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# Environmental Effects of Hydroelectric Power Development

*Alan D. Jassby*

October 1976

Lawrence Berkeley Laboratory University of California/Berkeley

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# ENVIRONMENTAL EFFECTS OF HYDROELECTRIC POWER DEVELOPMENT*

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October 1976

*Report prepared for the Ecosystem Impacts Resource Group of the Committee on Nuclear and Alternative Energy Systems, National Research Council, Washington, D.C.

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# I. INTRODUCTION

The obstruction and diversion of flowing waters by man has played a significant role in human civilization since the beginning of recorded history. The very transition from prehistory to the emergence of the oldest known regional civilizations in the Tigris-Euphrates alluvium and along the Nile, at the beginning of the third millenium B.C., was accompanied by manipulation of the local hydrographic regime. Indeed, the increase in efficiency of sedentary agriculture made possible by controlled draining and irrigation of these rich lands undoubtedly released a large portion of community resources for the development of the monumental and innovative cultural achievements of the Sumer-Akkad and Egyptian civilizations. Improved navigation resulting from these early water projects also speeded up the geographical dissemination of cultural innovation along the Tigris, Euphrates, and Nile rivers. On the other hand, large-scale transformation of the potential energy inherent in flowing waters to forms of energy directly useful to man is a relatively recent phenomenon. The Industrial Revolution of eighteenth century Britain coincided with the initial widespread use of water power in manufacturing and processing industries.

The total global hydroelectric power capacity is of the same order of magnitude as present fossil fuel use. The majority of this potential hydroelectric power has not been developed, and those areas with the largest capacity (Africa and South America) have the lowest percentage

of their capacity now in use (Hubbert, 1971). In contrast, dams are found on almost every major river system in the northern temperate zone, and more than 25% of the available hydroelectric power in North America is being utilized.

Dams are constructed for a variety of functions – power generation, flood control, irrigation, navigation, domestic and industrial water supply, recreation, and fish production – and any individual dam usually is designed to provide a number of services simultaneously. Regardless of the objectives, the production of a reservoir and the modification of downstream hydrographic conditions result in marked changes in the physical, chemical, and biological characteristics of the impoundment and downstream areas. The diversity of these changes, and the number of alternative causal pathways which can contribute to any particular effect, make it difficult to describe the environmental consequences of hydroelectric development within a rational scheme. A single important consequence may arise directly from dam construction, as well as from secondary or tertiary effects of the dam's presence. For example, water loss typically increases both because of the larger surface area for evaporation in the reservoir, and because of transpiration from aquatic macrophytes that can invade the shallow reaches of the reservoir as the current patterns, temperature structure, turbidity, and water chemistry change.

A second difficulty accompanying a general assessment of environmental effects is the uniqueness of each hydroelectric development. Differences in climate, geology, the size of the project, the pattern of water release downstream, etc., inevitably result in phenomena of

differing magnitude from one development to the next. Generalization as to which effects are overwhelming usually is not possible; the most that can be offered is an inclusive listing of potential problems of an ecological nature.

In what follows, I have classified the environmental consequences of hydroelectric development into physical, chemical, and biological effects. The problems discussed in each category often are consequences of effects discussed in preceding categories, but, as noted above, feedback and complicated causal pathways are inevitable. Demographic, health, and climatic issues that arise in conjunction with the building of dams are, for the most part, not covered. The exclusion of these issues is not intended to undervalue their significance. The resettlement of huge numbers of people (as many as 120,000 with the construction of the Aswan High Dam), the improvement of habitat for vectors of human parasites (especially the carriers of schistosomiasis and malaria in tropical regions), the dangers of dam failure, and the possibility of large-scale climate modification (a valid consideration for the huge proposed James Bay project in Quebec) are, on the contrary, problems of overwhelming importance that deserve special, detailed attention.

The geographical areas associated with the presence of a dam can be divided conveniently into the reservoir area itself; the downstream river channel and flood plain; and the estuarine and coastal waters that ultimately receive the impounded water. Physical, chemical, and biological effects differ among these areas and a given type of

effect may not be a problem in all three areas simultaneously, as will be made clear in what follows.

Over the past few decades, hundreds of articles have appeared on specific effects of dam construciton. Most of this information has been summarized in a number of reviews. The brief survey that follows is based primarily on these reviews and on personal experience with hydroelectric projects.

