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WATER CONSTRAINTS ON ENERGY DEVELOPMENT: A FRAMEWORK FOR ANALYSIS

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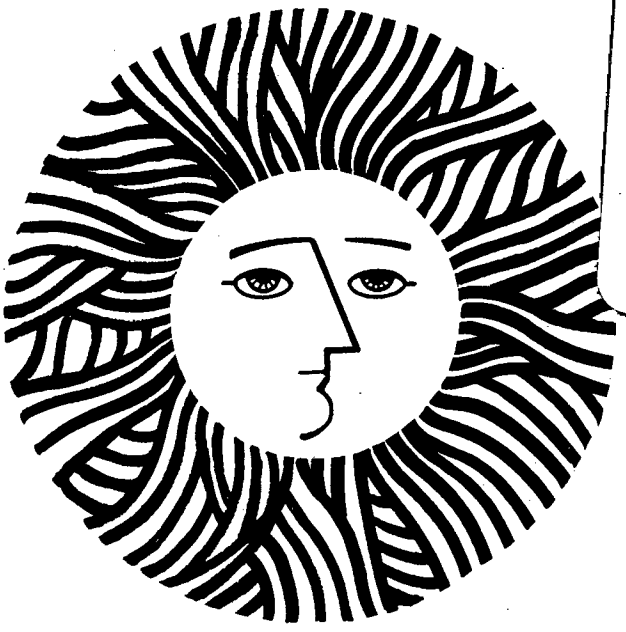

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WATER CONSTRAINTS ON ENERGY DEVELOPMENT: A FRAMEWORK FOR ANALYSIS

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INTRODUCTION

Scarcity of freshwater resources increasingly may constrain future paths of energy development for the following reasons:

- Rich and exploitable raw energy resources such as sunlight, oil shale, coal, uranium, and geothermal heat often are located in arid or semi-arid regions such as the Western United States.
- The newer energy technologies for electricity generation generally are more water intensive than the more traditional ones. For example, an LWR nuclear power plant requires about 50% more cooling water than a coal-fired plant, per unit of electricity produced (Pigford et. al., 1974). The thermal efficiency of most geothermal plants is even lower than that of the LWR, and the thermal efficiency of central station solar electric plants is likely to be even lower. Wind generation of electricity is an important exception, being significantly less water consumptive than any steam-cycle process even when materials requirements are tallied up. The use of dry cooling for steam-cycle electricity production avoids the cooling water problem but carries the penalty of higher direct costs.
- Among the newer technologies for producing liquid and gaseous fuels, many are more water intensive than the traditional ones. Coal and oil shale conversion are two examples of synthetic fuel supply options with enormous potential impacts on water quality and quantity (Braunstein, et. al., 1977). Bioconversion also may be quite water intensive, depending upon the technology for conversion and upon whether irrigated cropland is required for biomass production (Calif, 1976; Shore et. al., 1977).

- Reaction (perhaps overreaction) to the problem of thermal pollution has resulted in increasing emphasis on, and sometimes mandatory use of, wet cooling towers rather than the less water-consuming once-through method for cooling electric generating plants.
- Coastal sites for the location of energy facilities, with the concomitant use of seawater rather than freshwater for cooling and process water, are increasingly difficult to exploit because of increasing concern over the preservation of coastal zones and because of present drawbacks to the use of sea water in wet cooling towers or for coal conversion processes.
- Concern is mounting over the preservation of water supplies for ecological, agricultural, and recreational uses. Wild and free-flowing rivers are a type of ecological habitat and recreational resource which is fast becoming extinct in many regions of the world. Dams designed not only primarily for hydropower, but also dams designed to provide assured cooling water supplies for energy facilities are a continuing threat to rivers. In areas like the Western U.S. where scarce water is now the mainstay of agriculture, economic forces could lead to the diversion of water from agriculture to energy developers, with presently unknown consequences for society.
- A sequence of recent droughts throughout the world, including those in the Western U.S., in Northern Europe, and the Sahel have increased concern that the future may be drier than the past.

The implications for society are profound. First, nations whose energy supply is highly dependent upon continued supply of ample freshwater may find that their energy production is crippled during times

of drought. The social implications of this could be tremendous. Second, the problems of allocating scarce freshwater among energy and other competing users is likely to generate intense questioning of social values and lead to changes in the economic and political institutions presently set up for such allocation. Thirdly, the search for economical and less-water-intensive energy supply technologies, particularly for liquid and gaseous fuel production and for power plant cooling, and the search for new sources of freshwater such as desalination and use of ground water on an economically and environmentally acceptable basis, will challenge greatly our technological abilities.

