QUANTIFICATION OF
AQUATIC ENVIRONMENTAL IMPACT
OF ELECTRIC POWER GENERATION

J. Gruhl

Report #MIT-EL 73-004 April 1973

ENERGY LABORATORY

The Energy Laboratory was established by the Massachusetts Institute of Technology as a Special Laboratory of the Institute for research on the complex societal and technological problems of the supply, demand and consumption of energy. Its full-time staff assists in focusing the diverse research at the Institute to permit undertaking of long term interdisciplinary projects of considerable magnitude. For any specific program, the relative roles of the Energy Laboratory, other special laboratories, academic departments and laboratories depend upon the technologies and issues involved. Because close coupling with the normal academic teaching and research activities of the Institute is an important feature of the Energy Laboratory, its principal activities are conducted on the Institute's Cambridge Campus.

This study was done in association with the Electric Power Systems Engineering Laboratory and the Department of Civil Engineering (Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics and the Civil Engineering Systems Laboratory).

ABSTRACT

This project proposes a method for creating, to the extent of their predictability, the proper and timely forecasts of the aquatic ecosystem consequences of electric power system operation. A procedure is developed and intended for use in quantifying the ecological sacrifices associated with a number of desirable regional dispatch schedules. With the use of this technique, associated with a given reliability level, optimum scheduling schemes can be used to evaluate optimum dollar cost - environmental impact pairings.

A prerequisite of the model was that it be flexible enough for use in the evaluation of aquasystem impacts from either existing or hypothesized systems, that is, that it could be used either as an operational tool or as a simulation tool.

Specifically demonstrated is the feasibility of the quantification of various ecological impacts and its usefulness in effecting compatibility between the power generating facilities and the aquatic ecosystem into which they have been incorporated. The method of quantification involves a probabilistic systems approach which includes a due regard for the vagaries of nature. Essentially calculated is the change in desirability to man of the ecosystem as influenced by the losses of organisms, such losses being computed from the probabilistic curves of affected populations convolved with the probability of impact curves. Predictive techniques are developed for the avoidance of mortalities due to thermotoxic synergisms.

A discussion of an atmospheric model counterpart is presented to demonstrate the existence of compatible and consistent atmospheric quantification procedures.

This project is primarily intended as a state-of-the-art survey of the research areas contributing to this area with particular attention paid to the precise input modeling techniques available. However, a new method is presented for combining these inputs in a thorough and consistent manner to obtain a meaningful environmental impact measure.

Acknowledgement

The author would like to acknowledge the help of Prof. S. F. Moore, MIT Department of Civil Engineering, who offered his initial insights and final critical refinements of the model formulated in Chapter 4, as well as the use of his research collection, and direction in the accumulation of source material.

I would also like to thank Mrs. R. Seidman, librarian of the Region One Environmental Protection Agency, Needham, Massachusetts, for her assistance and for permission to use the library's collection of water research literature.

The help offered by Miss Nancy Huston is also much appreciated, both for her suggestions on methods of clarifying the text and for her proofreading.

Table of Contents

List of Illustrations

page

1. Introduction

A great problem to develop from this industrial era is the dilemma between the increasing demands for energy and the increasing demands that environmental qualities not be degraded. As the electric power industry assumes an ever increasing commitment to resolve the energy supply problem it is subjected to escalating societal pressures to:

(1) generate reliably a sufficient amount of electricity to meet any demands,

(2) retain or decrease its price rates, and

(3) minimize the impact of its generation efforts upon the ecosphere.

The solution to this problem will take a long and unremitting effort from all sectors of society. In the long-term (30 years) program of action must be included, among many other things, efforts to develop more efficient means of power generation and more efficient power utilization.[2] There can be no doubt that to reverse the trend of environmental deterioration a tremendous technological effort will be required.

There is, however, another aspect of the solution to the 'electric power-environment' dilemma which should be closely coordinated with (and is definitely not meant to be a replacement for) the technological advances, but is essentially a separate effort. This is the development of methods

---

[2] A detailed documentation of the course of action required from technological improvements is contained in a report by Philip Sporn, reference (1).

to assure the best possible operation of an imperfect power generation system. That is, until facilities which are perfectly compatible with the ecosystem are producing all of our power there must be a method for assuring that the imperfect plants are utilized in the least damaging manner. This effort breaks essentially into two segments. First, the plants must be sited to take the best advantage of the site options available.[3] Secondly, the operation of existing systems must be directed toward those objectives enumerated at the beginning of this section.

This optimum operation of existing systems is the overall project being undertaken in the author's Ph.D. thesis, of which this study is one portion.

1.1 Problem

For a more thorough description of the overall study of 'optimum operation of existing systems' of which this research effort is a part, the reader is directed to reference (4). However, a basic understanding of the interconnections involved can be gotten from figure 1.1-1 on the next page.

