalambakis, 1970, p. 798).

In planning large reservoirs allowance should be made for the possibility of earthquakes. Although they may not occur,
the magnitude of disaster possible, warrants considerable concern, and the planning of relief measures in case they may at some time become necessary.

* * *

This concludes the section dealing with physical effects. It will be seen in the following two sections of the chapter, which cover biological, and human and cultural effects, that there are extensive relationships between the three categories, and that many of the latter consequences stem from changes in the environment which are either induced by, or are a part of the physical effects which have been considered.

**THE BIOLOGICAL EFFECTS OF LARGE RESERVOIRS**

The creation of a large reservoir has a considerable effect on flora and fauna, not only within the reservoir basin, but also around its periphery and downstream from the dam. The effects are felt over a large area, in part because of the complex relationships and interdependencies between different species. To fully document the effect of removal of even one species from the structure of a complex ecosystem would be a task at least equal in magnitude to the preparation of this paper. An equally comprehensive documentation of the effects of changes in or removal of
the number of species involved in a large reservoir situation is likely impossible. Obviously, this section does not attempt such rigor, but rather focuses on the biological impacts which have had an obvious effect on man at various reservoir sites, and seeks to indicate the consequences of these impacts.

EFFECTS WITHIN AND IMMEDIATELY ADJACENT TO RESERVOIRS

Effect of reservoirs on riverine oxygen and nutrient levels

Before concentrating directly on biological effects, it is necessary to consider the biologically relevant physical and chemical situation within a newly formed man-made lake. This might be considered a physical impact, and as such would be expected in the previous section, however, the biological development brought about by the reservoir is so directly related to the physical and chemical composition of the new lake that the discussion falls most logically as a preface to coverage of the biological effects.

With the inundation of a terrestrial land area the vegetation of the area will be drowned. A natural consequence is decomposition of the plant and other organic matter at a rate governed generally by the availability of oxygen and the temperature. Thus, with the closing of a dam and
subsequent flooding of land, there will be a heavy demand for dissolved oxygen around the submerged organic material. Generally, the rivers on which reservoirs are located have a high dissolved oxygen content until impoundment occurs. This level is maintained in the natural riverine conditions by exposure of the water to the atmosphere, and constant mixing as it flows or cascades downwards, and to a lesser degree by gas exchange from aquatic plants. But, soon after a dam is closed and decomposition of terrestrial plants begins, the oxygen content of the impounded water is reduced or altogether eliminated. Lake Volta, impounded behind the Akosombo Dam in Ghana is typical. At the time of dam closure the river water was up to 300 percent saturated with oxygen. Within four weeks this level fell to sixteen percent saturation at the surface, and zero at a depth of ten meters. In the subsequent months, the surface oxygen level remained low and at depths of five and ten meters rarely reached ten percent (Ewer, 1966). Although reoxygenation occurs both directly from the atmosphere, and from inflowing water, it is unlikely to keep pace with the oxygen demand of decaying vegetation.

The initial decay of vegetation in reservoirs makes them quite unlike natural lakes. In a natural lake, the nutrient level is initially low, but gradually increases through geological time—the lake progresses from an oligotrophic state to
a eutrophic state. The reservoir, however, has a very high initial nutrient level brought on by the decay of submerged terrestrial organic matter and the consequent release of "stored" phosphates and nitrates. Later discussion will indicate the effect of this rich nutrient load on the populations within the reservoir. The progression of the reservoir is opposite to that of the natural lake (at least in the short term, until a post stability period is reached), and the nutrient level gradually falls as the organic material on the reservoir bottom decays, and the nutrients pass downstream from the dam.

The eutrophic state of a newly formed reservoir may be strengthened by thermal stratification of water. As noted previously, a thermocline is likely to develop in any large lake. The upper layer or epilimnion has contact with the atmosphere, and therefore maintains a high level of dissolved oxygen. However, there is little mixing of the epilimnion and the hypolimnion. Thus, as the oxygen in the hypolimnion is exhausted by decaying organic matter, there is no supply to replace it, except in some cases the relatively minor supply from the inflowing river. Only during the period in which the reservoir water overturns and mixes is there opportunity for restoration of the oxygen level in the hypolimnion.
The Kariba Reservoir on the Zambezi River provides an example of hypolimnion oxygen exhaustion during the annual period of stratification. When the reservoir reached its maximum depth, the upper 90 foot layer warmed during the summer months, and there was little mixing with the water below this level. Oxygen depletion followed stratification and the lower water remained devoid of oxygen until the lake overturned during the cool period in July and August. The situation repeats itself annually, however, as the mass of decaying organic matter is decreasing the length of the period with no oxygen shortens annually (Coulter, 1967). In the Kariba reservoir, as in many others, decomposition in a state with low dissolved oxygen levels also caused high concentrations of hydrogen sulphide. At the Brokopondo Reservoir in Surinam, hydrogen sulphide concentrations built up to such an extent that the pH of the river water dropped from 6.5 to 5.5 (Leentvaar, 1966). In contrast with most large reservoirs the expected stratification of water in Lake Volta has never occurred. Although there is minor temperature layering and considerable oxygen depletion, at no time has there been indication of distinct stratification preventing mixing of top and bottom waters (Ewer, 1966). Regardless of the exact course of events these three examples indicate the normal trend in newly filled reservoirs—a situation in which oxygen levels decline, nutrient levels rise, and the evolution of hydrogen sulphide leads to a decrease in the pH, or increased
acidity of the lake and downstream river waters.

The decomposition of organic matter is not the only factor which contributes to the high nutrient levels which are common to reservoirs. Even after decomposition has exhausted the supply of nutrients which may evolve from the reservoir basin,

"... fertility, while at a lower level than the exceptionally high initial stages, may well remain higher than would be the case in comparable natural waters, since inflowing rivers usually bring a greater volume of water, and with it nutrients into man-made than into natural lakes unless the latter are of relatively small size" (Jackson, 1966, p. 59).

In comparison with natural lakes which may take decades or even centuries to achieve inflow equal to their volume, man-made lakes are generally expected to fill within a few years after closure of the dam. This relatively high inflow and through flow, coupled with deposition of nutrient bearing silts, yields the potential for a continuing high level of biological productivity in reservoirs.

Effects of clearing reservoir basins

In the planning of large reservoirs, consideration is usually given to clearing of the basin which is to contain the impounded waters. Rationale for this procedure usually stems from aesthetic reasons, or the desire to create areas suitable for navigation or fishing without the snagging of
lines or nets. The clearing of vegetation may also have more direct biological implications. Commonly, where clearing is carried out, a good deal of the organic material will be burned within the basin. The ash left from this process will have the effect of considerably increasing initial nutrient levels as it is more soluble and requires less decomposition than would the material from which it was derived.

The effect of failing to clear a reservoir basin may be highly variable depending on the topography of the basin, and the vegetation being inundated. In a steep sided basin, all vegetation except that around the edges will be deeply submerged and will have little effect on water circulation within the reservoir. A relatively shallow reservoir such as Lake Volta may also be filled with a minimal amount of clearing. Here, the sparse savanna vegetation within much of the impoundment area will create few problems. Clearing of more extensive vegetation along some of the periphery can now be accomplished during draw-down periods. At the Brokopondo Reservoir, however, failure to clear vegetation has had a very definite effect. Circulation of water through the drowned vegetation is minimal and the lake has rapidly turned into a large swampy area, with stagnant water organisms and extensive growths of algal mats and duckweed (Leentvaar, 1966).
Preinundation land clearing around the shores of Lake Kariba brought unanticipated benefits soon after the dam became operational. A water weed, *Salvinia auriculata*, grew at a very rapid and completely unexpected speed while the reservoir was filling. During this period the water was held relatively stable by submerged vegetation, but as the water reached its maximum level the cleared land became inundated. Winds and wind created currents and waves were then able to blow the *Salvinia* around the lake and the motion broke up many of the weed masses, significantly reducing the problems which they had created.

Faced by the usual situation in which complete clearing of a reservoir bed would be prohibitively expensive, authorities may plan their action to maximize the effectiveness of a partial clearing. If biological productivity of a reservoir is considered to be of importance in the development of lake fisheries, but only small amounts of clearing are possible, the upper reaches of the water might best be cleared. Here the water will be shallow and photosynthesis may be expected to occur right to the bottom (Jackson, 1966). Clearing of the areas around river mouths will also prove to be advantageous, as here the greatest effect of dissolved nutrients carried in the inflowing water will be realized. Other clearing may be important to facilitate navigation and for aesthetic purposes. A comprehensive plan for clearing is
necessary to ensure the desired effect at both high water and draw-down. Clearing after inundation may prove to be a difficult and expensive undertaking.

**The effects of silting**

As discussed previously, the construction of a dam and filling of a reservoir changes the normal patterns of silt transport and deposition along a watercourse. Both within the reservoir and downstream from the dam, the slowed flow of water lacks sufficient energy to keep the silt in suspension. Deposition of this silt may cause biological problems.

On the Mississippi, with twenty-six dams between Minneapolis and St. Louis,

"... the flow of the water has become so slow that it can carry in suspension only the very finest silt and colloidal particles. All the rest settles, some of it on the mussel beds." (Bardach, 1964, p. 105).

The choking effect on the mussels is obvious. The Mississippi has also suffered a decline in numbers of paddlefish. This is

"... attributed mainly to the building of dams on the upper river; these have meant more silt and fewer sand and gravel bottoms which are the animal's preferred spawning sites." (Bardach, 1964, p. 113).

Excessive siltation at the upper reaches of reservoirs and around their shores, in addition to reducing animal populations, may also be expected to choke water plants, resulting
in a breakdown of the evolving chain of food dependencies between plants and animals. It should be noted at this point that silting is often an unnecessary problem

"... caused by soil erosion, itself a consequence of mismanagement of the (upstream) land due to bad agricultural practices" (Jackson, 1966, p. 60)

The effects of draw-down

Draw-down will have an effect on organisms living along the shore of a reservoir, and below the high water level. The effect can in some instances be quite beneficial. Emergent plants (rooted below water but emerging into the atmosphere, such as reeds and some grasses) often pose a problem to human activity along reservoir shores. Elimination through mechanical or chemical means is expensive, and may additionally be somewhat risky to other organisms. Rapid draw-down, however, can be used to expose roots and kill, at least for a short term, the plant populations. By the same technique spawning beds may be intentionally exposed to eliminate fish species which are considered undesirable. Games with nature, such as the use of draw-down to eliminate living organisms, are complex and risky, and must be preceded with cautious planning. Fish species which are considered undesirable may in fact be an important link in the food chain for a valuable fish species; unaesthetic water "grasses" and reeds may shelter communities of planktonic and other
organisms which are critical in food chains. Draw-down, such as that accompanying power generation in a low river flow period, may be a useful means of biological control, but it also has the potential to worsen already troubled situations.