A reliable assessment of the magnitude and implications of the water-for-energy dilemma requires both facts and a framework within which those facts can be structured and scrutinized. While disagreements abound on the topic of water constraints on energy development, rarely is the disagreement over the numerical values of relevant quantities such as the rate of water use by a cooling tower or the magnitude of the 30-year drought. More frequently, rational discussion is impeded by more fundamental disagreement over, or neglect of, broader issues having to do with the structuring of facts and uncertainties. More specifically, there is a disagreement about the answers to questions of the following sort:

- What should we assume about presently unknown future levels of supply and consumption of energy?
- How do we express our uncertainty about quantities pertinent to the water-energy interface, such as water consumption by an energy supply technology which is not now fully specified or in operation?

- What statistical aspects of runoff, river flow, and lake levels should be used to express available water supply under the stochastic conditions found in nature?
- What ecological and other criteria should be assumed for assessing whether a particular level of water consumption from a river basin is acceptable?
- How can we express the human consequences of the transfer of water to energy industries from natural rivers, lakes, and estuaries, and from other potential users?

Answers to these questions constitute what I call a framework for analysis. In the following I present, and argue the merits for, a particular framework. The approach presented was used in the U.S. National Academy of Sciences' CONAES study (Committee on Nuclear and Alternative Energy Systems). In that study it was shown that in the U.S., future reliance on coal and coal-derived synthetic fuels to meet present U.S. energy demand would be likely to create severe water problems in many regions unless extraordinary efforts are made to implement dry cooling and stringent water pollution abatement. The facts and framework used in the CONAES analysis of water constraints on U.S. energy development have been published (Harte and El-Gasseir, 1978); it is based on responses to that work that I now perceive the need to set forth and explain the framework used, because the major disagreements that have arisen result from different perceptions of the wisest answers to the 5 questions given above.

The production and conversion of energy can damage water resources in numerous ways. An abbreviated taxonomy of the classes of problems is shown in Table. 1. Also listed there are some examples of the major energy activities causing the problems and some of the human consequences of these problems. We discuss here only one of these categories of problems- that of water consumption.

FUTURE ENERGY PATTERNS

The CONAES analysis of water constraints on energy development adopted a scenario approach in which a variety of possible alternative futures were examined. Each scenario specifies a particular mix of energy sources and conversion operations. For example, included in a scenario involving expansion of the use of coal would be a specification of the rate at which coal is surface-mined and deep-mined, the approximate location of mining sites (by hydrological basin), the rate at which coal is burned directly and the rate at which it is first converted to synthetic fuels, the rate at which it is used to produce electricity, the mix of cooling modes employed, and the rate at which coal is transported by slurry pipeline out of particular hydrological basins. In addition, each scenario describes, with varying degrees of geographic specificity, the water sources to be used for energy development along with the sources and amounts of water needed for non-energy purposes. The scenarios are constructed to satisfy minimal consistency and common sense requirements such as follow from energy end-use constraints.

Often, analysis of the water-energy dilemma begins with a well-defined prediction for future energy and water consumption. The scenarios are not intended to be predictions of the future, but rather are hypotheses which can be used to determine the likely consequences of a wide range of possible futures. The use of scenarios avoids being locked into a particular set of assumptions or beliefs about the future, and are an essential tool in the planning process. Considerable confusion exists over what the future course of energy (and water) consumption will be. One can find

predictions ranging from a continuation of the historical growth in energy consumption to a decrease in total annual energy consumption over the next several generations. Frequently one or another of these projections is treated as if it were an inevitability and policy is geared toward its fulfillment. A preoccupation with prediction rather than planning of energy (and water) use, characterizes current response to the uncertainties of the future. It is not necessarily a response designed to provide future generations with the most desirable technological, environmental, and social legacy, and, as such, is a potential obstacle to rational water-energy policy.

UNCERTAINTIES AT THE WATER-ENERGY INTERFACE

The scenarios are useful constructs for analyzing water constraints on energy development only to the extent that the water requirements for the hypothesized energy activities can be specified. Unfortunately, in many cases we do not know with the desired precision what will be the water consumption per unit of produced energy. Thus even a precisely specified scenario does not necessarily lead to a precise estimate of associated water use.