## II. THE CHANGED PHYSICAL ENVIRONMENT

Except in those cases where the natural grade and discharge rate of a river results in sufficient energy to rotate the generator turbines, a dam is required to provide adequate head for power generation. The immediate effects of dam construction and controlled water release is the formation of a reservoir, increasing the shoreline, weight, and surface area of the water behind the dam site, and the modification of downstream hydrographic conditions. Current structure in the impoundment also is altered radically. These immediate changes in the shape and motion of the pre-existing water supply produce directly certain problems of ecological interest, as well as instigating a chain of events leading to more indirect effects.

### A. Earthquakes

An enormous local increase in mass supported by the earth's surface accompanies the filling of deep reservoirs behind new dam structures.

The increased pore-fluid pressure may be sufficient to initiate or increase earthquake activity in the vicinity of large reservoirs, as has been well evidenced at approximately 30 sites all over the world (Gupta and Rastogi, 1975). Certain of these quakes, such as the 1967 one at Koyna, India, have caused extensive destruction of human lives and property. The difficulty of earthquake prediction in general

makes it impossible to determine the exact conditions under which seismic activity is enhanced by water impoundments. The presence of faults and the added stresses produced by a reservoir obviously are causal factors, but no inclusive generalizations can be made as yet, certain large reservoirs being completely aseismic.

B. Temperature structure

Most reservoirs are deep enough to develop the typical temperature structure of lakes in adjoining regions. In temperate areas during summer, the interactions between solar heating, wind-induced mixing, and convection currents at night generally produce an upper layer of uniform temperature (epilimnion) underlain by a denser layer at $4^{o}C$ (hypolimnion). A transitional region (metalimnion) separates the epilimnion and hypolimnion. This temperature structure can be modified by 2 phenomena peculiar to reservoirs. First, silt-laden inflowing waters may produce currents of sufficient density to penetrate the hypolimnion, displacing cold water which upwells into the epilimnion. Second, water can be discharged downstream from layers below the surface in many reservoirs, unlike natural lakes in which predominantly surface outflows lead to a higher loss of heat (Kittrell, 1965). The resulting modifications of the heat budget and temperature structure are too dependent on particulars of morphology, climate, inflow rates, and discharge levels to make any useful generalizations. It should be noted, however, that the upper layer of a stratified reservoir exhibits higher temperatures that those of the preceding river system, and that spring heating and cooling both are delayed because of the larger water volume.

Downstream water temperatures depend on the level from which water is discharged. Discharge from 2 levels simultaneously produces intermediate temperatures and thus permits some measure of control. Fluctuating discharge rates and release of water above $0^{o}C$ occasionally is utilized to maintain ice-free conditions downstream (Neel, 1966), extending navigability over longer time intervals.

C. Water loss

The increased surface area, surface temperature and wind speeds in reservoirs leads to a higher evaporative loss than in the river system preceding dam construction, despite the decrease in surface water motion. The loss of water may be critical in arid or semi-arid areas where supplies are lowest and evaporation rates highest. Seepage into underlying rock strata is an alternative, though usually less important, sink for inpounded water. The evaporative losses from reservoirs in the western United States is approximately $2 \times 10^{10}$ $m^3$ per year (Symons, et al., 1964), enough to supply the domestic water needs of about $10^8$ people. Water loss from the Colorado River projects alone is sufficient for the requirements of $4 \times 10^6$ people (van Hylckama, 1971). Attempts have been made to decrease evaporation by applying a monomolecular layer of fatty alcohols such as hexadecanol to reservoir surfaces (Neel, 1966), but the disturbing effects of turbulent motion usually render these ineffective.

Bodies of water downstream also may be subject to significantly lower water levels as a result of upstream evaporation. For example, power projects on the Volga River have resulted in a lowering of Caspian Sea levels (Davis, 1971).

The variable incursion of emergent aquatic macrophytes into reservoirs makes prediction of evaporative loss impossible from physical considerations alone. Losses due to evapotranspiration by "water weeds" can be enormous. Water hyacinth (*Eichornia crassipes*), for example, can increase water loss 3 to 8 times the evaporation rate from weed-free surfaces (Holm *et al.*, 1971). A vegetation cover of 15% thus may be capable of doubling losses from a reservoir. A reasonable estimate of the range of water loss can be made in the planning stages of an impoundment if evapotranspiration rates of likely invaders under local conditions is known.