The annual optimum production and maintenance scheduler of figure 1.1-1 has been developed and is capable of generating optimum schedules for various dollar costs and environmental

---

[3] This is a problem receiving a great deal of research effort, see for example reference (2). The author's particular project is also to be used as a simulation technique for the evaluation of specifically hypothesized expansion alternatives, as explained in reference (3).

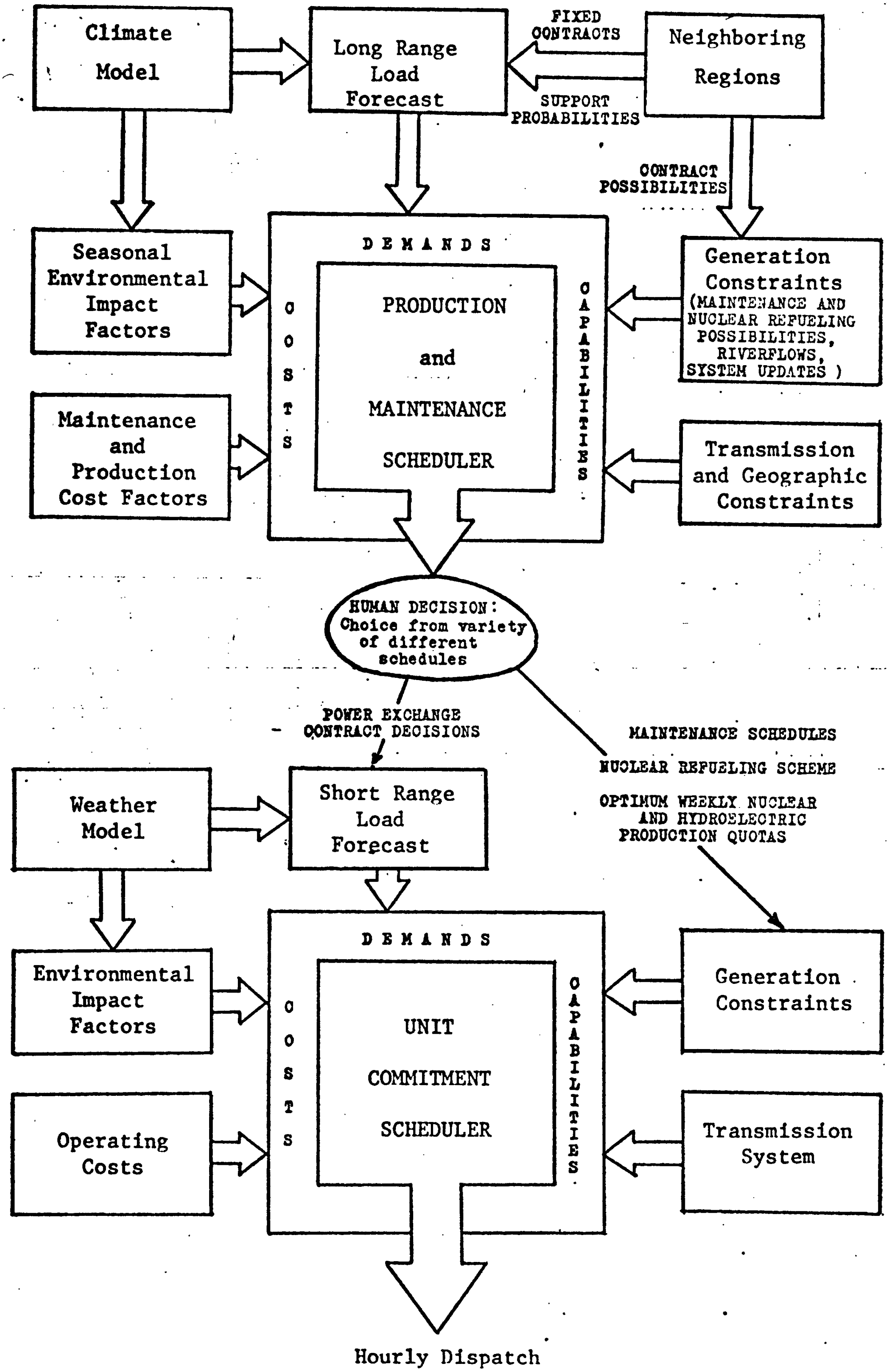


Figure 1.1-1 Block diagram representation of the overall system operation procedure

impact units.[4] A similar output can be gotten from the existing unit commitment scheduler,[5] that is, optimum schedules can be gotten for any desired mix of dollar costs and any or all of the relevant environmental measures. Figure 1.1-2 shows all possible optimum dollar - water impact pairing consequences.