More precise estimates would certainly make the energy-planning process easier, and thus there is some justification for making a best guess as to a particular value of water use and working with that guess. At the present time, however, the advantages of being able to present precise numbers are far outweighed by the loss of information that occurs

when the full range of uncertainty is obscured. A considerable amount of field experience will be required before the water requirements for reclaiming surface-mined land in semi-arid or arid regions are known confidently, and even then future water requirements will be found to vary with climate conditions and precise future geographic site, neither of which is presently predictable. Moreover, preliminary results on water consumption from demonstration sites may be misleading if optimum conditions are chosen.

The extent to which dry cooling will be used in the future for steam cycle electricity generation depends a lot on presently unpredictable economic factors such as the price of water as well as on the pressures from regulatory agencies. The amount of water to be consumed or significantly impaired in quality by an oil shale mine and retort facility depends on presently unknown factors including the hydrological stability of ground water formations, the price and effectiveness of water-pollution-abatement equipment, and the regulatory actions taken by political bodies.

The uncertainties are clearly enormous. In the CONAES study, the upper and lower limits to water consumption within a given scenario sometimes differed by nearly an order of magnitude. For example, in one scenario calling for 48×10^{18} joules of coal to be mined in the U.S., with 16×10^{18} joules of synthetic gaseous and liquid fuels produced from part of that coal mostly in the more water-abundant Eastern U.S., additional water consumption in three major Eastern U.S. hydrological basins would range from between 1.7 to 8.8 km^3/year. This amounts to a 50% to 250% increase above present total water consumption in that region (Harte and El-Gasseir, 1978).

Just as scenarios are preferable to prediction because they allow exploration of a range of possible futures, so a portrayal of the full range of uncertainty in the water requirements of future energy technologies is more useful than selection of a "best guess". A spectrum of water consumption estimates, ranging from water-wasteful to water-conserving, will allow the consequences of all the alternatives to be explored, whereas focusing on a particular precise guess as to water requirements of a new technology provides only the illusion of accuracy.

APPROPRIATE MEASURE OF WATER SUPPLY

The scenarios portray possible future paths of energy development and the per-unit-energy water consumption figures allow estimation of the water requirements for energy within each of the scenarios. What is needed next is a proper measure of natural and regulated water supply against which water consumption for energy can be compared. In many analysies of energy-water problems, a comparison is made between consumption and mean runoff, because mean runoff is the hydrological parameter most easily obtained and understood. This can be highly misleading, however.

In particular, knowledge of mean water supply does not provide an adequate basis for analysing either the water supply constraints for energy technologies or the environmental consequences of consuming a given fraction of that available supply. The reason is that runoff is not constant in time (whereas industrial consumption is to a great extent) and

thus consumption of water can reduce runoff by a large fraction during certain times of the year, or during certain years, even though, on the average, consumption reduces runoff only by a relatively small amount. Because aquatic ecosystems can be sensitive to reductions below natural flow, even if those reductions only occur at widely spaced random intervals, and because sporadic shortfalls in water supply to a water-dependent energy-supply industry can have major social consequences, it is clear that an appropriate description of the variability of runoff, as well as of the average runoff, is essential to the type of analysis under discussions.

A start along these lines requires appropriate indices of natural fluctuation. For the case of stream flow, we have advocated the use of a two-variable index, denoted ${}_xQ_y$. This quantity is the x-day, y-year low flow, and is defined as the lowest flow rate, averaged over x consecutive days of the year, expected on the average every y consecutive years. The quantity ${}_xQ_y$ is important both to the water consumer and to the ecologist studying impacts of the consumption. For the water consumer it allows calculation of the amount of water storage needed to survive periods of drought, or it can be thought of as a measure of the degree of flexibility in operating schedule needed to accomodate to droughts (for example, it tells how often and for what period of time it is necessary either to switch to more expensive, but less water-consuming, modes of cooling during dry times or to shut down operations altogether and transfer customers to other suppliers). For the ecologist concerned with the maintenance of riparian and estuarine habitat, the double degree of freedom in ${}_xQ_y$ is also important. Simpler indices, such as the z-percent

flow (i.e., the flow exceeded all but (100-z)% of the time) do not easily make contact with information about the tolerances of aquatic organisms to periods of uninterrupted stress. Because ${}_xQ_y$ provides information about both the duration of the drought (x) and the frequency of it (y), it is a richer statistical measure of flow and one upon which site-specific water consumption criteria for industry can be constructed.