**Weed growth in reservoirs**

High nutrient levels which are common in the evolution of reservoirs provide an ideal environment for growth of water plants. Though there are few species of floating vascular plants, their presence in tropical reservoirs has created a number of unexpected problems. Temperate reservoirs have been affected to a lesser extent, as floating vascular plants are not adapted to growth in cool climates. Three plant species have been the cause of most tropical reservoir weed problems: *Eichhornia crassipes* (water hyacinth), *Salvinia auriculata* (water fern), and *Pistia stratiotes* (water lettuce).

Lake Kariba has suffered from the greatest growth of water plants. Soon after impoundment began, *Salvinia* was noticed floating in the water and within three years the growth covered areas totalling 250 square miles (Coulter, 1967). As the growth of *Salvinia* was unexpected, no measures had been planned for its control.

"However, once the cleared sections were flooded
the mats of weeds soon broke up under wave and wind action, and today the infected areas are confined to those regions where bush clearing was not carried out, where semi-submerged trees are abundant and in most river estuaries and bays." (Harding, 1966, p. 18).

Even though the situation was thus relieved at Lake Kariba, *Salvinia* and *Pista* still grow in the reservoir and present problems in the intended reservoir operations.

At least minor weed growths have been documented within or downstream from most tropical reservoirs. In the Jebel Auliya Reservoir on the White Nile, *Eichhornia* grows extensively and a major program has been required to prevent its spread downstream into Lake Nasser. At the Brokopondo reservoir in Surinam, *Eichhornia* has spread rapidly through the shallow, almost stagnant reservoir. With the outbreak of *Salvinia* at Lake Kariba there was considerable fear that the weed would also infect Lake Volta, however this has not been the case. In fact, *Salvinia* has not posed a problem in any reservoir except Kariba; it is a good example of a new species finding an empty niche in the ecosystem and growing explosively in ideal conditions and with a lack of organisms dependent on the species for food. In Lake Volta, there has been some, though not extensive growth of *Pista*. The dam has, however, brought about plant growth downstream of the reservoir. Rapid development of *Potamogeton octandrus* and *Vallisneria aethiopica*, both submerged species, is considered to be due to a lack of river bed scouring by annual flood waters (Hall and Pople, 1968).
The growth of water plants in reservoirs can pose a variety of problems: (1) they may be blown into channels blocking inflowing water, or being sucked into outflow structures and turbines, (2) they may impede or prevent navigation, (3) they can bring about deoxygenation and cause fish losses, (4) they can substantially reduce reservoir volume, and (5) they can, through evapotranspiration, cause a substantial increase in evaporation losses. On the final point, one researcher is cited as stating that *Eichhornia crassipes* can bring about a six-fold increase in evaporation (Little, 1966). If this is actually the case, extensive growth of this weed could prevent the operation of some reservoirs, for evapotranspiration would equal inflow.

Plant growth in temperate reservoirs may be considered a less serious problem than in tropical reservoirs. Few floating vascular species are found in temperate areas, so growth is limited to the periphery of the reservoir where light penetration to the bottom is possible. A depth of 30 feet is the maximum from which submerged plants are likely to grow. Emergent plants will grow even closer to the shore. Though they can be unaesthetic and deleterious to some human shore uses, they provide a habitat for many of the micro-organisms upon which reservoir fauna will be dependent for food.
Shore vegetation around reservoirs

In addition to growth of water weeds within a reservoir, changes may be expected in plant species around the edge of a reservoir and in some cases downstream from the dam. In the proximity of the reservoir shore, the ground water table is likely to rise relative to its old position, and rather than experience seasonal fluctuations, its level will relate to the reservoir level. Vegetation similar to that around the shores of natural lakes is to be expected. In areas with minor relief, swamp and marsh development is likely, while in well drained areas with greater relief, there will be little change, except at the immediate edge of the water. Moderation of temperature extremes will be reflected by the vegetation around a reservoir, providing the moderation is maintained year round by ice-free conditions. If creation of the reservoir results in climatic changes, the vegetation throughout the areas affected will undergo a long term change.

The controlled flow of the river will cause vegetation changes downstream from a dam. Seasonal fluctuations in the water table will be reduced or eliminated and there will usually be a net reduction in soil moisture content along the banks (Lagler, 1971). In estuarine areas the controlled flow of waters has caused the drying of marshes. Sedge
marshes in the Peace-Athabasca delta, for example, are being effectively drained, and dense willow thickets are likely to take their place (Schultz, et al., 1970). This unanticipated effect of the Williston Reservoir will seriously reduce the foraging area for bison of Wood Buffalo National Park.

EFFECTS ON THE FAUNA OF THE RESERVOIR AREA

Insect populations

The impounding of large quantities of water in reservoirs provides an ideal breeding habitat for a variety of insects, both in the swampy shore areas, and in the modified, reduced flow downstream from the dam. Often these insects develop to become carriers of serious disease as discussed in the immediately following section.

Examples of insect population changes can be documented for most reservoirs. The Jebel Auliya Reservoir, built upstream from Khartoum on the White Nile in 1937, provided an environment suitable for insect breeding within the reservoir and also downstream from the dam (Lewis, 1966). Draw-down of the reservoir results in the formation of pools surrounded by sand bars, which provide a habitat for larvae of the mosquito, Anopheles gambiae, which is the carrier of human malaria. Downstream from the dam, floating rafts of
papyrus become stranded along the river banks and support an ecological succession leading to the growth of *Anopheles pharoensis*, a less dangerous species of mosquito.

Changes in fish populations have led to increases in insect populations. Near Astrakhan, at the mouth of the Volga River, the declining level of the Caspian Sea has eliminated spawning grounds for the belyi amur, a fish which feeds on mosquitoes. With the increase in swamp area and decrease in populations of belyi amur, the mosquito population has grown and begun to carry malaria (Goldman, 1970).

Although not strictly within the parameters of a discussion of reservoirs, the closing off of the Dutch Zuider Zee by dykes in 1935 led to an interesting insect population increase. Without natural fish predation on the larvae, midges of the *Tendipes* group rose in clouds from the moist swampy areas which were still drying in 1938 (Vaas, 1966). This situation fortunately has not repeated itself, as the reclaimed land has become too dry to support the midge larvae.

**The effect of reservoirs on the carriers of disease**

Reservoirs frequently create habitats suitable for the growth of carriers of diseases. These disease vectors lead
to considerable loss of livestock, economic hardship, and human suffering if they are not quickly brought under control. The principal diseases carried from reservoir conditions include bilharzia, malaria, trypanosomiasis (sleeping sickness), and ochoceriasis (river blindness). In addition to growth of populations of disease vectors, populations of insects may grow which cause epidemic allergies in human populations, or which are a general nuisance. The problem of reservoirs leading to growth of disease vectors and insect pests is greatest in the tropics.

The problem of malaria has been increased in the United Arab Republic by the building of dams. In Sudan, Anopheles gambiae, the vector of malaria, breed in reservoirs and irrigation canals (Lewis, 1966). Malaria has also become a problem around the still forming Lake Nasser (Dorcey et al., 1972). Though the mosquito can be brought under control by spraying of breeding areas with pesticides or oils, such measures present unanticipated costs and harmful side effects.

With the creation of Lake Kariba, there has been a problem with trypanosomiasis, which is carried by the tsetse fly. Parasitic blood trypanosomes have infected the natives' cattle, causing serious disease and presenting extra problems for the groups of people dislocated from homes within the reservoir basin (Henkin, 1969).
Although propagation of the blackfly, *Simulium*, the carrier of ochoceriasis, is not promoted by the existence of reservoirs, the fly has presented problems during construction of tropical reservoirs. The fly requires fast flowing water for egg and larval stages, and ideal breeding sites are often in the vicinity of dam construction projects. Blindness is not always a consequence of bites by the fly (Warmann, 1969), but understandably the possibility provokes fear amongst construction workers, and in cases this fear has led to construction slowdowns. In any case, the completion of dams and slowing of waters in reservoirs is an effective deterrent to further breeding of the flies, except in confined locations such as spillways, which can be carefully watched for infection. Elimination of ochoceriasis should be a goal in the construction of any reservoirs in areas where the disease is prevalent.

The greatest disease hazard introduced by reservoirs is schistosomiasis or bilharzia. The disease is caused by a Trematode blood fluke, hosted in an immature stage by snails which find a habitat in slow or stable water. Reservoirs are an ideal breeding ground for the snail hosts, as compared to the natural flowing river. Two forms of the disease are prevalent, the urinary *Schistosoma haematobium*, and the more dangerous intestinal *Schistosoma mansoni* (Henkin, 1969). Existence of water weeds such as *Salvinia* further improves
the habitat for snails, and increases the hazard of infection (Hira, 1969). The effect of schistosomiasis on human populations is discussed in the section dealing with human and cultural effects.

The Aswan High Dam has led to increased populations of the fly, *Tanytarsus*, which brings on an asthmatic allergy in large portions of the population. The problem became so acute at Wadi Halfa, a town near the shore of Lake Nasser at the border between Egypt and Sudan, that an asthma camp had to be built in the desert, and relocation of the town was considered.

The problem of diseases born from newly created reservoirs is far from being solved. Even if massive inputs of biocides were successful in controlling or eliminating vectors of disease from reservoirs (and as yet this is not the case), the side effects of such measures could outweigh the benefits. Luckily, temperate reservoirs have not led to the development of serious human disease vectors. On the other hand, they must be recognized as potential breeding sites for livestock parasites and disease vectors, and insects which cause considerable human nuisance. Continuing research is essential to reduce disease and insect problems brought about by reservoir construction in all climatic areas.
The effects on wildlife

The filling and existence of a reservoir can have wide ranging impacts on wildlife. During the filling of reservoirs the most sudden effects occur, as animals are stranded on high portions of ground within the reservoir area. Strand- ing of animals by the rising waters of Lake Kariba aroused world wide attention, and with the help of voluntary funding from all over the world a last minute rescue operation was launched in which some three-thousand animals including birds, reptiles and miscellaneous mammals were transported from islands to the reservoir edge (Clements, 1959). By contrast, there appear to have been few animals endangered at Lake Volta, even though rescue procedures were poorly planned and executed (Asibey, 1969).

Of greater long term significance than the initial effect of rising reservoir waters, is the change in animal habitats brought on by the construction of dams and the filling of reservoirs. Inundation of limited grazing areas may threaten animal species, or downstream changes in habitat may reduce food supply. Sedge marshes at the Peace-Athabasca delta are drying as a consequence of reduced flow in the Peace River. These marshes are critical for the foraging of bison, and provide a habitat for large populations of muskrat which have provided trapping income for native
people. Further changes may come about in this delta area as the lakes dry and there is a reduction of the area suitable for migratory birds and various other fur bearing animals (Schultz et al., 1970).