D. Landslides, erosion, and sedimentation

Altered current structure, and the saturation of soils which previously were subject to limited water infiltration, can affect markedly the physiography of the watershed. The most dramatic effect is landsliding. "The Temple", a limestone-covered butte in Lake Mead, has been severely scarred by anumber of landslides (Gould, 1954). Occasionally, landslides into reservoirs have had disastrous consequences. A massive slide into the Variant Dam reservoir in Italy in 1963 displaced most of the reservoir's water, killing large numbers of people in the flood plain below (Goldman and Hoffman, in press). In general, severe undercutting of steep slopes is most commonly found in arid areas.

Many slower changes in physiography accompany dam construction, but the long-term results of these changes can be of great significance. A decrease in current velocity when inflowing water enters the reservoir frequently results in the deposition of suspended sediment and formation of a delta. The subsequent rise in the upstream river channel may require construction of levees to prevent flooding, as in the case of Elephant Butte Dam on the Rio Grande (Ortolano et al., 1973).

The smaller silt particles that do not settle in the headwaters are carried into the reservoir itself in "density currents" (i.e., currents whose density is increased due to the presence of particles), which sink to a level determined by the temperature structure of the reservoir (Neel, 1966). These currents often carry sediment the entire distance to the dam and slowly lose the suspended silt to large areas of the reservoir bottom. Siltation decreases reservoir capacity and may proceed at rates sufficient to limit seriously the lifetime of reservoirs. It is estimated, for example, that the Bhakra-Nangal Dam in India may lose its entire storage capacity within 40 years (Hagan and Roberts, 1975). A strip of land around the rim of reservoirs often becomes unable to support vegetation as the water levels fluctuate markedly during normal operation. If these bare slopes are steep, waves are capable of eroding the banks and the eroded material also ends up on the reservoir bottom. The problem is accentuated with increased human recreational use of the large shoreline created by the reservoir (Hagan and Roberts, 1975).

Erosion and sedimentation in the downstream river channel depends largely on the sediment content of the discharged water. When the level of discharge coincides with the level of a density current, layers of fine silt can be deposited on the river bed below the dam. High velocity downstream flow that existed during seasonal flooding prior to dam construction are no longer present to flush out those sediment accumulations. Discharge of silt-laden waters is common especially when the clay soils of a watershed are subject to constant erosion through an inadequate vegetation cover. In most reservoirs, however, the mean content of suspended materials is decreased in the discharge, and downstream waters generally become more clear on an annual basis. Bank erosion and bed scouring, with subsequent downstream displacement, sometimes accompany an irregular discharge regime in these cases. For example, downstream displacements of sediment to Needles, California following construction of Hoover Dam on the Colorado River was responsible for local flooding at Needles (Thomas, 1956).

Marked changes in sediment load and hydrography also can modify the delta and shorelines of receiving waters. Decreases in the rate of delta formation at the mouth of the Tigris and Euphrates Rivers during the last millenium are correlated with increases in water diversion activity upstream (Davis, 1971). More recently, water impoundment projects on the Nile River have resulted in severe recession of the delta shoreline (Kassas, 1972). Interference with the sediment renewal process of beaches beyond the delta poses an additional problem accompanying reservoir formation.

## III. WATER CHEMISTRY

Water quality in reservoirs is affected by such a myriad of feedback processes involving both physical and biological phenomena that numerous exceptions can be found to any generalization. Attention must be paid to the details of a particular project for sound prediction of even the qualitative chemical consequences of reservoir formation. The most common effects are discussed in what follows.

### A. Salinity

Increased evaporation from reservoir surfaces leads to a concentration of total dissolved solids over prior river conditions. The diversion of impounded water for irrigation usually accentuates this effect by large increases in the salinity and hardness of irrigation return flows. Colorado River projects provide an exceptionally dramatic example of these processes. Salinity increases from about 50 ppm in the Colorado headwaters to over 1000 ppm by the time this water flows into Mexico, after passing through numerous man-made reservoirs (Holburt and Valantine, 1972). High evaporation and irrigation use both are implicated in salinity changes, and these changes are expected to continue. Even at present, dissolved solids concentrations have reached the point where agricultural use of Colorado River water can cause damage to fields in the lower reaches of the system.