Evaluation of the ${}_xQ_y$'s in most of the world's hydrologic basins (or for most major rivers) has not been carried out. The relation between mean flow and a particular ${}_xQ_y$ will depend upon many factors, including the extent of flow regulation in the basin and the seasonal distribution of rainfall. In many regions the raw data (daily runoff figures) exist with which to calculate the ${}_xQ_y$'s; the importance of doing those calculations extends beyond just energy-related water impact evaluation.

CONSUMPTION CRITERIA

Suppose that the energy-related water consumption within a given scenario is specified and, in addition, estimates of the available water supply in the form of information of the ${}_xQ_y$'s for the relevant hydrological basins is at hand. Some criteria are still needed which will allow judgments to be made as to the severity of the impacts of the additional consumption. Two types of criteria are needed: one would provide energy developers and consumers with a measure of the vulnerability of energy production to drought; the second would incorporate ecological information and allow an estimation of damage to riparian and estuarine

life based on knowledge of water consumption and runoff statistics. Ideally, the criteria would be in the form of critical water consumption levels below which the impacts are considered acceptable.

In siting a water-consuming facility along a river, it is important that not only the mean flow be adequate but also that the actual instantaneous flow be nearly always adequate. The practical meaning of "nearly always" will depend on storage capacity and acceptable shutdown time when drought conditions prevail. For a given acceptable amount of shutdown, knowledge of the ${}_xQ_y$'s allows the minimum storage capacity to be determined. For example, consider a facility that consumes river water at a rate C. In order for the facility to continue operation through a particular ${}_xQ_y$ low flow period, where $C \geqslant {}_xQ_y$, the required water storage capacity would have to exceed $(x)(C - {}_xQ_y)$. It is clear that when C only slightly exceeds ${}_xQ_y$, even a small percentage increase in the consumption rate can necessitate the construction of a large percentage increase in storage.

Pursuing this line of reasoning, a consumption criterion based on a suitable fraction of appropriate ${}_xQ_y$'s could be formulated. The choice of x and y, as well as the choice of the acceptable fraction will depend on numerous factors such as the size of water storage facilities, the availability of other forms of energy to fall back on in the event of below-average water supply, the willingness of society to reduce energy and water consumption during drought periods and the evaporation rate from storage reservoirs. Needless to say an adequate consumption criterion based on these considerations has yet to be formulated.

The second type of criterion is one designed to protect aquatic ecosystems from excessive water consumption by society. Much information

exists suggesting that the health of streams and estuaries is closely linked to maintenance of natural patterns of stream flow, although the uncertainties are large. Among the types of effects of flow alteration which have been studied are interference with nesting habitat for aquatic organisms (Hynes, 1970; Hazel, 1976; Brusven and Macphee, 1976), changes in the rates of flushing and transport of minerals and organic materials (Lauff, 1967), changes in the temperature regime of the water (arising, for example, from flow diminution causing the creation of still pools which heat up), altered ambient chemical conditions (for example, depressed oxygen levels due to temperature increase, or diminished ability of a river to dilute pollutants), and altered circulation patterns and salt water-fresh water mixing in estuaries (Lauff, 1967). Adverse effects can occur from either diminished or increased flow, relative to natural conditions. For example, excessive flow resulting from discharge from storage facilities during the normally dry late-summer season in many parts of the world can be destructive to bottom-living organisms that rely on low-flow periods to secure nest sites on bottom materials, and can also interfere with the incubation habits of certain fish species. The diversity of organisms that can successfully co-exist in an aquatic habitat is also flow-rate dependent and often is reduced by flow-rate alteration.

As is often the case in environmental impact science, even a large amount of data, and a qualitatively well-understood situation do not necessarily allow the deduction of quantitative predictions or provide the needed information to set standards with confidence. In the case of stream-flow alteration, this is particularly true today. A very rough

guideline for estimating ecologically permissable flow reduction has been formulated (Samuels, 1976) and discussed (Harte and El-Gasseir, 1978); it states that consumption of water from a river should not exceed 10% of $_7Q_{10}$. This guideline guarantees that during the 7 consecutive days of lowest flow, expected on the average every 10 years, flow reduction would not exceed 10%. Of course, if the consumption rate is constant even this guideline might permit 50% or even 100% of flow to be consumed perhaps every 50 years or every century.