Careful consideration must be given to wildlife habitats in the planning of reservoir projects. It is not enough to simply assume that animals will go away from the reservoir area and that all will be well. For many species a particular habitat at a particular time of the year is critical, and its removal may eliminate the species population from the area.

EFFECTS ON ANADROMOUS FISH

**Upstream migration of fish**

The damming of large rivers has resulted in serious population declines of anadromous or migratory fish species. For the fish, construction of a reservoir poses a variety of threats to both upstream and downstream migration. The dam itself is, of course, a major barrier to the fish. However, in the upstream migration, problems may arise soon after entry into the river.

The first change a migratory fish is likely to experience
because of an upstream dam, is in the temperature of the river water. During spawning season the water in a river may be at a considerably higher temperature than would be the case if the reservoir was not present. Migratory species along the North American Pacific coast are generally capable of withstanding temperatures under 68 degrees Fahrenheit, however, after storage in a reservoir this temperature may be exceeded. A minor temperature change may be all that is required to change a marginal environment into a lethal one (Hoar, 1956).

Some fish may be expected to spawn between the estuarine area and the first dam on a large river. Even if temperature modification does not pose a threat, other factors may prevent normal development of the eggs. Discharge of reservoir waters from below the thermocline may bring the dissolved oxygen content below the minimum required for development (Hoar, 1956). In the autumn, when many salmon spawn, hypolimnion oxygen content is likely to be near its minimum annual level. Siltation of spawning grounds below reservoirs may also threaten development of eggs. Water levels are naturally low in the autumn, but dam storage can reduce levels further and the slower, lower volume downstream discharge will lower capacity for moving silt downstream and beyond spawning areas.
The dam is a major obstacle for fish. Current practice in North American and European projects is construction of fish ladders through which the fish may proceed from downstream of the dam to an exit within the reservoir. Placement of the entrance of fish ladders is a critical factor in determining their usefulness. Fish apparently prefer to head into the strongest current. If the water flowing from the ladder does not attract their attention, they will continue upstream to the base of the dam. The success of fish ladders is also limited by their height, and for dams over about 100 feet in height, spawning success is low.

Once an anadromous fish is safely within the reservoir there are still hazards which may prevent spawning. Current through the reservoir can sweep fish over the dam or through the turbines, events that will probably prove to be too much of a strain for a fish which is nearing the end of its life. Careful placement of ladder exits should minimize the possibility of the fish being swept downstream. However, too great a current reduction at the reservoir exit of the fish ladder will confuse the fish, which is dependent on current for navigation. Further, circular currents may occur within the reservoir, leaving the fish swimming in circles, rather than through the lake. Delay within the reservoir may prevent spawning. Cumulative delay in several reservoirs increases the probability of spawning failure.
A final hazard to spawning is the inundation of spawning beds under reservoir waters. Fish such as salmon are dependent on rapid water flow to supply oxygen to the eggs, so shore zones are of little use for spawning. Spawning beds in the main river may be lost for miles upstream from the dam and the reduction of effective length of the tributaries will lead to crowding.

Efforts to minimize the effect of dams on the spawning pattern of anadromous fish have been less than altogether successful. The experience gained in a large number of projects is, however, leading to the design of considerably improved facilities for handling fish.

**Downstream migration of fish**

Even after successful spawning and hatching of fry has come about in rivers blocked by dams, the young fish may encounter difficulties in their journey downstream. Two basic problems exist: passage of the fish through reservoirs, and damage to the fish as they pass from reservoir to river, whether through turbines or over spillways.

The reservoir lake presents a completely unnatural situation for fish such as chinook salmon, which normally spawn below any lakes on a river. As the young fish enter the
reservoir and current slows, they may delay their downstream trip, spending several weeks feeding in the reservoir. When they continue, the reservoir waters will have warmed, and being a cold water fish, they are likely to head upstream to the reservoir inflow, which will be colder river water (Bardach, 1964). Such confusion may cancel the migratory urge, and the fish will live a modified life cycle in the reservoir.

Passing through or over a dam creates a hazard in the downstream movement of all migratory fish. Riding the water over a dam spillway may cause a young salmon

"... to be subjected to considerable changes in pressure or ... a vacuum for a brief period. Water passing over the spillway of a dam may fall free of the spillway face and produce a 'cavitation' phenomenon which actually amounts to a local vacuum. Hamilton and Andrews consider cavitation the most important possible cause of injury to downstream migrant salmon on spillways and in turbines." (Hoar, 1956, p. 21).

The alternative to passage over the spillway is passing through the turbines. Though the young fish may obviously suffer from bruising and abrasion, the trip is not so dangerous as it at first sounds, for the turbine blades are widely spaced and the rotation is relatively slow. Scottish experiments indicate a mortality rate of ten to twenty percent in test situations with a 170 foot head of water. The cumulative effect of subjecting downstream migrants to a number of reservoirs and dams must be recognized (Pyefinch, 1966).
EFFECTS DOWNSTREAM FROM RESERVOIRS

Effects resulting from the release of fouled waters

At various times of the year it may be desirable to exhaust water from below the thermocline, flushing sediments from the reservoir bottom. This procedure must be carefully considered, as the release of deoxygenated water may have harmful effects on the downstream flora and fauna (Jackson, 1966). The bottom waters are likely to also contain concentrations of hydrogen sulphide and other chemicals which develop after anaerobic conditions occur.

Effects of the loss of downstream sediments

Failure to release sediments from a reservoir may have several effects on downstream biology. These include the lack of silt which is essential in maintaining the fertility of soil on the alluvial river banks, reduction in nutrient levels, and changes in the estuarine environment.

Loss of fresh supplies of silt from river banks will lead to decline in soil fertility, especially in locations where agriculture is practiced on the alluvial flats. Along the Nile River fertilizer is already required because of the capture of sediment behind the Aswan High Dam (Sterling, 1971).
Even in cases where alluvial soil is not cropped, reduced fertility may lead to changes in vegetation along the river and within the river channel. These vegetation changes may be reflected by changes in populations of dependent animals. Further discussion of the effect of lowered silt deposition downstream from dams is found in the following sections.

**Effect of reduced flows on downstream fish**

Reduced downstream flow resulting from the operation of a dam may seriously reduce spawning activity of fish species which spawn in lakes or estuarine areas. In the Caspian Sea, which has dropped by 2.5 meters from damming and diversion of inflowing rivers, the spawning area suitable for sturgeon has been reduced in area by one-third (Goldman, 1970). This factor, coupled with oil pollution, has brought a sizeable decline in the sturgeon catch and a drop in caviar production. The Peace-Athabasca delta and Lake Athabasca are also suffering from water shortage, in this case caused by impoundment of water in the Williston Reservoir. In the delta area pike spawning beds have been exposed in all but the deepest channels, while along the lake shores the spawning beds of the cisco have been exposed for two consecutive winters.

"... It is to be expected that the commercial fishery in Lake Athabasca will collapse within three to five years as recruitment to the harvestable fish populations
of walleye, pike, and lake trout declines, and as stocks of cisco are eliminated as the basic food supply for the carnivorous species listed above."

Although the creation of a reservoir may bring into existence a habitat suitable for the existence of different fish species to those in the riverine situation, it must be remembered that elimination of the riverine conditions is likely to eliminate or reduce populations of some existing fish species.

**Estuarine changes and off-shore fisheries**

The combination of downstream changes in the nutrient and silt load induced by reservoirs, and changes in estuarine salinity will bring about biological consequences in the estuarine and the off-shore areas. These effects may in turn bring about serious economic losses.

The change of estuarine salinity brought about by reduced river flow and greater inland tidal penetration may reduce desirable habitats for some species and enlarge the habitats of others. As an example, the Volta Dam has decreased flow on the lower Volta River. There are indications that rising salinity has had an adverse effect on the clam, *Egeria*, which is of considerable economic importance, and which is not found in other large rivers along that part of the African coast (Ewer, 1966). The Volta problem should
be lessened considerably by this time, as flow was initially very low during the reservoir filling stage. Now, in an operational stage, the river flow is back to a higher level and it is hoped that the clams will reestablish themselves. If they do, it is a case of good luck rather than planning.

Though increasing salinity decreased the habitat for Egeria, it may increase the habitat suitable for other organisms. Thus oysters which have been protected from the oyster drill, Urosalpinx cinerca, by low salinities which are unfit for the drill, may now fall prey when river damming reduces flow and increases estuarine salinity. Again, economic interests may be destroyed.

The estuarine habitat is of great importance as an area of high nutrient levels which support the productivity of off-shore fish species. With high nutrient levels from the inflowing river, relative to the sea coast generally, estuaries are capable of supporting large and productive biological communities. Dams, such as the High Aswan, may seriously alter the rate of input of these important nutrients. At the delta of the Nile,

"... the lack of (Nile) sediment has reduced plankton and organic carbons to a third of what they used to be, either killing off the sardines, scrombroids and crustaceans in the area or driving them away" (Sterling, 1970, p. 46).

As a result of decreased biological productivity in the Nile
delta area, nutrients necessary to maintain the sardine population are no longer available. The catch which used to amount to approximately 18,000 tons per annum before the operation of the High Aswan dam had dropped to 500 tons in 1968 (Dorcey, et al., 1972).

Though the form of and effects of changes in estuarine areas induced by reservoirs cannot be predicted with a great deal of accuracy, recognition of their likelihood should be given in the planning of a large reservoir. This should be followed by careful monitoring of estuarine conditions after closing of the dam, and inclusion of plans for decreasing initial water storage if necessary to maintain desirable estuarine conditions.

THE BIOLOGICAL STABILIZATION OF RESERVOIRS

The establishment of a stable, interdependent biological community in a reservoir is not a rapid process. Initially the high nutrient level of the newly formed lake will lead to high productivity and great population growth of many species. This situation should persist for several years, with growth of weeds such as the Salvinia in Lake Kariba and high fish catches as indicators. A few years after the filling of a reservoir, however, biological production will decrease and some species populations will decline. This
process is brought on both by the decrease in nutrient levels and by the inability of some species to adapt. At Lake Kariba, the initially high population of bream, *Tilapia mortimeri*, declined rapidly after 1968, either because of inability to adapt completely to the lacustrine situation, or because of population adjustments relative to its predator, the tiger fish (Coulter, 1967).

The creation of a new habitat is very likely to present niches which will not be filled naturally for many years. This factor may encourage introduction of new species, which appear to be highly desirable, and which may be well equipped to contend with adverse conditions such as draw-down or water turbidity. However,

"... the whole question of introducing organisms to environments foreign to them and where they may have no natural enemies or parasites is delicate and fraught with danger ..." (Jackson, 1966, p. 63).

An example of a species which has been introduced in tropical areas is the carp, *Cyprinus carpio*. This fish breeds well in most of the situations where it has been introduced, and heavy fishing is required to prevent destruction of other organisms growing on the lake bottoms (Jackson, 1966).