Salinity changes in downstream delta areas also may result from a totally different process in certain projects. Artificially-reduced flows permit salt-water intrusions upstream from receiving waters into areas where agriculture traditionally has depended on low-salinity river water for irrigation, as in the Delta area of San Francisco Bay.

B. Solution and precipitation

Mineral solution and precipitation also contribute to altered levels of total dissolved solids, especially in areas where bed materials are composed of soluble materials such as gypsum and limestone. Solution processes usually dominate during reservoir filling. The landsliding in Lake Mead previously mentioned resulted from mass dissolution of the limestone cap on The Temple. In this same reservoir, huge amounts of gypsum bed materials dissolved in the decade following dam construction (Howard, 1954).

Mineral precipitation processes result largely from the increased photosynthetic activity that develops in reservoirs, i.e., as marl formation following an alteration in dissolved inorganic carbon equilibria when algae and aquatic macrophytes provide a sink for certain carbon species. These $CaCO_3$ precipitates decrease, in turn, the concentrations of certain plant nutrients (e.g., inorganic phosphate) and dissolved organics by adsorption to particle surfaces (Wetzel, 1975).

C. Nutrients

Stratification of pH, $O_2$, $CO_2$, and inorganic nutrients resembles that of deep, natural lakes (Symons, 1969). A predominance of biological autotrophic processes in the upper layer and decomposition processes in the lower layers results in the following changes with increasing depth: lower pH, lower $O_2$, higher $CO_2$, and higher inorganic nutrients (in particular, phosphorous and nitrogen-containing ions). A transitional period during reservoir filling often is observed during which the decomposition of submerged terrestrial vegetation and dissolution of newly-covered soil materials lead to an increase in dissolved nutrients. This pulse of nutrients diminishes as reservoir water is displaced downstream and aquatic vegetation assimilates these substances. Exchange of inorganic and organic materials with silt particle surfaces also modifies reservoir water chemistry, the direction and magnitude of this influence depending on details of silt composition, silt inflow rates, density currents, and reservoir volume and retention time. Release of materials from silt trapped in the reservoir sometimes leads to continuously increasing availability of dissolved nutrients. The attractiveness of reservoirs to waterfowl also can lead to nutrient enrichment via decomposition of the fecal matter of flocks of ducks and geese (Neel, 1966).

Decomposition processes in the hypolimnion may lower oxygen and redox potential to the point where reduced forms of sulfur, iron, and manganese are produced in large amounts. These reduced substances are extremely soluble and are toxic at high concentrations. Water discharged from hypolimnetic levels thus can contain large concentrations of plant

nutrients and of materials toxic to more complex forms of life. On the other hand, water discharged from the epilimnion has been stripped, to varying extents, of dissolved inorganic nutrients. Regardless of the discharge layer, the discharge process itself often ensures that the released water is well-oxygenated.

## IV. BIOLOGICAL CONSEQUENCES

### A. Plankton

Replacement of a river system with a reservoir leads to conditions favoring denser phytoplankton growth. The quieter waters permit deeper light penetration as suspended particles contributing to turbidity settle out. Nutrients become available through leaching from silt, newly-inundated bed materials, and submerged terrestrial vegetation, as outlined in the previous section, and temperatures in the illuminated portions are higher. All of these conditions favor higher growth rates and larger standing crops of phytoplankton. Slower turnover times of the reservoir water, compared to the previous river system, ensure that relative losses of phytoplankton biomass to downstream areas will be slowed, particularly when withdrawals occur from below the photic zone. Productivity pulses resulting in massive phytoplankton development are marked immediately after inundation (Coche, 1974), a time when, as we have seen, nutrient availability also becomes maximal.

Algal development usually is higher immediately downstream from the dam as well. Epilimnion releases provide a large source of phytoplankton directly, and hypolimnion releases provide levels of inorganic nutrients sufficient for fast phytoplankton growth, although turbid discharges may have the opposite effect. Mixtures of discharges from these two levels leads to proliferations which can exceed those in the reservoir itself. Further downstream, plankton levels drop and, because

of nutrient stripping and algal sedimentation, often fall below levels reached prior to dam construction (Neel, 1966).