PLACING THE IMPACTS IN A HUMAN CONTEXT

The framework for analysis assembled so far allows the determination (within the range of uncertainty) of the energy-related water consumption in each hypothetical future described by the scenarios. Moreover, it allows comparison of that consumption with the appropriate statistical measures of the available water resource, and provides a rough yardstick for gauging the severity of the ecological impacts of that consumption and the consequences for those concerned with continuity of energy supply. A fifth ingredient is needed in order to complete the analysis, however, for it is important that the human consequences of increased water consumption be assessed. Aside from their intrinsic value, natural ecosystems provide a number of goods and services of irreplaceable value to society (Westman, 1977; Harte and Jassby, 1978); while they can readily be identified and discussed abstractly, they are difficult to take into account in planning energy or other development activities.

Table 2 provides a map of the stages of ecological, and associated human, impact of technological activities. Present levels of ignorance or uncertainty generally increase as one travels down the map and to the

right. Thus much more is presently understood about the nature of the pollutants resulting from energy activities than is known about their ecological effects, and more is known about the direct effects of these pollutants on human health than is known about the human consequences of ecosystem degradation. Perhaps least understood of all is the feedback loop characterizing societal responses to losses of goods and services hitherto provided by healthily functioning ecosystems.

A major impediment to our ability to incorporate environmental impacts directly into the decision-making process is present ignorance about how to measure the human costs of environmental degradation. Some of these costs can be fairly readily translated into economic terms, once the environmental damage is accurately understood and described (in itself, often a difficult task.) An example is the cost of direct damage to fisheries from water pollution. But other costs of environmental damage are quite resistant to monetary evaluation (for instance, the social cost of degraded recreational opportunity) and it is quite difficult to devise ways to know whether or not the energy produced at the expense of such damage is "worth it". Likewise, it is often difficult to know whether the substitution of water pollution for air pollution leaves society better or worse off in the aggregate. At the moment the customary antidote for this type of uncertainty is to attempt to understand better and describe the separate environmental and social consequences of alternative energy policies, leaving judgments about total welfare to the political processes. It is not clear that society can or should do better than this with more refined economic tools. The use of esoteric economic tools to perform the task of valuation of the loss of natural goods and services carries with it dangers, removing certain choices from the political arena to the hands of a very few specialists.

But if the political arena is to be the place where values are assigned to natural goods and services and tradeoffs are decided, it is important that information concerning environmental damage be available to the public in a form most likely to lead to rational assessment. Examples of ways not to present information abound in the literature on risk. For example, frequently one sees statements of the type: The water consumed annually by a proposed coal-slurry pipeline to transport U.S. Western coal will be only one-hundredth that used annually by farmers for irrigation in the Great Plains. Or, in the same spirit, a comparison is made between probability of death from a release of nuclear materials from the uranium fuel cycle and the probability of death for Californians from an earthquake. The deception infused into risk assessment from such comparisons results from attempting to compare the risks of activities which have non-commensurable benefits (Budnitz and Holdren, 1976).

Risk assessment focused on comparisions of comparable risks of various pathways of energy strategies for achieving common benefits is likely to be most illuminating. An example from the CONAES report illustrates this approach. There are many ways to increase the use of coal. It can be burned directly to satisfy some end uses, or it can be converted to electricity first, or it can be converted to gaseous or liquid synthetic fuels with these fuels either used directly or converted to electricity. Because different pathways for using coal may be optimum for different end uses or benefits, overall assessment of the optimum pathway is likely to be a futile effort. The CONAES study considered a particular end use - that of home-heating. Ruling out direct coal burning in the home for obvious reasons, the choices remaining are electric heating (with the electricity produced either from coal directly or from synthetic coal-derived fuels) versus direct heating with synthetic fuels. Which of these is most appropriate? Here again, the problem is too broadly

stated to allow a simple answer. The consequences of the pathways will be different for different types of ecosystems and will very likely be non-comparable. A more manageable comparison can be achieved by looking at a particular type of risk, and so the CONAES study focused upon a comparison of water consumption in each of the coal pathways for home heating (Harte and El-Gasseir, 1978). As long as the same benefits are being compared (in this case the heating of homes) comparison of this common measure of risk is useful.