Ultimate stabilization of reservoir biota will take many years. Russian research in this regard has been quite extensive and findings might be summarized by these examples:
"Where reservoirs have been observed for longer periods, previous assumptions of quick stabilization had to be revised. In the Utchinsk reservoir on the Moska-Volga canal zooplankton became more or less stabilized only after ten years and then is still subject to annual fluctuations. Bottom faunas on the Volga reservoirs were still labile after eighteen to twenty-three years." (Rzoska, 1966, p. 152).

Adjustment of the populations of the many species affected by any reservoir project will take considerable time, and it will not be until the complex relationships between species are balanced that biological stability occurs.

* * *

This concludes the section dealing with the biological effects of reservoirs. Though, to a biologist the depth and level of the material covered may seem superficial, it will be most useful as part of the background which is necessary in order to approach compilation of the impact identification framework. The nature of some of the effects which have been discussed should also serve to reinforce the fact that a new and more comprehensive approach is necessary in the planning of large reservoirs. Though secondary effects cannot be predicted with absolute certainty, it is definitely possible to indicate potential effects, based on past experience, and to make well based judgements as to the effects of particular proposed reservoir projects.
THE HUMAN AND CULTURAL EFFECTS OF LARGE RESERVOIRS

Creation of a large reservoir will have a considerable effect on the lives of many people. For some, there may be advantages, but almost certainly for others there will be serious drawbacks. The reservoir's existence will open opportunities for new life styles, for new forms of land use and for improved access into previously remote areas. However, the inundation of a large land area will erase, in practical terms forever, the opportunities previously existing on that land. It is essential that the human aspects of reservoir creation be considered carefully, and that proposed projects do not become single objective structures, advantageous only to a specific user group which may be many miles from the site.

Early planning of the opportunities a large reservoir creates for the local population is essential. Several points support this statement. First, construction of facilities for human use within, or immediately adjacent to the reservoir is less expensive before reservoir filling than after. Harbours and channels can be more easily constructed while the land is dry than after inundation. So too, clearing of areas along the shore for fishing or recreation is a far less complex operation before the existing vegetation is flooded. A second factor which necessitates
early planning of such operations as the relocation of indigenous populations is the possibility of early completion of the dam. The Italian construction firm responsible for construction of several African dams has proven itself capable of completion of the structures before the dates set as goals by the governments initiating the projects. Unexpectedly early opportunity to start filling a reservoir may bring a crisis response to relocate people several months ahead of the date planned, and before reasonable surveys have been completed on sites for relocation. Comprehensive reservoir basin planning at an early date may minimize costs incurred and the disruptions to indigenous populations, and create a better atmosphere for introduction of new opportunities.

It has been stated that:

"... there are obvious opportunities around man-made lakes for all stages in the succession of man's activities, for the hunter, the fisherman, the pastoralist, the cultivator and the urban and industrial worker. Before the inundation, the opportunities for human activity are, as a rule, very much more limited. Thus the creation of a lake is generally followed by a diversification and a flowering of human endeavor." (Worthington, 1966, p. 5).

It is unfortunate that there is good evidence that the atmosphere suggested by the latter part of this statement is not often achieved, let alone achieved in a smooth and harmonious manner. African reservoir developments provide examples:

"... Irrespective of government attitudes towards the local population and their development, in the Kariba, Volta and Aswan High Dam schemes little attention was
paid to the resettlement process until after dam site preparations were initiated." (Scudder, 1966, p. 99).

"... Experience gained from Kariba, Aswan High Dam and Volta schemes has shown conclusively in each case that there is too little time between the initiation and completion of dam construction to carry out and implement the minimal research needed for effective rehabilitation at the time of resettlement. Rather, resettlement becomes a crash program to get the people physically moved before the river is sealed off. At that time the water level of the new lake can be expected to rise rapidly." (Scudder, 1966, p. 100).

Without early planning of the human aspects of a dam construction and reservoir operation project, there will be a less than harmonious relationship between the local population and the newly created environment. In the following sections attention is turned to some of the specific problems which reservoirs have created, and to some of the opportunities which unquestionably are lost. Also considered are some of the new opportunities which may be expected.

RESETTLEMENT OF INDIGENOUS POPULATIONS

Early and comprehensive planning of relocation procedures is a prerequisite for successful operation of a reservoir project. Where such planning is lacking, a number of problems are bound to occur. Even in cases in which every attempt is made to minimize difficulties, there will be unavoidable crisis situations as people prove themselves to be individuals rather than numbers. Depending on the
part of the world in which the development takes place, the problems encountered will be highly variable. Resettlement of Tonga and We groups in Rhodesia and Zambia is a vastly different situation to relocation of farmers living in the United States.

Crowding of relocated people

As a result of relocation, crowding is a potential danger, especially in cases in which relocatees have lived off the old landscape at a subsistence level. Through the years a lifestyle of this type will build up a suitable balance between population and self-renewing resources. Sufficient land will be available so that soils are not over used to the extent that their productivity decreases. Game resources and palatable natural vegetation will be in an approximate balance with consumption. The population will have devised sanitary procedures adequate to prevent excessive growth of disease vectors in disposal areas. This balance can be broken when relocation occurs, either because of insufficient effort on the part of authorities, or because of inability of authorities to comprehend the reasons for customs, and inability of the relocated groups to realize the need for new and different life styles.

The Kariba project on the Zambezi River provides one of
best examples of the effects of crowding of relocated people. In one case a group of Tonga were moved from the Zambezi banks to Siagatube, where the soil was too poor for agriculture. No effort had been made to encourage a change in farming procedures and as a result of the people's inability to sustain themselves, a second move was forced upon them (Reeve, 1960). In another case, although a second move was not required, the results were equally unhappy:

"... In about 1956-57, a small group of the Tonga tribe with a population of about 1,500 under their chief, Mola, was moved from the Zambezi valley as the lake began to fill onto a dry mopane clad hillside near the Bumi River. Here their system of agriculture would not work (they normally had grown a tall variety of sorghum which failed to mature under the drier conditions, and although they had been provided by the Agriculture Department, with a small, early maturing variety, they could not be persuaded to grow it). While they lived on the banks of the Zambezi they were able to supplement their diet with fish and rodents but now they had been moved from the fishing area and the rodents were less plentiful than they had been by the Zambezi, they suffered from severe malnutrition." (Apted, et al., 1963, p. 3)

The history of relocated Tonga and We people presents much the same story from one group to the next. It is estimated that in ten to fifteen years their new land will be so eroded and infertile as a result of overuse, that even subsistence agriculture will be virtually impossible (Scudder, 1969).

Malnutrition of the groups of relocated people is a problem in itself, but the effects may be worsened where
people who are used to foraging come across poisonous plant species which are similar in appearance to those which they are used to using, and which they therefore expect to have palatable parts. In the Kariba area people who sought supplemental food from a familiar looking tuberous root suffered severe depression of blood sugar levels and widespread vomiting sickness (Waddy, 1966).

Inadequate sanitary facilities and unfamiliar methods of obtaining water and disposing of wastes have complicated Kariba settlement. The Tonga, who had traditionally drawn their water from the river and its tributaries were supplied with bore-hole wells (Cole, 1960). These holes proved useful pits for refuse disposal, and not surprisingly, their contamination brought on serious outbreaks of disease.

The lake as a social barrier

Often the relocation of indigenous groups along a river bank prior to filling of a reservoir will break down social ties which have grown between people on opposite sides of the river. Though access across the river at the dam site may be superior to any form of access which existed prior to construction, settlements along the reservoir shores will be almost inaccessible to other settlements on the opposite shore.
Lake Kariba has placed a barrier between groups of the Tonga who formerly made frequent visits across the river. Kinship and friendship ties have been suddenly broken by the miles of water and sometimes by additional miles of bush which separates the population of the two sides. Similarly, Lake Volta has effectively split Ghana into two. Fifty-two new villages surround this large, dendritic lake, but communications along the shore and across the lake is difficult. Even if a trip across the lake was planned, the native craft would prove to be totally unlakeworthy in the event of a storm.

The problem of the barrier presented by the creation of a large lake seems insolvable at present. In technologically advanced areas, new roads may make up for the lack of cross river contact. In less advanced areas, even if roads were provided, they would have little utility in permitting social contact, at least in the near future.

**Disease: physical and psychological**

Following relocation there is often a marked decline in the health of the population. This stems both from contact with new forms of disease vectors, and from a general lowering of the morale of the people involved. The latter, psychological factor cannot be overlooked, as there is evidence that
resistance to disease decreases and the death rate increases after groups are relocated. The very real stress accompanying resettlement and adjustment must be credited for decreasing the population's ability to contend with day to day problems (Scudder, 1966).

Of greater concern, however, are the longer term changes in disease patterns which are brought about by reservoir construction. Perhaps of greatest concern is the spread of bilharzia in tropical areas. This parasite induced disease is transmitted to people by contact with certain snail species which can exist only in relative stable waters: reservoirs and slow running irrigation canals are ideal habitats. In the worst cases, infection with bilharzia can result in paraplegia or death, and since the construction of large African reservoirs, death rates from the disease have risen sharply. The disease appears to have a number of other undesirable effects. Dysentry is the most obvious, but there are indications that height and weight are retarded and that physical stamina is lowered by the disease (Jordan and Randall, 1962). The effect that substantial portions of the population suffering from bilharzia will have on anticipated development remains to be seen. Certainly, it will be an undesirable effect and a most serious drawback for groups who already have many other problems in readjustment and development.
CHANGES IN LAND UTILIZATION AND EMPLOYMENT

Fishing

Creation of a large reservoir presents an environment well suited to the development of fisheries; either commercial, or recreational, or both. If a commercial fishery is likely to develop, consideration must be given to imposition of catch quotas to ensure a sustained yield. Without such regulation the initial high level of biological productivity is likely to encourage expansion of fishing beyond the level which the reservoir is capable of maintaining. Overfishing and depletion of stocks will, of course, lower the reservoir's productivity for a number of years.

Access is a factor in development of a viable commercial or recreational fishery. Consideration is required in the matter of incentives for groups prepared to risk capital in the establishment of collection and processing services.

The matter of anadromous fish is one which presents a problem to authorities planning a dam construction project. At Kariba it was decided that migratory species did not warrant the extra cost of fish ladders; consequently, large numbers of eels gathered near the face of the dam soon after it was closed. Without ability to complete their life cycle
the continued existence of the population is jeopardized. For the last several decades the attitude towards anadromous fish, at projects on European and North American rivers, has been quite different to that apparent at Kariba. Perhaps the last major dam constructed without heed for migratory salmon was the Grand Coulee on the Columbia River. This project, started in the 1930's, eliminated over 1,000 miles of major rivers and creeks suitable for spawning. Bonneville Dam, constructed near the mouth of the Columbia River during the same period, had no initial planning for fish ladders, but after construction had started the outcry of conservationists forced inclusion of fish handling facilities (Bullard, 1968). Had they not been included, what today amounts to a multi-million dollar industry would not exist.