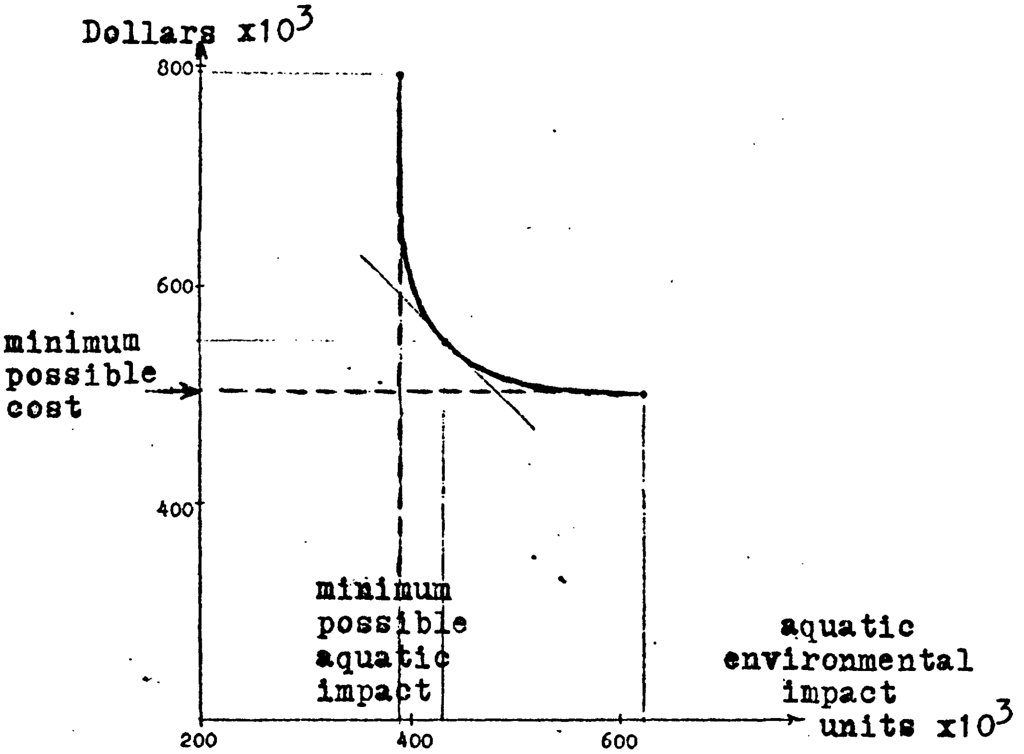


Figure 1.1-2 Range of all dollar - aquatic environmental impact pairings available from optimum schedules.[6]

The problem contended with in this project is the development of those aquatic environmental impact units, associated with the aquasystem ramifications of electric power operation, mainly the thermal pollution of those facilities.

Not only is there no existing scheme for the quantification

---

[4] Contained in reference (5).

[5] Contained in reference (6).

[6] From reference (7).

of such ecological impacts, but it is in fact not known whether or not it is useful or even meaningful to talk about such a measure as an ecological impact unit.

1.2 Results

The most marked impression which results from even a brief study of the dynamics of aquatic ecosystems is the unusually strong stability they exhibit. Because the aquatic organisms are linked tightly in a predator-food chain, homeostasis, any loss of a portion of one species' population results in the increased availability of its food sources and the decrease in the number of its predators, making an ideal environment for the comeback of the depleted species or a replacement by a more suitably adapted organism.

This inherent stability is particularly evident with respect to natural[7] perturbations, for example temperature. Stable natural water habitats are known to range from the -15° C (4° F) of parts of the Arctic Ocean to 85° C (185° F) of some hot springs. Thus, any long range study of the ramifications to man of temperature changes in aquatic ecosystems must disgard any attempts at the measurement of the instabilities induced in favor of efforts to compile a survey of the relative desirability to man of the resultant stable habitats.

---

[7] An unnatural stimulus in an aquatic habitat would include any peculiarly man-made perturbations, such as concentrations of acetone, sulfuric acid, etc. Unnatural changes, in general, have singularly significant ramifications because organisms may not have mechanisms which have evolved for adaptation to these stimuli.

The conspicuous scarcity of mathematically descriptive material in all the fields of ecology is apparently based mainly[8] upon the suspicion, which I feel is well-founded, that the use of numerical descriptors may overshadow many of the problems and interrelationships contributing to the incredible complexity of the intertwining life processes. Insofar as these exposed insights of ecologists are also valuable and useful products of their investigations these insights are used in this project. That is, quantification is avoided until the last stage of this assessment, and any intermediate numbers created are related to physically significant, and thus measurable and correctable, quantities or processes.