Water consumption for home heating is of course only one example of a "common-benefit, common-risk" comparison. We submit that the total effect on overall energy strategy risk analysis of having a large number of such comparisons for various risks and various benefits would be far more useful than what would emerge from the same amount of effort put into optimization programs based on cost-benefit analyses and attempts at finding conversion units for inter-risk and inter-benefit comparisons.

CONCLUSION

A study of the impacts of future energy development on freshwater resources carried out as part of the U.S. National Academy of Sciences' CONAES study led to the identification of severe constraints on U.S. energy development that could arise in the future because of the geographic and temporal variability of the freshwater resource. The present essay is not intended to summarize the results of the CONAES work on water-energy problems, but rather to describe the components of the

analytical method developed for that study.

Five facets characterize our assessment method.

- Specification of future patterns of energy supply and demand takes the form of scenarios, which describe possibilities rather than predictions. The scenarios allow exploration of a great range of possible futures and avoid entrapment in a particular, and very likely incorrect, guess as to what the future will look like.
- The water requirements of future energy activities often are highly uncertain today; this uncertainty is reflected in the per-unit-energy water requirements which accompany the scenarios. By not obscuring the range of uncertainty with a "best guess", the consequences of various intensities of water conservation effort by the energy industries can be assessed.
- The freshwater resource is described by a set of quantities calculable from daily runoff measurements. These statistical parameters provide considerably more information about temporal variability of water supply than are provided by means and variances.
- The information encapsulated by these parameters is of direct relevance to aquatic biologists and to energy suppliers and consumers. They are an appropriate basis for constructing measures of impact which, with more empirical input, could eventually be reformulated as standards or guidelines for acceptable water consumption.
- Only a very preliminary and incomplete effort has gone into the important problem of placing the impacts of water consumption in a human context. Two broad approaches can be discerned. In one, an integrated assessment would be attempted, in which all impacts are reduced to a

common, probably monetary, measure. In the second approach, which we advocate, impact analyses of the "common-risk, common-benefit" type are carried out, and the political process is relied upon to resolve the problem of integration.

Our purpose in describing, and arguing the merits for, a particular method of analysis is twofold. First, we have found that a considerable amount of debate and criticism triggered by the CONAES water-energy study results from fundamental and not easily recognized confusion and sometimes disagreement about the underlying assumptions in our assessment approach. Analysts who prefer to work with predictions of future energy levels rather than scenarios, or who prefer to take a best guess as to the water consumption of a presently non-operating energy technology rather than to deal with the present full range of uncertainty, or who prefer to compare water consumption with mean runoff rather than with the statistical measures we employ, find it difficult to find a common ground for discussion partly because of our failure to state clearly what we are doing and why we have adopted our particular methods. Second, we are hopeful that the approach presented may be of use in assessing the constraints of other scarce resources upon energy development.

ACKNOWLEDGEMENT

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CATEGORY OF PROBLEM	CONSUMPTION	POLLUTION	WITHDRAWAL
MAJOR ENERGY ACTIVITIES POTENTIALLY CAUSING THE PROBLEM	COOLING (PARTICULARLY WET COOLING TOWERS) PROCESS AND CHEMICAL FEED-STOCK WATER FOR SYNTHETIC FUEL PRODUCTION RECLAMATION SLURRY PIPELINING	SYNTHETIC FUEL PRODUCTION AIR POLLUTION ABATEMENT COAL AND OIL SHALE MINING SLURRY PIPE-LINING	SAME AS CONSUMPTION (PARTICULARLY ONCE-THROUGH COOLING)
MAJOR POTENTIAL CONSEQUENCES	LOSS OF RIVER AND ESTUARY HABITAT LOSS OF RECRE-ATIONAL OPPOR-TUNITY ECONOMIC LOSS TO FISHING AND FARMING	ECOLOGICAL DAMAGE HUMAN HEALTH HAZARDS ODOR AND OTHER AESTHETIC LOSS ECONOMIC LOSS TO WATER USERS	ENTRAINMENT AND ENTRAPMENT OF ORGANISMS NEED FOR STORAGE FACILITIES WITH THEIR CONCOMITANT PROBLEMS