The attitude of authorities towards fishing will have a major influence on occupations of many of the people affected by reservoir projects. The potential for gainful employment represented by fisheries warrants careful consideration and planning, whether in a developed area or a developing one, and whether the fish are anadromous or spend their full life cycle within the reservoir.

Agriculture

Creation of a reservoir may have both positive and
negative aspects in the field of agriculture. It would seem a fair assumption that if operations are properly executed the positive aspects of increasing agricultural output through irrigation should at least equal the negative aspects which include inundation of existing farmland and loss of sediment deposition on downstream alluvial farms.

The problem of over-cropping of agricultural land may arise as a negative consequence of intensification or expansion of farming into previously unfarmed areas. The ability of the soil to maintain fertility, especially in tropical areas, is not as great as the average farmer who wishes to maximize the value of his crops is likely to desire. Over-cropping the land will lead to soil infertility; over-irrigation or over-grazing will lead to erosion. Steps must be taken to ensure that these problems are not permitted to arise after the agricultural opportunities afforded by a reservoir are taken-up by the local population.

Recreation

Creation of a large reservoir will have a considerable effect on recreational opportunities. These will be initiated by construction or improvement of access roads to the dam site, and will be enhanced as the reservoir fills and the lake level stabilizes. The importance of tourism should not
be underestimated, for it is estimated that the demand for outdoor recreation will triple in the three decades preceding the year 2000 in areas such as the United States, as working hours are decreased and affluence increases.

Consequences of recreational activity may adversely affect the general condition of the reservoir area. Overuse of roads, camping areas, wildlife and fish will not only decrease the value of the recreational experience, but also may have a long term effect on the suitability of the location for further activity.

PERMANENT LOSS OF NATURAL AND HISTORIC FEATURES

As a reservoir fills it may inundate and ultimately bury under silt, natural and historic features which are of great cultural value. These may include locations of great scenic beauty, burial grounds of significance to related offspring, historical points of interest and prehistoric and unknown locations where artifacts might one day have been found. Though consideration of these features and sites would appear to have been minimal, there will be increasing pressure for such consideration in future projects.

In the reservoir development of the Columbia River we may look to several examples of loss of important sites.
Celilo Lake, behind the Dalles Dam, inundates Celilo Falls which was a site of great natural beauty, and which also had significance with respect to treaty Indian fishing rights. At least one anthropologist also believes that the lake covers remains of one of the oldest settlements in North America. Continuing upstream, it is undisputed that the series of large reservoirs cover many petrographs which might have provided a valuable historic record of the culture and religion of early inhabitants. Near the confluence with the Snake River, the Lower Monumental Dam inundates a location where bones dated between eleven and thirteen thousand years old were uncovered in a last moment excavation effort by the United States Army Corps of Engineers (Bullard, 1968). Many other sites of aesthetic value have also been eliminated along the course of the Columbia River.

There is little alternative to the inundation of sites considered to be of value, so long as reservoir construction projects are considered to be a necessary element in the development process. Careful inventories of the land to be inundated may enable measures to be taken to preserve at least those elements of the landscape which are removable. Extensive film records may also play their part in compensating for the ultimate loss.

* * *
The human and cultural effects of the building of dams and creation of large reservoirs are generally consequences of impacts within the physical and biological classes. As there is a degree of uncertainty about the occurrence and extent of these impacts, it follows that there will be a degree of uncertainty about human and cultural effects. There is certainty, however, that reservoir projects will provoke secondary effects. Further, there is evidence that these effects have been unanticipated in past projects, and that a lack of consideration and planning has worsened effects which might have been satisfactorily reduced or prevented.

THE EFFECT OF UNPREDICTABLE NATURAL EVENTS

The final type of effects to be discussed are those which result as a consequence of the presence of the dam and reservoir, coupled with some naturally occurring, but totally unpredictable, natural event. In themselves, the natural events may have serious consequences for man, but because of the presence of the dam and reservoir, the consequences are considerably compounded.

Probably the most disastrous natural event which could affect the operation of a dam and reservoir is a high magnitude earthquake. This seismic activity could, at worst, cause
collapse of a dam and intense downstream flooding, perhaps combined with the washout of other dams. A lower order effect might involve the creation of a wave within the reservoir, either directly, or by displacement of water by a landslide. In this case there would be potential for serious damage to shore facilities and for spilling of large volumes of water over the dam.

The proponent of a reservoir scheme can indicate the improbability of an earthquake disaster. Based on both the background of seismic activity in an area, and the engineered features of the dam to resist vibration of its foundations, it is possible to establish a high degree of improbability for damage from earthquakes. It is recognized, for example, that clay core, rock walled dams have a high resistance to damage from seismic activity. Nevertheless, there is always the possibility of an earthquake leading to the destruction of a dam. Where a dam, such as Kariba, has been built using the concrete arch principle, with a major fault parallel to and nearby the Zambezi River, the potential must be increased considerably (Church, 1968).

Another natural event which may lead to unexpected impacts is a change in hydrological patterns. Unexpected long-term changes in rainfall have the potential for rendering a dam virtually useless, or for overfilling a reservoir.
The Owen Falls Scheme, built during 1949 to 1954, provides an interesting example (Lane, 1970). Here, a rock weir has been used at the outflow of Lake Victoria into the White Nile to raise the lake level. Based on 50 years' data, the outflow capacity of the scheme was ample, however in 1961 inflow increased by 50 percent over the previous maximum in what by then amounted to 66 years of records. The outflow was exceeded by inflow, and lake waters rose, inundating port facilities, factories, roads, houses, and agricultural land.

Prevention of events such as earthquakes and changes in the hydrologic cycle is obviously impossible. Allowance must therefore be made in initial planning in case unexpected natural events lead to impacts of disastrous scale.

* * *

Within the pages of this section the effects of dam building and reservoir creation have been documented and discussed. Examples were selected from a large number of reservoir projects at various sites in both tropical and temperate environments. Coverage was given to concrete arch and earth fill types of dams; to impoundment of waters in relatively shallow reservoirs in areas of minor relief, and to impoundment within narrow, steep sided river valleys. Though there can be no guarantee that every secondary effect
of every reservoir project which has been or will be built is covered, the examples represent major effects which have been experienced at the locations indicated in the text. Also, they provide the background for building of the impact identification framework which is discussed in the next chapter.
3. DEVELOPMENT OF AN IMPACT IDENTIFICATION FRAMEWORK

RECOGNITION OF THE NEED FOR IMPACT IDENTIFICATION

The need for a comprehensive approach in identification of the impacts of large scale construction projects has received increasing recognition in recent years. In the United States, the "National Environmental Policy Act of 1969" requires that all federal agencies "... identify and develop methods and procedures ... which will insure that presently unquantified environmental amenities and values may be given appropriate consideration in decision making along with economic and technical considerations" (Section 102(2)8).

To meet this requirement, undertakings by federal agencies affecting the quality of the human environment must be preceded by a detailed statement of environmental impact, including indication of not only the irreversible and irretrievable commitments of resources, but also the relationship between short-term uses of the environment, and enhancement of its long-term productivity.

The Food and Agricultural Organization of the United Nations recognized the probability of creation of problems with the development of reservoirs in their 1969 publication entitled "Man-made Lakes".

"Man-made lakes or reservoirs are usually built for some 'primary' purpose, but the construction or presence
of reservoirs can create 'secondary' problems which may involve economic loss and human suffering, unless reservoir planning in its earliest stages thoroughly considers both primary and secondary aspects." (Lagler, 1969, p. vii).

Under the auspices of the Food and Agricultural Organization and with the cooperation of other United Nations agencies, international assistance is now available to countries undertaking reservoir planning, construction, or research.

TECHNIQUES FOR IMPACT IDENTIFICATION AND AN IDEA

The general increase in concern over impacts of large construction projects on the environment has led to creation of new techniques to aid in their identification for purposes of evaluation or minimization of their negative effects. Two such techniques inspired consideration of the development of a technique for reservoir impact identification. The first technique is a matrix approach to impact identification and evaluation developed by Luna B. Leopold and others (1971), and described in a United States Geological Survey publication entitled "A Procedure for Evaluating Environmental Impact". The second, developed by Jens C. Sorensen (1971), a University of California, Berkeley graduate student in Landscape Architecture, uses stepped matrices for identification of points of resource use conflict and degradation in the multiple use of coastal zones. Consideration of the former technique led to the belief that its early application
in assessment of large construction projects such as reservoirs would fail to adequately identify the multiple order consequences of specific impacts. On the other hand, the latter technique appeared to show a methodology for comprehensive illustration of multiple order consequences in a specific subject area. From it, the idea was developed that identification and illustration of the complex of multiple order consequences of large reservoir construction projects would be a useful procedure in the planning of such projects, if secondary effects were to be anticipated and their consequences minimized. A step by step, cause to effect, or impact to consequence representation would aid in comprehensiveness.

The Leopold environmental impact evaluation technique is suggested as a prerequisite to initiation of a large project (Figure 1). Its compilation is preceded by a report on the existing environmental character, or what might be termed an environmental inventory. This inventory forms the basis for selection of elements of the environment which may be modified, eliminated or removed by the proposed action. A comprehensive list of environmental elements which are likely to be subject to impact is provided as one axis of the matrix which is included with the publication. The other axis of this matrix lists the possible actions of construction projects, and from it the actions involved in
A. Statement of objective

B. Technological possibilities for achieving objective

C. Proposed alternatives

D. Report on the existing environmental character

E. Alternative engineering plans

F. IMPACT IDENTIFICATION and evaluation

G. Assessment of impact

H. Recommendations

Figure 1. Position of impact identification in the assessment of alternative plans. (adapted from L.B. Leopold, et. al.)
a specific project are selected. A probable impact between an action and an element of the environment is indicated by a slash line across the respective matrix location. As an example, a reduced matrix for a phosphate mining lease is shown (Figure 2).

After the identification of impacts, an evaluation procedure is executed. For each impact two appraisals are made; first, the "magnitude" of the impact, or what might be described as the effectiveness of the action in altering or contributing to the destruction of the environmental element, is evaluated on a one to ten scale. This is followed by assessment of the "importance" of the impact, again on a one to ten scale. Consideration of Figure 2 will indicate how moderate impacts on rare or unique species are considered highly important, while minor impacts of erosion are considered to be of low importance. Following numerical evaluation of impacts, a subjective assessment of the impacts of high magnitude or importance is suggested.