Quantifying the effect of heat on an aquatic organism is not a trivial task, due to the number of synergistic effects which significantly diminish tolerances to thermal stresses, see figure 1.2-1 on the following page. These effects are considered in the results of this study, being included in the form of measurements of water quality (for unfavorable physical factors and toxins), recognition of the food chain limiting processes, secondary mortalities (that is, stressing biological factors) and time variations in sensitivity (solar and lunar photoperiods).

A number of existing studies have shown that thermal

---

[8] Some mathematical unsophistication can be seen to play a small role as evidenced by some lack of sufficient statistical treatments, few multivariable experiments and insufficient concern for differentials between perturbed and control systems.

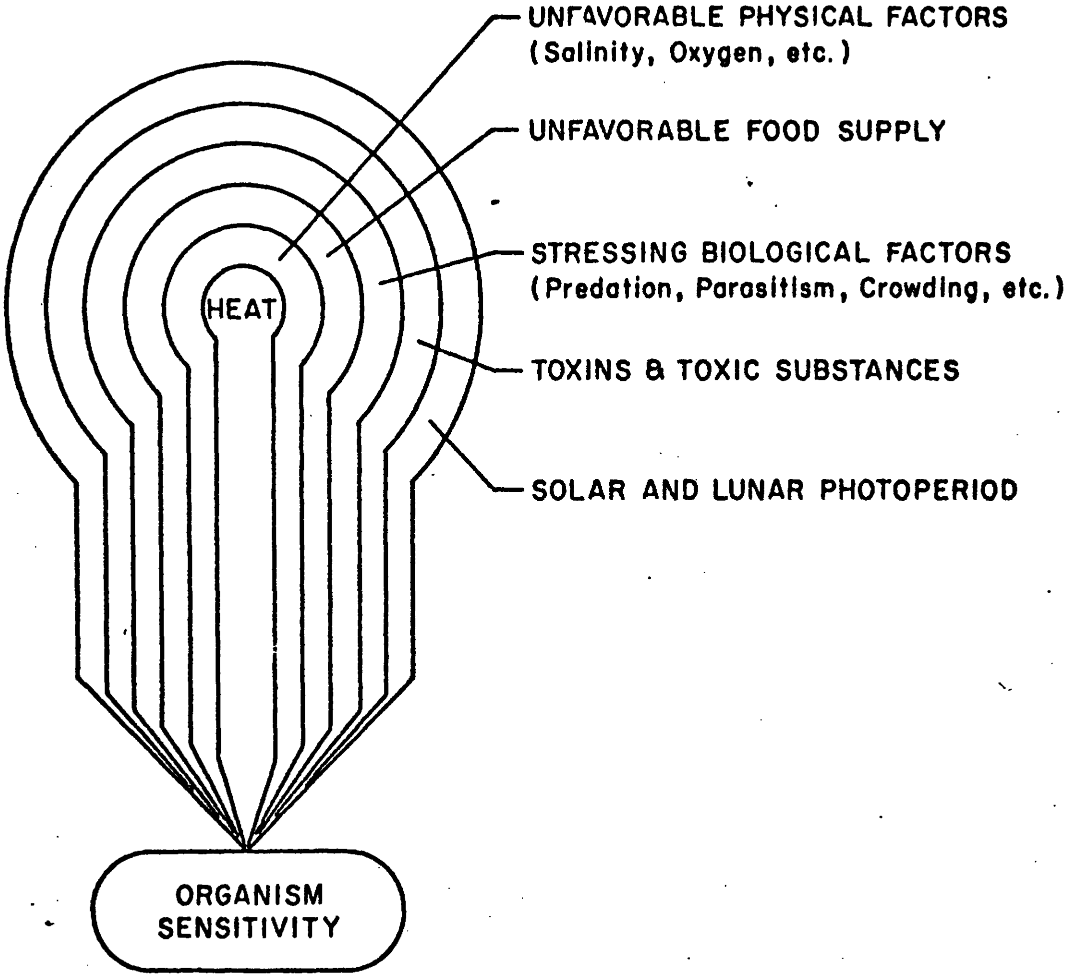


Figure 1.2-1 Other factors which aggravate an aquatic organism's tolerance for thermal stress.[9]

tolerance also is known to vary with the different life stages of an organism, refer to figure 1.2-2 on the next page. These effects naturally fall into the portion of the model which