B. Aquatic macrophytes

The same conditions favoring high phytoplankton growth rates lead to invasion of reservoir areas by aquatic macrophytes, particularly in shallow parts not subject to much turbulent water motion. These water weeds are capable of covering entire bays, and the freely-floating forms may spread over the majority of the reservoir surface. Water hyacinth (*Eichornia crassipes*) is the chief offender in warm regions of the earth. Submerged macrophytes are a more serious problem in the United States, the most troublesome being *Ceratophyllum*, *Egeria*, *Elodea*, *Myriophyllum*, *Najas*, and *Potamogeton* (Holm *et al*. 1971)

Heavy infestation of macrophytes has many ramifications. Water is lost through transpiration, and both water flow and navigation are obstructed. Fishing and other recreation potentials are diminished. Water inlets or outlets sometimes are clogged by massive developments, and the plants serve as habitats for vectors of serious disease, particularly schistosomiasis and malaria. Chemical, biological, and mechanical control sometimes are effective when provision is made in the planning stages of the project. Although these macrophytes have potential value as food or soil amendment, economic problems associated with harvesting, processing, and transportation preclude their use except perhaps on a local basis.

C. Benthic organisms

Benthic biomass in the reservoir itself can be expected to increase with higher plankton productivity, but little data is available to confirm this. A shift in species composition accompanying the deposition of finer-grained sediments also could be anticipated. Downstream from the dam, irregular discharges discourage benthic development. Aquatic insects with a flying stage are least affected by the altered hydrography, whereas sedentary organisms have the greatest difficulty maintaining populations (Neel, 1966). Cold hypolimnetic releases containing low $O_2$ and high levels of toxic reduced substances such as sulfides decrease benthic faunal productivity downstream. Muddy discharges produce several opposing effects, any of which may dominate; for example, silt-laden water decreases phytoplankton development and avilability through turbidity increases, but may signify a net increase in the food supply by providing sufficient organic material adsorbed to particle surfaces. Further downstream, the combination of lower phytoplankton productivity, lower annual silt load, and delta recession often entails decreased benthic production.

D. Fisheries

Hydroelectric dams usually preclude the persistence of anadromous fish species, serving as effective barriers against migration to the spawning grounds. Certain projects have special structures that permit passage of fish while, more frequently, downstream hatcheries are constructed to propogate the anadromous species. In California, temperature variations, water quality, and disease have rendered salmon and steelhead hatcheries much less effective than originally planned (Hagan and Roberts, 1975).

In the reservoir itself, altered temperature structure implies a shift in species composition, usually to warm-water species. The production of anoxic conditions in the hypolimnion through organic decomposition processes forces the fish to seek oxygen in the upper warmer epilimnion where temperatures may exceed the tolerances of the original species. Anoxic conditions in the hypolimnion are ameliorated by placement of the generator intakes below the expected thermocline depth. Anoxic water then is flushed out preferentially and the hypolimnion can participate as a habitat for fish. Game fish production may increase after reservoir formation, but the high numbers observed during the first years are not sustainable. These large initial populations develop in response to the pulse in phytoplankton productivity, which, as we have seen, slowly subsides as the reservoir ages. Conditions that follow favor the reproduction of competitors that are not as suitable for sport fishing. However, total standing crop of the fish community as a whole does increase gradually as the reservoir ages, probably in response to the increased fertility and area of benthic and littoral environments (Stroud, 1966). Estimates of the change in community composition and in potential fish harvest are extremely difficult to make (Holden, 1969). Although conditions often favor an increase in such food supplies as mosquito larvae, the size of these supplies depends on unpredictable features such as the extent of macrophyte development.

Nitrogen supersaturation of water downstream from the dam sometimes results when air is entrained into water during the discharge process.

The dissolved nitrogen concentration of body fluids increases and interior bubbles may form when fish move into the lower pressures and higher temperatures of the upper layers. Death often ensues. Nitrogen supersaturation is a common effect in widespread reaches of the Columbia River at certain times of the year (Smith, 1972). The net effect of dam construction on downstream fish populations is as variable as the discharge regimes, water quality, temperature, and turbidity downstream from the dam site. Scouring by clear discharged water and sedimentation of silt in muddy discharges both inhibit spawning activity. Macrophyte development, however, in waters receiving nutrient-rich regular discharges, provides increased cover and foraging possibilities.