The novel method of impact evaluation presented in the Leopold publication warrants consideration for application to planning of large projects such as reservoirs. However, it might be argued that the point at which such an assessment is made is not the correct point for commencing evaluation. Rather, a method is necessary to improve the understanding
### Environmental Elements

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**Key**

- **Magnitude of Importance**
- **Index**
  - 1: Low
  - 2: Medium
  - 3: High
  - 4: Very High

*Figure 2: Environmental Impact Matrix for a Phosphate Mining Lease.*

*Adapted from L.B. Leopold, et al.*
of impacts, their interactions and their multiple order consequences, thus ensuring a fully comprehensive evaluation. To this end, the Sorensen study appears to provide a useful framework, upon which modifications can lead to a derivation of a comprehensive impact identification methodology.

The Sorensen study undertakes identification of use conflict and resource degradation of a coastal zone. A stepped matrix approach is used, in which the prospective coastal zone uses are initially identified along a vertical axis. Each of these uses has a requirement for certain facilities which are identified as "causal factors" on the second, horizontal matrix axis. This in turn leads to a third, stepped matrix axis upon which "possible adverse impacts" including initial and consequent conditions are identified. For example, residential and crop farming uses might be considered (Figure 3). Irrigation, a necessity for crop farming, may be a "causal factor" leading to increased surface runoff, an "initial condition" leading to increased cliff erosion as a "consequent condition", and finally to undermining of residential structures as a "second order condition". Through comprehensive development of this approach a series of matrices is developed which indicate the impact of one use upon another, and the environmental degradation resulting as a consequence of a particular use.
USES OF LAND

Crop farming
Residential development

Note: arrows indicate linkage from "use of land" to "causal factors" to "initial impact" to "consequent impact" to "effect".

Figure 3. Layout of stepped matrix framework (adapted from Sorensen, 1971)
Turning to consideration of reservoirs, it is readily apparent when reviewing the literature, as has been documented in the previous chapter, that although creation of reservoirs can lead to fulfillment of a number of objectives, the secondary effects resulting from their operation are unexpected, and are often significantly harmful. The planning approach to construction of these reservoirs has obviously failed, either because of its inability to provide comprehensive impact identification, or because of a desire to prevent recognition and evaluation of all impacts and their consequences. If the former is the case, any methodology to improve impact identification has potential for serving a useful function; if the latter, public awareness of the potential impacts has been purposely reduced, and decisions made on behalf of the public cannot be seen as representing the opinions that they would have, had they more complete information.

Adaption of the Sorensen, stepped matrix approach to planning of large reservoirs may serve to ensure a comprehensive approach to evaluation of secondary effects. Whether these effects are evaluated in conventional benefit-cost terms, or with an approach such as Leopold's, or both, it is essential that all effects which can possibly be predicted are fully evaluated, and that attention is paid to other potential effects, the consequences of which are
uncertain. Failure to do this invalidates the decision to construct one of two or more alternative projects to meet an objective such as supply of electricity or reduction of flood hazard.

**THE IMPACT IDENTIFICATION FRAMEWORK**

The "Impact Identification Framework for Large Reservoirs" (Figure 4, pocket) was developed through the combination of aspects of the Leopold and Sorensen approaches with the data which had been accumulated to compile the preceding chapter. The comprehensive approach of Leopold's technique provided a basis for an even more comprehensive focus on a specific field such as reservoir development, while the format presented in the Sorensen study was ideal for adaptation to "objective--operational method--impact--consequence" presentation of the relevant material.

In the case of reservoirs, certain primary objectives are fairly obvious: flood hazard reduction, hydroelectric generation, supply of irrigation water, facilitation of navigation and facilitation of recreation. Occasionally other objectives may have been included in reservoir plans, however, it would be difficult to make the case that these other objectives are of primary concern in the development of most large reservoirs. The objectives which have been
identified above are synonymous with the "uses" identified for the application of Sorensen's technique. "Methods of execution" are the operational procedures by which the objectives are obtained in a reservoir project. Thus, construction of a dam, disruption of local population, initial reservoir filling, draw-down, etcetera, are the means or methods of execution by which the objectives are achieved. Some methods of execution are essential for achievement of the objectives, and are indicated as such on the framework. Other methods of execution will be essential for only certain objectives. Draw-down, for example, is essential for a reservoir which is to provide a reduction of flood hazard, even though it may have an undesirable effect on recreation and navigation. It should be noted that in cases where a particular execution method is essential for one, but not all of the objectives of a multi-purpose reservoir project, the whole range of potential effects of that method of execution must be considered. To remove the potential of these effects it is necessary to discard the objective which requires the particular method of execution. Thus, it may be seen from the framework that the broader the objectives of a reservoir construction project, the wider the range of potential secondary effects.

Stepping of the matrix leads to identification of impacts at the primary level, and then to a network of the
multiple order consequences of these primary impacts. It does not follow that every impact and consequence indicated in the framework will occur because of a particular reservoir project. In fact, it is impossible that the whole framework could apply to any one project, as it has been developed for reservoirs in different climatic areas, and some effects are exclusive to certain limited areas. The framework becomes a check list for the identification of impacts and consequences which must precede evaluation procedures. Evaluation is not intended to be a central issue in this study. It may be monetary, as in benefit-cost, it may follow a scheme such as Leopold's, or it may be subjective (a simple example of an evaluation method has been provided in the instructions on the framework). The primary objective of the framework, however, is to ensure that a comprehensive identification of secondary effects permits a complete evaluation, regardless of the procedure used.

It will be noted that some effects are indicated a number of times on the framework, either stemming directly from methods of execution, or from multiple order consequences. Rather than go through the complete set of consequences in each of these cases, reference is made to a point on the framework at which the complete presentation may be found. This serves to simplify the framework and reduces its size. It would, of course, be possible to separate these recurring
impacts from the framework for illustration as impact subframeworks. Little advantage is seen in this form of separation, at least for the purpose of presenting the methodology, so such separation has not been attempted. For actual application of the framework, however, a final presentation format might be adopted in which linkages of probable impacts are indicated to their ultimate probable or potential consequence, while other, improbable linkages are terminated at the point at which the first improbable consequence is indicated.

The term "final consequence" is open to criticism, because in effect the final consequence will never be indicated. If downstream erosion causes undercutting of bank facilities, the damage to bank facilities might be considered as a final consequence. Another approach would be to give an indication of the remedial measures required to prevent destruction of the bank facilities. But, this remedial measure may be considered to have consequences elsewhere, and so on ad infinitum. The whole discussion, though not the criticism, breaks down. Thus, for presentation purposes, termination is generally at the consequence which precedes the direct effect on man, at the direct effect on man, itself, or at the remedial measure which is necessary to alleviate the effect.

***
The framework which had been developed appears to have potential for indicating the broad range of consequences or secondary effects to which development of reservoirs may lead. Though it is realized that omissions in the framework will probably be found, as it stands at present, the principal effects which are likely to be experienced at any proposed reservoir are indicated, and the technique allows for a more comprehensive appraisal to be made before construction of dams than has been the case in past projects. Through early identification of secondary effects, the framework also permits planning to minimize negative consequences or maximize positive consequences.
4. APPLICATION OF THE FRAMEWORK

In this chapter the impact identification framework is applied to a particular reservoir construction proposal. This should serve two useful purposes. First, it provides an example of application of the framework, indicating its intended capabilities and limitations. Secondly, it allows consideration of the utility of the technique so far as its objective of indicating potential impacts is concerned, and it provides a basis for considering various uses of the technique. This consideration leads to an overall evaluation in the next, and final, chapter of the study.

THE PROPOSED RESERVOIR

The proposal to be used as an example is one for a large dam on the Fraser River at Moran, approximately 220 miles upstream from the mouth of the river at Vancouver, British Columbia (Figure 5). The dam, if built, would control the flow from approximately 51,000 square miles of the Fraser River's approximately 91,000 square mile watershed. With a total height of over 800 feet, the dam could develop an effective head of 732 feet with its high water reservoir level of 1520 feet.

Moran Canyon has been recognized for several decades as
Figure 5. The Fraser River Basin
a potential site for hydroelectric development. In 1936 the British Columbia Department of Lands suggested three potential sites between Lytton and Quesnel for the construction of dams. Of these, the Moran site was recognized to have the greatest potential, with 580 foot high rock bluffs on either side of the river providing the foundation for a 1,640 foot long dam structure (B.C. Department of Lands, 1936).

Serious consideration was given to the Moran site during the 1950's by the Moran Power Development Company (Potter, 1957). The company proposed an 840 foot high, 2,400 foot long dam with a head of 732 feet. The company was advised by the provincial government that in the event that they should apply for the water licence which would be required for the development, a reserve on the Lytton to Quesnel stretch of the Fraser River would prevent its issuance. Further, under provincial and federal legislation, approval by various fisheries agencies would be required before the dam construction could commence. While the dam proposal received consideration over a period of several years, construction was never started (Canada Department of the Environment, 1971a).

The Federal-Provincial Fraser River Board suggested, but did not recommend, development of the Moran Dam in its investigations leading to a 1963 report on flood prevention
in the Fraser Valley between Hope and the delta. As sugges-
ted, the dam would raise the water level by some 740 feet to
the 1,520 foot elevation during high water periods. At this
level an artificial lake would be created extending approxi-
mately 170 miles upstream to a point a few miles south of
Quesnel. With a 292 foot draw-down, the usable storage
capacity was estimated at 9,582,000 acre feet. A firm out-
put capacity of 1,191,000 kilowatts could be provided, based
on 1946-47, which was a low water year, though the average
output would be 1,689,000 kilowatts, and the installed capac-
ity would be 3,600,000 kilowatts (Canada Department of the
Environment, 1971a).

In 1971, with initiation of a study by the B.C. Energy
Board on British Columbia's power requirements to 1985,
speculation rose on a possible recommendation for develop-
ment of the Moran site. For the present, however, develop-
ment seems unlikely in light of provincial Premier Bennett's
28th March, 1972 statement to the effect that his government
will not build a Moran dam (The Sun, 28 March, 1972).
Though construction thus appears highly unlikely in the near
future, consideration of the potential effects of the dam
will not be a wasted exercise. The site will continue to
be an attractive one from a hydroelectric engineering view-
point, and it is likely to be considered for some time
into the future.
CHARACTER OF THE PROPOSED RESERVOIR AREA

Before attempting completion of the impact identification framework, some attention must be given to the present characteristics of the land and water areas which might be affected by construction of a dam. In the case of the Moran proposal, consideration must be given to the Fraser River basin and the coastal areas into which the river drains.

Geography and hydrology

The Fraser River basin occupies an area of 89,000 square miles within the southern half of British Columbia. Rising in the Rocky Mountains, the river flows northwestward along the Rocky Mountain Trench to a point northeast of Prince George. Here the river turns westward, then southwest and south, to flow past Prince George and southwards cutting deeply into the Nechako and Fraser portions of the Interior Plateau. Near Lillooet, the river enters the Coast Mountains and flows through a great gorge known as the Fraser Canyon to Yale, a small community sixteen miles north of Hope. Mountains hem the Fraser—the Cascades to the east, and the Coast Mountains to the west, until it flows onto an alluvial flood plain near Hope. The flood plain widens over the last 80 mile stretch, which is known as the Fraser Valley, and the river flows into the Gulf
of Georgia through a delta area immediately south of the City of Vancouver.