TABLE 1

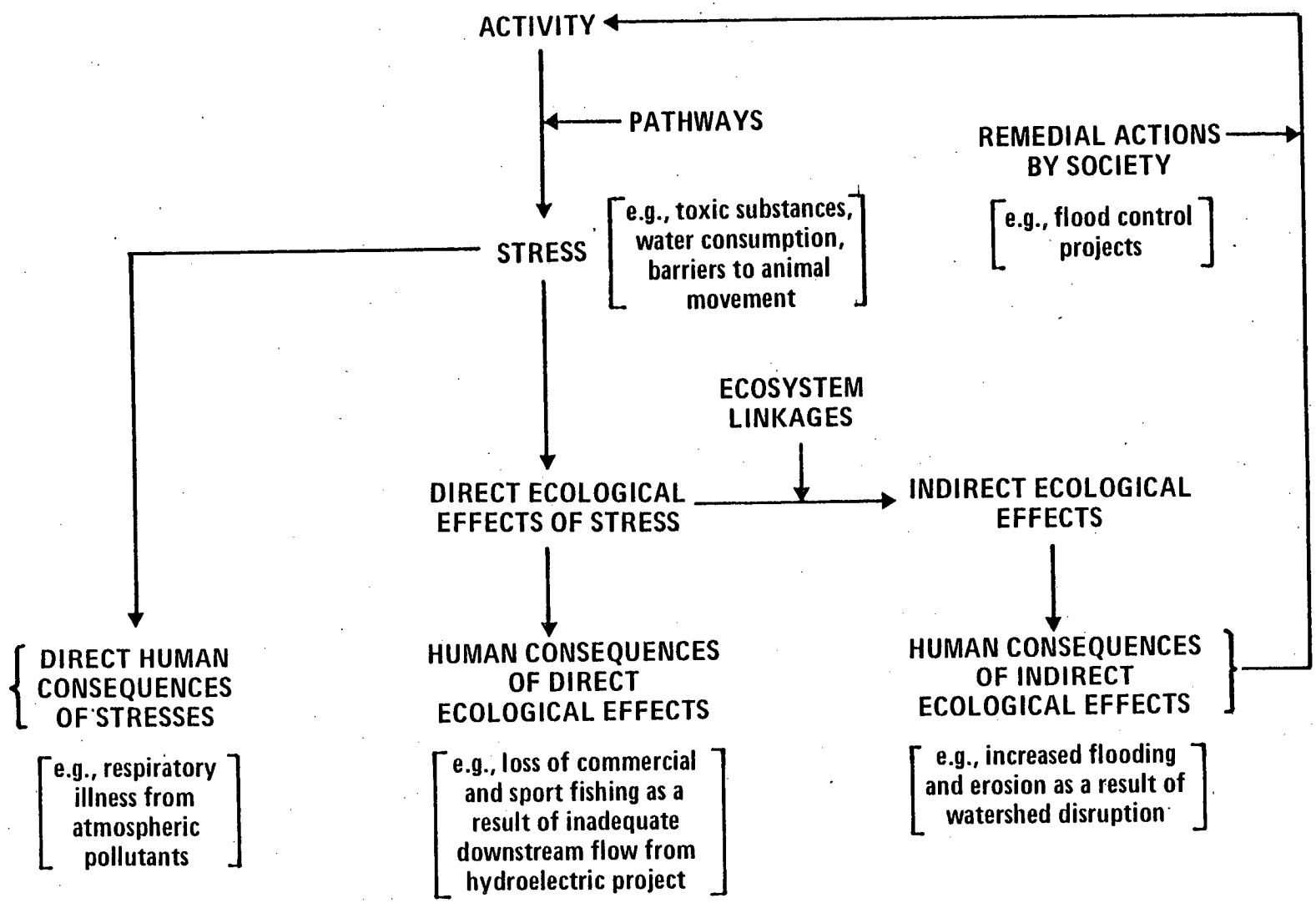
ACTIVITY
PATHWAYS
REMEDIAL ACTIONS BY SOCIETY
e.g., flood control projects
STRESS
e.g., toxic substances, water consumption, barriers to animal movement
ECOSYSTEM LINKAGES
DIRECT ECOLOGICAL EFFECTS OF STRESS
INDIRECT ECOLOGICAL EFFECTS
DIRECT HUMAN CONSEQUENCES OF STRESSES
e.g., respiratory illness from atmospheric pollutants
HUMAN CONSEQUENCES OF DIRECT ECOLOGICAL EFFECTS
e.g., loss of commercial and sport fishing as a result of inadequate downstream flow from hydroelectric project
HUMAN CONSEQUENCES OF INDIRECT ECOLOGICAL EFFECTS
e.g., increased flooding and erosion as a result of watershed disruption

TABLE 2

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