---

9. Excerpt from reference (8), page 174.

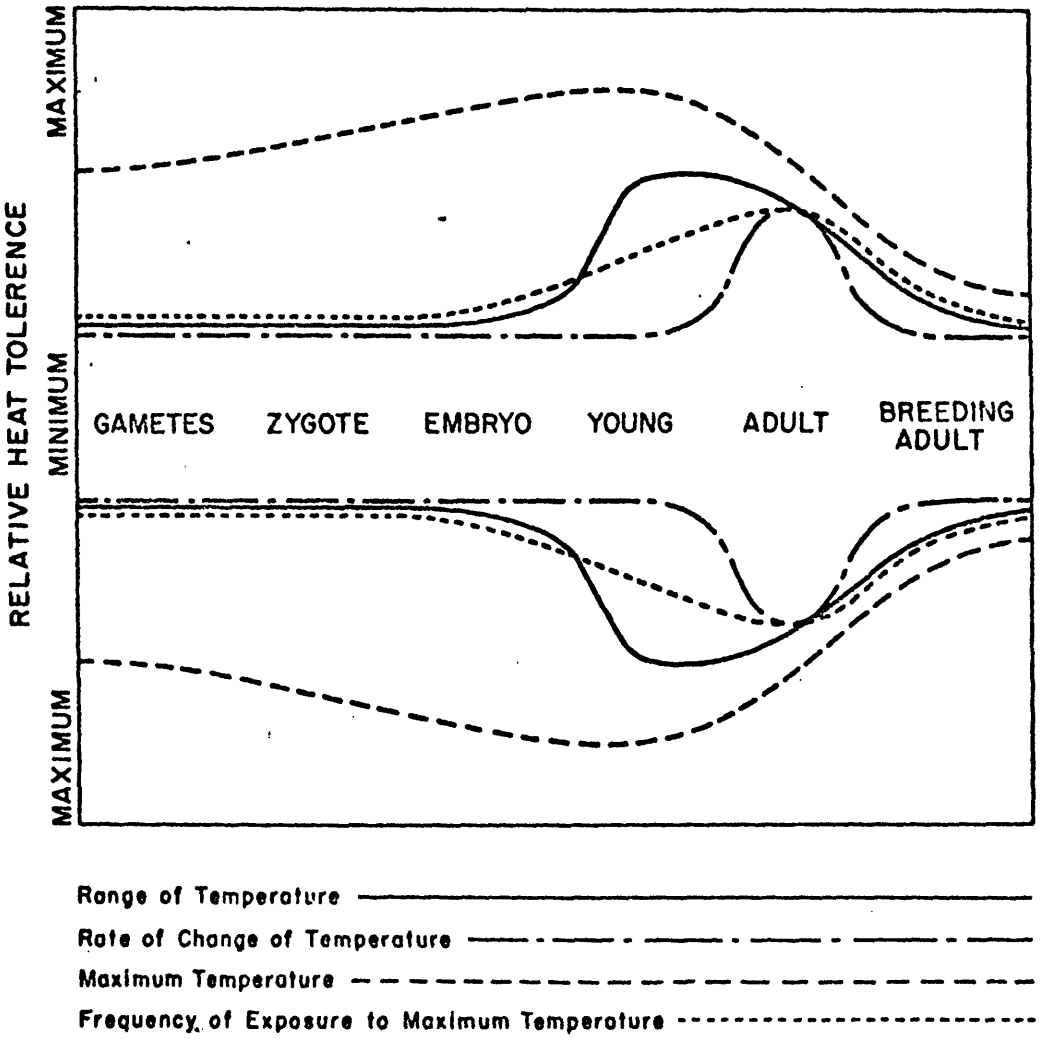


Figure 1.2-2 Thermal tolerance variation with changes in life stages.[10]

considers time variations in sensitivity.

The resultant model developed by this investigation is contained on the following page, as figure 1.2-3, in its simplified systematic block diagram form. The operations of the various modules of this representation are defined and in some cases examples are presented. Particular detail