River flow is highly variable, with a 55 year average at Hope established as 95,500 cubic feet per second. A high flow of 536,000 cubic feet per second was recorded on 31st May, 1948, and a low flow of 12,000 cubic feet per second on 8th January, 1916 (Canada Department of Energy, Mines and Resources, 1970). The 1948 flow resulted in extensive flood damage to the Fraser Valley.

Climate and weather

Climate of the Fraser River Basin varies considerably from west to east and from south to north. Control is established by west to east moving pressure systems. Precipitation is in the 60 to 100 inch per annum range from the river mouth to Yale. Between Yale and Lillooet, precipitation decreases rapidly to less than 15 inches per annum. Within the Interior Plateau, precipitation remains light, until near the eastern edge an increase is brought about as air masses rise to pass over the Columbia and Rocky Mountains. Though along the inland course of the main stream precipitation is generally light, higher elevations throughout the watershed receive between 30 and 100 inches annually.
During the winter the northern part of the basin lies under cold arctic air, with mean daily temperatures in January in the range of zero to 20 degrees Fahrenheit. Occasionally the cold air masses penetrate south beyond the Canada-United States boundary, though generally January temperatures in the Fraser Valley are in the high 20's and low 30's. In the summer, high pressure air masses predominate over the whole Fraser River Basin, with mean daily temperatures in July in the range of 60 to 70 degrees. Elevation and the distance from the effect of coastal temperature moderation exert control over the maximum temperatures reached during the summer. In the Fraser Canyon, and as far north as Quesnel, maximum temperatures in the high 90's are common.

Vegetation

Vegetation in the basin reflects variations in climate and elevation. In the immediate vicinity of the proposed reservoir, light precipitation leads to an open canopy forest-grassland. This grades from an arid ponderosa pine (Pinus ponderosa) and bunchgrass zone at the southern end to a more moist "Cariboo parkland" zone at the northern end which includes trembling aspen (Populus tremuloides), cottonwood (Populus trichocarpa), lodgepole pine (Pinus contorta), and interior Douglas fir (Pseudotsuga menziesii var. glauca).
The northern portion of the basin is subalpine forest, with Engelmann spruce (*Picea engelmannii*), lodgepole pine (*Pinus contorta* var. *latifolia*), and mountain hemlock (*Tsuga mertensiana*) predominating. South and east of Prince George, as the Fraser flows from the Rocky Mountain Trench, the lower elevation vegetation of the "Columbia forest" reflects heavy rainfall, with western red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), and western white pine (*Pinus monticola*) forming a partially closed canopy forest. Varied forms of alpine vegetation and subalpine forest are found at higher elevations around the basin's perimeter (Chapman and Turner, 1956).

**Wildlife**

A variety of wildlife species find suitable habitats within the Fraser River Basin. Large species include black-tail deer (*Odocoileus hemionus columbianus*-coast, *O. h. hemionus*-mule), California bighorn sheep (*Ovis canadensis californiana*), moose (*Alces alces andersoni*), mountain caribou (*Rangifer tarandus montanus*), and elk (*Cervus canadensis nelsoni*). Areal extent of these species is best described in terms of wintering range, which is considerably confined by snow depth, relative to summer range. Deer are common throughout the lower valley areas, except along the Rocky Mountain Trench and in the Fraser Canyon. California
bighorn sheep are far less common, being confined in the winter to limited grounds northwest of Lillooet and southwest of Williams Lake. Moose are relatively abundant throughout the interior portion of the basin, while caribou and elk are found only in the eastern part of the basin.

Fur bearing animals found within the basin include mink (*Mustela vison*), muskrat (*Ondatra zibethica osoyoosensis, O. z. spatulata*), beaver (*Castor canadensis saqittatus*), marten (*Martes americana abietinoides*), and fisher (*Martes pennanti columbiana*). These animals may be found in most wild lakes, or along creeks and rivers within the basin, and support a viable trapping industry. Also present in the basin are grizzly bear (*Ursus arctos horribilis*), black bear (*Ursus americanus cinnamomum*), wolves (*Canis lupus columbianus*), coyote (*Canis latrans incolatus, C. l. lestes*), fox (*Vulpes fulva*?), cougar (*Felis concolor missoulensis, F. c. oregonensis*), lynx (*Lynx rufus pallescens*), and a variety of small rodents. (Cowan and Guiguet, 1965).

**Anadromous Fish**

The Fraser River Basin is an important spawning area for salmonoid fishes including

"... major populations of sockeye and chinook salmon, significant numbers of steelhead trout and a few pink salmon. The adults of these species migrate
upstream to spawning grounds located on the main stem and various tributaries, and the fry or smolts migrate downstream to the sea. In addition, very large numbers of sockeye, chinook, coho, pink and chum salmon and steelhead trout utilize the Fraser River and its tributaries for feeding, transportation or spawning downstream from Moran." (Canada, Department of the Environment, 1971a, p. 16).

Upstream migration periods for sockeye and pink salmon at Moran Canyon are from late June to mid-October, while downstream migration is from early March to late June. If all other species are considered, migration is in progress at virtually all times of the year.

Access in the proposed reservoir area

Some of the major impacts of the Moran Dam reservoir will be felt in the area inundated by, and immediately adjacent to, the reservoir. This compromises a narrow strip of land some 170 miles long, but seldom more than a mile or two wide, stretching between the Moran railway siding at the south end and Kersley at the north end. Access throughout the area is good. The British Columbia Railway is approximately a mile from the dam site at an elevation about 1,000 feet higher than the river. The Trans-Canada Highway passes through Lytton, 40 miles south of Lillooet, and a secondary highway joins the two centres. An all weather loose surface road connects Lillooet to Pavillion
which is twenty-one miles to the north, and three miles south of Moran. Lillooet, a community of some 1,500 persons, and Clinton, a smaller community to the northeast, are both approximately twenty-four miles from the dam site. Upstream from the dam site there is a fairly good access along the river's east bank in the form of all weather roads and trails. Access to the west side of the river may be gained by bridge at Lillooet and near Williams Lake, and by cable car and cable ferry at a number of points between Pavillion and Alexandria. Transportation facilities paralleling the river are less developed on the west side than on the east, however an all weather road runs from Riske Creek (twenty-three miles southwest of Williams Lake) to Quesnel.

Economic structure of the proposed reservoir area

The main industries in the area near the Fraser River and between Lillooet and Quesnel are forestry and agriculture. Commercial forest cover within the actual reservoir basin is minimal. Likewise, minimal amounts of agricultural land are within the proposed reservoir basin because of the steepness of its sides. Cattle ranching, which is carried out throughout the Cariboo area would not be significantly affected by the reservoir.

Only a small number of homes and farms are located
above Moran, and below the 1,520 foot contour, the elevation of high water in the proposed impoundment. Relocation of the residents of these homes would, of course, be necessary.

* * *

This completes a brief survey of the characteristics of the area which would be affected in the event that a dam is constructed at Moran Canyon. The amount of detail provided here is adequate for initial identification of potential impacts, and compilation of the framework may be undertaken without greater detail. Once potential impacts are thus indicated, other techniques should be applied to predict their probability, and to evaluate their importance.

**POTENTIAL IMPACTS OF THE MORAN RESERVOIR**

An impact identification framework has been completed for the Moran Dam proposal (Figure 7, pocket). Based on the material which has been provided in the preceding pages, the framework has been marked to indicate potential effects and their degree of probability. This leads to the following subjective discussion of some of the factors indicated by the framework. Reasons for expecting various effects are mentioned along with material from several studies which have already been carried out, and which complement the framework.
Construction of the Dam

Construction of a large dam at Moran Canyon would require an influx of several hundred construction workers, along with various service and support industries. Whether Lillooet or Clinton is used as the centre to accommodate this population, or an altogether new townsite is built, undesirably high population densities are improbable. Though development of slum areas by an influx of unskilled and unemployed persons is also unlikely, planning will be required. Permanent houses are unlikely to accommodate all those who come to work on the dam or in the area. Mobile homes are a probable consequence. These can provide attractive accommodation, however, attention must be given to provide a suitable location and services for the units, if sanitation and aesthetics are to be maintained at a high level.

Improved access to the Moran area, and publicity which is likely to accompany a dam building project within a few hours driving time of a major population centre, will attract large numbers of recreational visits. Consideration should be given to increasing camping facilities in the area, supplementing the existing Provincial Government campsite at Marble Canyon. Possible conflicts between campers and land holders, and littering and overuse of
attractive roadside points may thus be minimized.

Disruption of local population

Only a small number of homes would require relocation if the Moran Dam is built. Adequate attention to relocation may be expected, and though readjustment stresses for those involved are unavoidable, the process is likely to receive adequate attention to ensure that these will be minimized.

Initial reservoir filling

As the river valley is narrow and steep sided for the entire length of the proposed reservoir, stranding of animals on raised ground surfaces by rising water would be minimal. Small rodents would be displaced from habitats along the river banks and benches by impounded waters, however these species are not dependent on habitats of limited extent, and their displacement would bring only minor population readjustment.

Vegetation in the proposed reservoir basin is limited and minimal clearing would be required. Consideration of eutrophication and its consequences would be required during the planning stages. Absorption and seepage also require further consideration by geologists and engineers though it
has been suggested that the reservoir bed is impervious and insoluble (Fraser River Board, 1956, p. E103). Charging of aquifers, leading to the supplementation of surface water supply downstream from the dam, could be highly desirable for agricultural purposes.

Creation of artificial lakes

With the creation of a lake behind a dam at Moran, there are no animal species which appear to be endangered by loss of critical habitat. Winter ranges for the California big-horn sheep, \( Ovis \) canadenis \( \text{California} \), would be slightly reduced at the confluence of the Chilcotin and Fraser Rivers in the Riske Creek area. This factor might be serious when combined with other threats to the relatively small population of the species.

As indicated in Chapter 2, prediction of the extent of seismic activity induced by filling the reservoirs is impossible. A major, though inactive fault crosses the river downstream from the dam site, and there are a number of other major faults in the Fraser Canyon area.

Heavy sedimentation of the Moran Reservoir is probable, as the river carries a heavy silt load. It is estimated that 19,000,000 tons would be deposited annually in the reservoir.
(Pretious, 1972). Loss of this load will lead to increased erosion by the Fraser River below the damsite, both in the canyon and in the valley until a new stabilization occurs. After this time, reduced sediment load in the lower Fraser may allow construction of a channel suitable for navigation of deep sea ships as far inland as Chilliwack. There will be a loss of silt addition to Fraser Valley farmland as irrigation waters will carry a reduced silt load. The effect of this loss, and the effect of the loss of silt in the estuarine area remains speculative.