In delta and bay areas, a decrease in fishery production often reflects the decrease in mean annual load of nutrients borne by the river far from the dam site. A drop in eastern Mediterranean fish harvests has been attributed to construction of the Aswan High Dam on the Nile River (George, 1972).

## E. Wildlife

Reservoir formation results, of course, in the submergence of habitat for terrestrial wildlife, although the larger shoreline increases the carrying capacity for certain species. Opportunities for the establishment of waterfowl such as ducks and geese also improve. Depending on the species composition and populations of the original terrestrial community, the loss in harvestable protein may be greater or smaller than the yields of reservoir fisheries. Areas rich in game fauna, such as the Gwenbe

Valley later flooded by Lake Kariba, generally have a higher faunal productivity than the fisheries established after inundation (Balon, 1974). Attempts to transfer wildlife out of an inundation area have been ineffective, as in Operation Noah at the Lake Kariba project (Goldman and Hoffman, 1975). In the case of endemic or rare species, care must be taken to ensure that transplantation results in establishment of viable populations before the onset of inundation.

The increased sedimentation of suspended matter upstream threatens wildlife dependent on downstream beaches for their survival. Goldman (1972) expressed concern for the future of certain rare or endangered Central American waterfowl that would be threatened by a proposed dam on the Honduran Rio Humuya. These birds utilize portions of Caribbean beaches for nesting, as do the 90% of the world's green turtles that breed in sandy areas that could be altered by the dam's discharge regime. A complete wildlife and bird census is necessary to become acquainted with the problems peculiar to any particular hydroelectric project.

## F. Agriculture

Losses of any agricultural land in the inundation are compensated somewhat by the increased irrigation opportunities and control of flooding downstream. However, a major difficulty accompanies each of these two potential benefits. Decline in water quality, especially the increases in salinity by evaporative processes and in heavy metals by hypolimnetic water releases, may render long-term damage to the agricultural fields. Saltwater intrusion accompanying reduced flows

may be detrimental especially to downstream delta agriculture. In addition, periodic floods deposit nutrient-rich silt on agricultural lands that may be a major factor in maintaining soil fertility. A number of complicated economic impacts (Hagan and Roberts, 1975) also may result from the sudden changes in agricultural practices spurred by dam construction.

G. Recreation and scenic values

Boating and swimming activities are favored by reservoir formation, insofar as they are not hampered by aquatic macrophyte development. Loss of wild game opportunites are not compensated for by the presence of larger fish populations, most warm-water species not being suitable for angling. Coastal tourism can be hindered by beach erosion, but the larger reservoir shoreline permits increased aquatic recreation upstream.

Loss of "wild" river systems through dam construction has proceeded to the extent where remaining pristine areas have become valuable aesthetic resources to large numbers of people. Reservoirs are common and any scenic value they offer certainly is not unique. On the contrary, the denuded strip of land caused by drawdown, the increase in macrophyte populations, and the coloring of clear waters by phytoplankton development are an unsightly alternative to the magnificent lotic systems that reservoirs sometimes replace.

## V. CONCLUSION

The construction of reservoirs change the patterns and extent of human utilization of the project area. The problems of erosion, sewage disposal, fertilizer runoff, etc., ultimately make themselves felt in the water quality of the reservoir and downstream. These problems are similar to those accompanying any urbanization process, but their magnitude is impossible to estimate without a detailed study of the conditions unique to any hydorelectric development. As in the case of more direct effects of reservoir construction, each water system deserves its own specialized study of climatological, geological, and limnological conditions if any acceptable projections are to be made and proper mitigating procedures to be planned.

Despite the difficulties of estimating even the direction of an effect, let alone its magnitude, following reservoir construction, this outline does make one fact clear. Reservoir formation entails large-scale ecological changes, many of them undesirable. Although generation of hydroelectric power produced no immediate pollutants, in contrast to the use of fossil fuel, nuclear, or geothermal energy, the indirect effects on water quality, surface geology, health hazards, and aesthetic appeal weigh heavily against its unrestricted expansion. In addition, long-term climatic changes make it difficult to forecast catchment area precipitation and subsequent power generation capacity of any given site. The notion that hydroelectric power is a "clean" and dependable alternative to other, more obviously polluting energy sources is not a viable one.

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