---

10. Excerpt from reference (8), page 181.

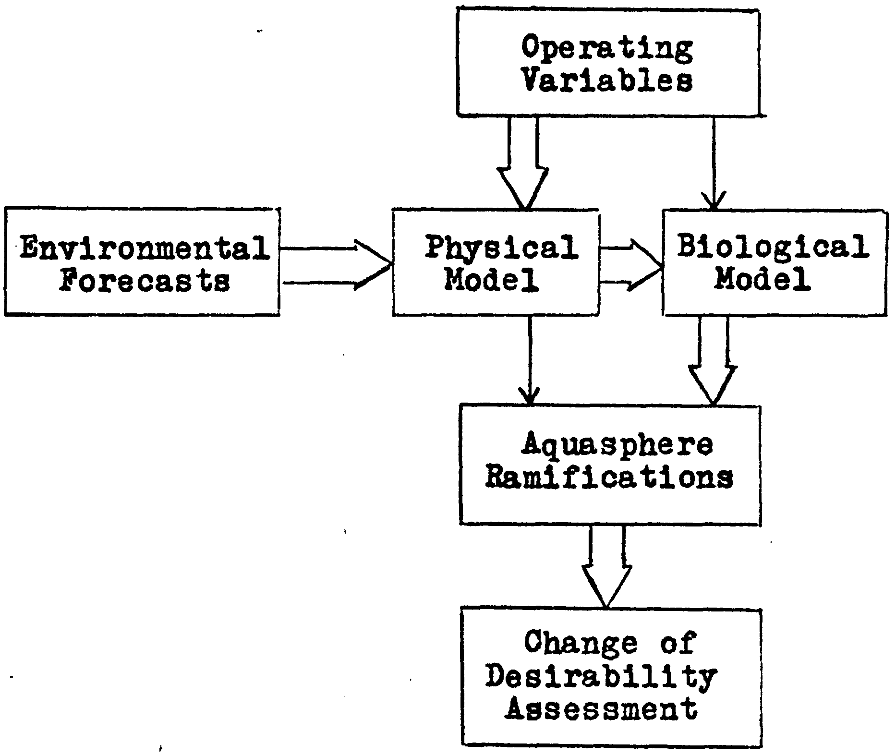


Figure 1.2-3 Simplified general systematic representation of aquasphere impact

is paid to the biological model with a further module breakdown and exact descriptions of its different functions.

In determining a method for the collection of required information, an investigation of the study of thermal stress through an examination of physiological processes was rejected. The argument for the rejection of this technique included the fact that the effects on such processes as neural and endocrine transmissions and cellular and genetic integrity were very complex time-varying problems, see figure 1.2-4.[11] This problem is further complicated by heat dosage collection,

---

[11] Excerpt from reference (6), page 190.

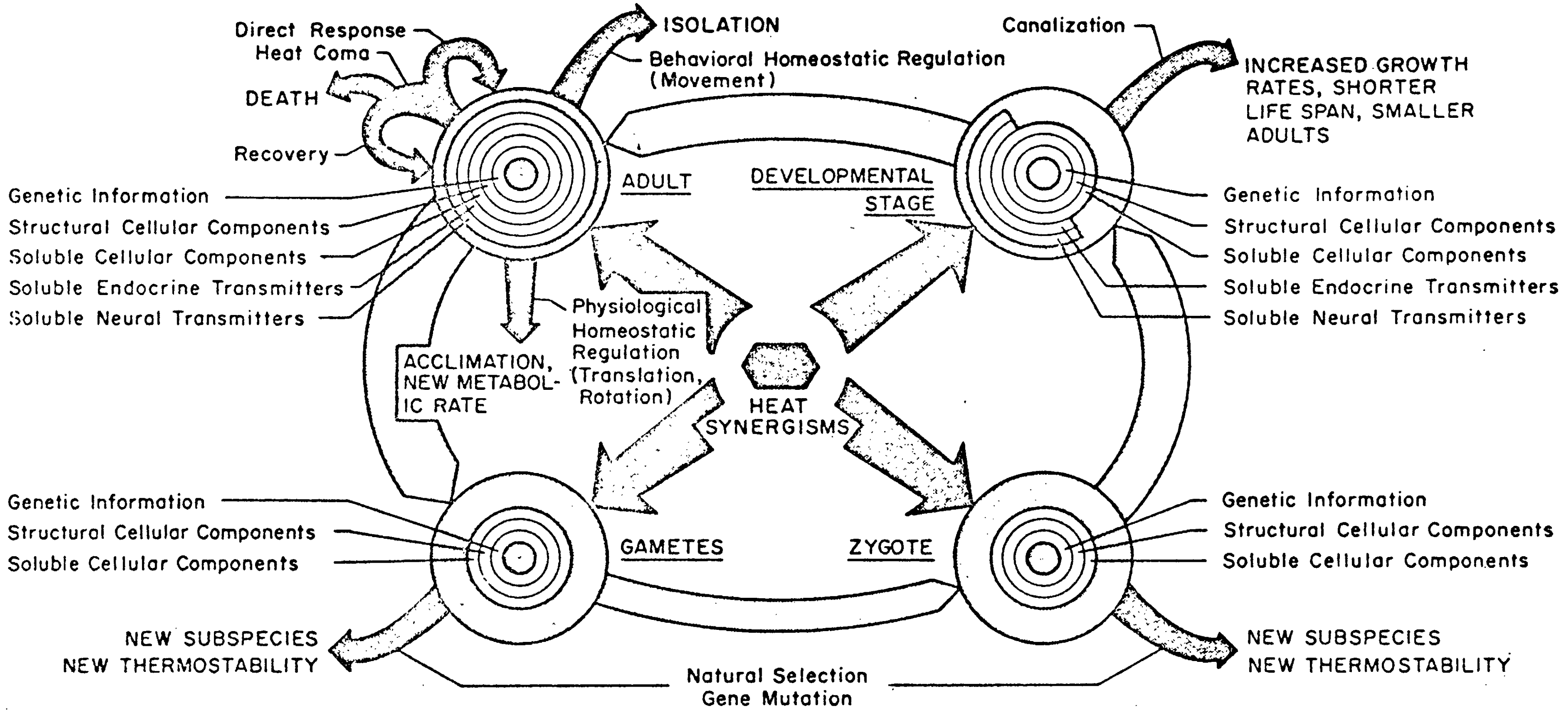


Figure 1.2-4 Time variable effects of heat on the physiological processes of an aquatic organism

mutagenetics, canalization, movement from thermal stress areas, and acclimation processes.