Evaporation from the reservoir could be quite extensive during hot, dry summer periods and resulting humidity combined with temperature modification would cause at least minor climatic change. These changes would be reflected by vegetation in the area in the vicinity of the reservoir. Precipitation of evaporated water would be unlikely until air masses are moved across the Interior Plateau, and at this distance any difference in precipitation is not likely to significantly affect vegetation.

Thermal stratification of the artificial lake is most likely. A depth of 700 feet near the dam will permit establishment of considerable temperature gradient between surface and bottom waters during the warm summer months. Whether or not eutrophication or other biological activity would lead to
hypolimnion oxygen depletion and subsequent release of fouled waters requires further study.

The reservoir is unlikely to promote growth of any disease vectors of significance to man. Extensive draw-down however, may lead to breeding of mosquitoes, which are already a nuisance in the area. The Fraser River Board's Moran Dam proposal involves draw-down to a maximum of 292 feet below high water level. In addition to providing a habitat for breeding of insects, this extent of draw-down would seriously limit the recreational use of the lake.

**Downstream flow changes**

If a dam is built in the Moran Canyon downstream flow on Fraser River will be considerably stabilized. This may lead to advantages in navigation, when in combination with the reduced silt deposition, flow stabilization will permit deep sea navigation inland as far as Chilliwack, and year round use of shallow draft boats upstream to Hope or Yale (Pretious, 1972). Changes in estuarine salinity will be towards the direction of stabilization at a year round level, with a reduction of the high dilution of salt by fresh water at high flow in the spring, and the low dilution of low flow in the winter.
Anadromous fish

The effect of the Moran Dam on anadromous salmonoid fish species has had considerable attention, and it is in this field that there is least uncertainty as to the dam's consequences. A 1971 report on fisheries problems related to the Moran Dam concludes:

"1. The minimum effect of Moran Dam would be the destruction of all salmon and steelhead trout populations that spawn upstream from the dam.  
2. It is probable that the catches in commercial, sport and Indian food fisheries of salmon and steelhead trout populations that utilize the Fraser River and its tributaries downstream from Moran would be reduced by about 50 percent due to environmental changes in the river estuary." (Canada Department of the Environment, 1971a, p. 197).

Flow reduction at critical periods of the year, temperature changes in the temperature of downstream water, and problems in handling fish at the dam within the reservoir would all contribute to the high loss of fish.

* * *

In this brief example of the application of the impact identification framework, it has become apparent that the
technique can be put to good use. The potential secondary effects of construction and operation of the dam and reservoir system appear to cover a broader range than that which has generally been expected. By putting the cause and effect relationships into the logical "impact-multiple order consequence-final consequence" format, it is possible for either expert or layman to understand why the reservoir could cause certain effects. The lack of certainty about many of the potential consequences of construction of the dam at Moran Canyon clearly indicates the need for considerable serious and detailed study before any decision to build the dam is made.
5. DISCUSSION AND CONCLUSIONS

An impact identification framework for large reservoirs has been developed within this study. The framework uses a stepped matrix approach to identify "objectives", "methods of execution", "impacts", and "multiple order consequences". Within the range of the classes of factors which are considered, the principal secondary effects which have been experienced at a representative selection of world reservoirs have been included. Further additions to the framework will serve to add to its comprehensiveness and improve its utility. As a relatively new approach to the pre-evaluation identification of factors which should be included in evaluation procedures, the technique shows considerable potential.

Why is an impact identification approach necessary in the planning of construction of dams and creation of reservoirs? We need look no farther than recent history for an answer to this question. Virtually every large reservoir project which has been constructed has led to effects other than the achievement of its primary objectives. These effects may be classified as impacts and resultant consequences. They directly and indirectly affect man, causing suffering, economic loss, and in some cases unanticipated benefits. They also lead to feedbacks, or reduction of the project's ability to meet its primary objectives.
Too often, it would seem, failure to anticipate the impacts of a large reservoir project has misled assumptions on the project's overall feasibility. Recognition of impacts during early planning stages may thus present a better basis for comparison between the desirability of different alternatives for achieving similar objectives. Recognition of impacts and their consequences before they occur also permits preparation for minimizing negative effects and maximizing positive ones.

A second question may be posed concerning the certainty with which secondary effects can be predicted. Is it possible during planning stages to predict, with a high degree of certainty, the sequence and magnitude of all impacts and their consequences. Of course, it is not. Though some effects, such as those of a high dam on upstream spawning anadromous fish species, are predictable with absolute certainty, the basis for predicting other effects is less certain. The effect of a dam on patterns of downstream erosion and deposition, for example, can be predicted, but there will be a lower degree of certainty about the prediction. Consequences such as the effect of a mass of reservoir water on the earth's crust cannot be predicted with any certainty at all. Though uncertainty is inherent in the process of predicting the course of consequences stemming from reservoir development, the impact identification
framework technique allows for identification of potential consequences. Further analysis may lead to assessment of the probability and magnitude of consequences, and bring the analysis to a stage at which it is possible to express consequence potentials in terms such as: "low probability-low magnitude", "low probability-high magnitude", "high probability-low magnitude", and "high probability-high magnitude". This process can be quite valuable during planning stages, as it rapidly indicates points at which feasibility studies are weakened by uncertainty; and consequently the value of expected benefits may be considered relative to the effects of "low probability-high magnitude" consequences. Thus, although there is not a high level of certainty about the occurrence of some potential effects at particular reservoir projects, the utility of the impact identification framework is not reduced.

Consideration should be given to the ways in which the impact identification framework may be put to use. The primary objective is, of course, identification of impacts and consequences during the planning stages for a large reservoir projects. For this purpose the framework should be of value to agencies undertaking the planning of reservoirs, and to bodies which must pass plans for such reservoirs. With its impact-consequence format, it will also be useful for conceptualization of logical sequences
for investigative studies. In that many different phenomena may lead to identical consequences, the framework could be put to use in conceptualization of models to be used for predictive or experimental purposes.

Public education is another use to which the framework may be applied. Planners, through the planning process, have a primary responsibility to indicate to the public or their representatives, the consequences of various forms of action for achieving an objective. For a person unfamiliar with reservoirs, the relationship between a large man-made lake in some remote area which he has never seen, and the off-shore fishing industry, the spread of disease, the facilitation of navigation, or similar consequences, may be completely unclear. The framework illustrates these relationships in a relatively simple, step by step manner. Its use can increase public understanding of the consequences of actions undertaken on their behalf, thus leading to a more solid foundation for decisions leading to the creation of reservoirs.

As a final potential use to which the framework may be applied, there is opportunity for increasing credibility between decision makers and their planning agencies, and various advocate groups and individuals. Open use of the impact identification framework will allow realistic
appraisal by both proponents and opponents of proposed projects. It allows for specific criticism where there are differences of opinion as to the occurrence of certain secondary effects, or as to their magnitude and evaluation. Thus, by improving the level of understanding and communications between those with different opinions, the framework may prove to be quite valuable.

Two suggestions are made for improvements to the framework impact identification approach for large reservoirs. First, further study should be applied to ensure the highest possible degree of comprehensiveness. Though, in its present form, the framework will indicate most of the potential impacts at any proposed reservoir site, inevitable omissions remain to be filled-in. A second refinement could lead to a less cumbersome framework format. This would involve separation of impacts which are common to all reservoirs from those which are common only to a specific type of reservoir in a specific climatic area. Then the procedure would involve completion of the framework common to all reservoirs plus one of a choice of other frameworks dealing specifically with situations such as: "tropical high dams", "tropical earth fill dams", "temperate high dams", and "temperate earth fill dams". This more manageable format would not reduce the framework's comprehensiveness.
In conclusion, the desired check list form of impact identification framework has been devised. The stepped matrix approach to impact identification is sound and logical, and the "Impact Identification Framework for Large Reservoirs" appears to have adequate potential for serious application to reservoir development investigations.

***
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## OBJECTIVES

1. Fish habitat 
2. Irrigation supply 
3. Recreation 
4. Navigation 
5. Hydroelectric generation 
6. Sedimentation of reservoir 
7. Formation of shoreline swamps 
8. Reduction or elimination of historic sites 
9. Creation of new lakes, marshes 
10. Provision of habitat for micro-organisms 
11. Release of fouled waters 
12. Unplanned land use 
13. Seismic activity and earthquakes 
14. Unemployment 
15. Undercutting river bank facilities 
16. Filling of bays 
17. Formation of shoreline swamps 
18. Increased short term and long term change in biota 
19. Breeding of snails 
20. Increased incidence of bilharzia 
21. Reduced or elimination of biological habitat 
22. Oxygen depletion 
23. Increased river bank erosion 
24. Provision of habitat for micro-organisms 
25. Prevention of ice formation 
26. Improved recreation potential 
27. Improved navigation 
28. Increased sunlight penetration 
29. Erosion of shore facilities 
30. Formation of lakes, marshes 
31. Habitat for micro-organisms

## INSTRUCTIONS

- **NOTE:** All shading in the matrix indicates the potential linkages of effects. 
- **IMPACT:** To the multiple order consequences of this evaluation. 
- **Systematic Linkage:** Indicates the potential linkages of effects.

### IMPACT IDENTIFICATION FRAMEWORK FOR LARGE RESERVOIRS

#### OBJECTIVES

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### IDENTIFICATION FRAMEWORK

The matrix above illustrates the potential linkages of effects. Each cell in the matrix represents a potential linkage of effects, with shading indicating the extent of these linkages. The matrix is structured to allow for a systematic evaluation of the potential linkages of effects, with shading in the first and second steps indicating the potential linkage of effects. Further shading may indicate the importance of these linkages on an evaluative scale. For example, shading in the first and second steps may indicate the potential linkage of effects. Further shading may indicate the importance of these linkages on an evaluative scale.

### METHODS OF EXECUTION

- **Narration:** Indicates the potential linkage of effects.
- **Commentary:** Indicates the potential linkage of effects.
- **Direct Observation:** Indicates the potential linkage of effects.
- **Discussion:** Indicates the potential linkage of effects.
- **Testing:** Indicates the potential linkage of effects.

### Figure 4

The figure above illustrates the potential linkages of effects in more detail. The shading in the matrix indicates the extent of the potential linkages of effects, with further shading indicating the importance of these linkages on an evaluative scale. The matrix is structured to allow for a systematic evaluation of the potential linkages of effects, with shading in the first and second steps indicating the potential linkage of effects. Further shading may indicate the importance of these linkages on an evaluative scale.

### Conclusion

The matrix above illustrates the potential linkages of effects in more detail. The shading in the matrix indicates the extent of the potential linkages of effects, with further shading indicating the importance of these linkages on an evaluative scale. The matrix is structured to allow for a systematic evaluation of the potential linkages of effects, with shading in the first and second steps indicating the potential linkage of effects. Further shading may indicate the importance of these linkages on an evaluative scale.