Thus, the collection of information, and formulation of models, were based on broad input-output experiments with no attempt to identify the states internal to the organisms, and the literature was surveyed with this perspective.

These cause-effect results of heat applications are primarily a function of exposure duration, that is, more precisely, total thermal dose, refer to figure 1.2-5. On the basis of existing predictive models built from input-output

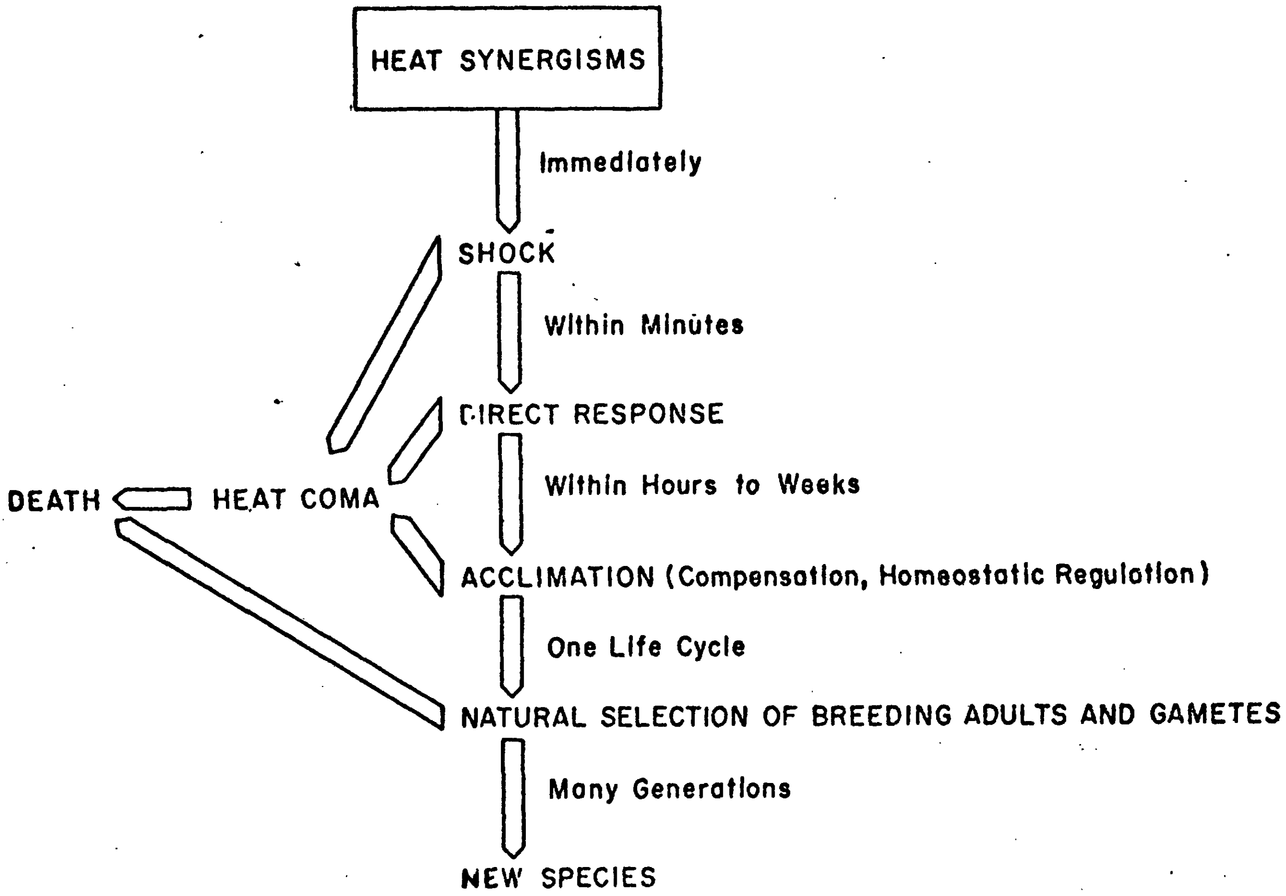


Figure 1.2-5 Results of thermal experiences as a function of duration of exposure.[12]

---

[12] Excerpt from reference (8), page 175.

experiments a consistent and complete procedure is developed for assessing aquatic impacts of power generation, and the existence of a compatible technique for atmospheric systems is demonstrated.

1.3 Implications

The considerable magnitude of the temporal variances of impacts to aquatic systems from electric power generation demonstrates the significant environmental gains which can be realized from incorporation of ecosystem forecasts within the power system's operational process.

With a quantifying tool such as that presented here, and a scheduling algorithm,[13] tradeoffs can be evaluated between dollar costs, system reliability levels, and ecological impact; and the use of hypothesized system additions such as new generation or abatement equipment can be simulated and evaluated.

The considerable effort spent in setting the basis for this environmental model was directed toward the creation of a solid foundation. Some areas of the modelling will undoubtedly provoke constructive criticisms and it is intended that these refinements will be applied to the initial foundation. There are areas where little data is available and it is hoped that the availability and apparent usefulness of this model will manifest the need for research to fill those gaps in the existing information.

---

[13] Such as is available in reference (6) and reference (7).

2. Consequences of Thermal Loadings

A very emotionally packed issue in the utility industry-environmentalist impasse is the thermal enrichment-thermal pollution argument. Each side has protected its own interests by sectioning out its best arguments before a legal system, which then is required to draw lines between issues, lines which both sides agree are somewhat arbitrary. What is required is an integrated view of the entire problem.

Thousands of years ago, before man had made a significant impact upon his environment, the ecosystems around the world, including water environments, were most probably in very stable modes, homeostatic. Under those stable conditions with temperatures wavering about the optimal[14] it would be just as likely that water temperatures would drop lower than optimal as rise warmer than optimal. The situation has changed slightly with time, in particular with deforestation slowly pushing water temperatures toward upper tolerances, but the existence of colder than optimal temperatures is still a common occurrence- especially in northern latitudes. In fact, if any generalization can be made about temperature, which has been called the 'master factor' in aquasystems, it is that temperature increases escalate productivity[15] in water

---

[14] Optimal temperatures are defined with regard to the entire organism's energy conversion efficiency as determined from respiratory, activity and growth measurements.

[15] For an example of accelerated fish growths see reference (9) page 602.

habitats.[16]

So the most logical approach to a solution for the problem of thermal loadings must begin with a complete investigation of the implications of power plant operation followed by an assessment of the desirability of the operation associated ramifications.

2.1 Thermal Waste Production and Dissipation

Both nuclear and fossil-fueled power plants produce heat in the process of converting fuel to electricity. Limited to about 60% efficiency by the Second Law of Thermodynamics, and further reduced to 40% to 30% efficiency by imperfect production equipment, the waste heat problem can be seen to be considerable. Although the average efficiency of power plants has been rising steadily, from 17% in 1930 to 33% in 1966,[17] sizeable gains in efficiency are a thing of the past. The problem is further complicated by the fact that the cheapest form of power for the immediate future, nuclear power, is not only less efficient overall, but nuclear power further intensifies the thermal pollution water problem by not sending any considerable amounts of heat up its stacks, as fossil plants do.[18] Figure 2.1-2 displays some of the data relative to this issue.

---

[16] The desirability of the resultant increased populations, however, may be less than that of the initial situation.

[17] For this and further information see reference (10).

[18] See, for example, reference (11), page IX-19.

ENERGY TO:	POWER	STACK	WATER
Average U.S. Plant	33.0%	15.5%	51.5%
Fossil, current	39.5%	15.0%	45.5%
Fossil, predicted future	42.5%	15.0%	42.5%
Nuclear, current (Calvert Cliffs)	29.5%	4.5%	66.0%
Nuclear, predicted future, (breeder)	41.5%	3.5%	55.0%

Figure 2.1-2 Table of efficiencies of current and predicted future fossil and nuclear generating facilities[19]

The outlook for more efficient power 10-20 years from now includes: magnetohydrodynamics, electrogasdynamics, thermionic electric power generation, ocean thermal gradient heat machines,[20] tidal energy machines,[21] aerogenerators (wind machines),[22] geothermal power, fuel cells,[23] nuclear stimulation of tight gas sands,[23] solar energy plants,[24] solar photosynthetic energy,[25] and farther off in the future is the potential for hydrogen fusion energy.[26]

Whereas these techniques are still in the developmental

---

[19] Adapted from data presented in reference (12), page 248.

[20] Reference (13), Appendix 2 describes the possibilities and lists 28 related references.

[21] See reference (14) or reference (13), Appendices 3 and 4 which lists 14 references.

[22] Described in reference (13), Appendix 6 with 11 references.

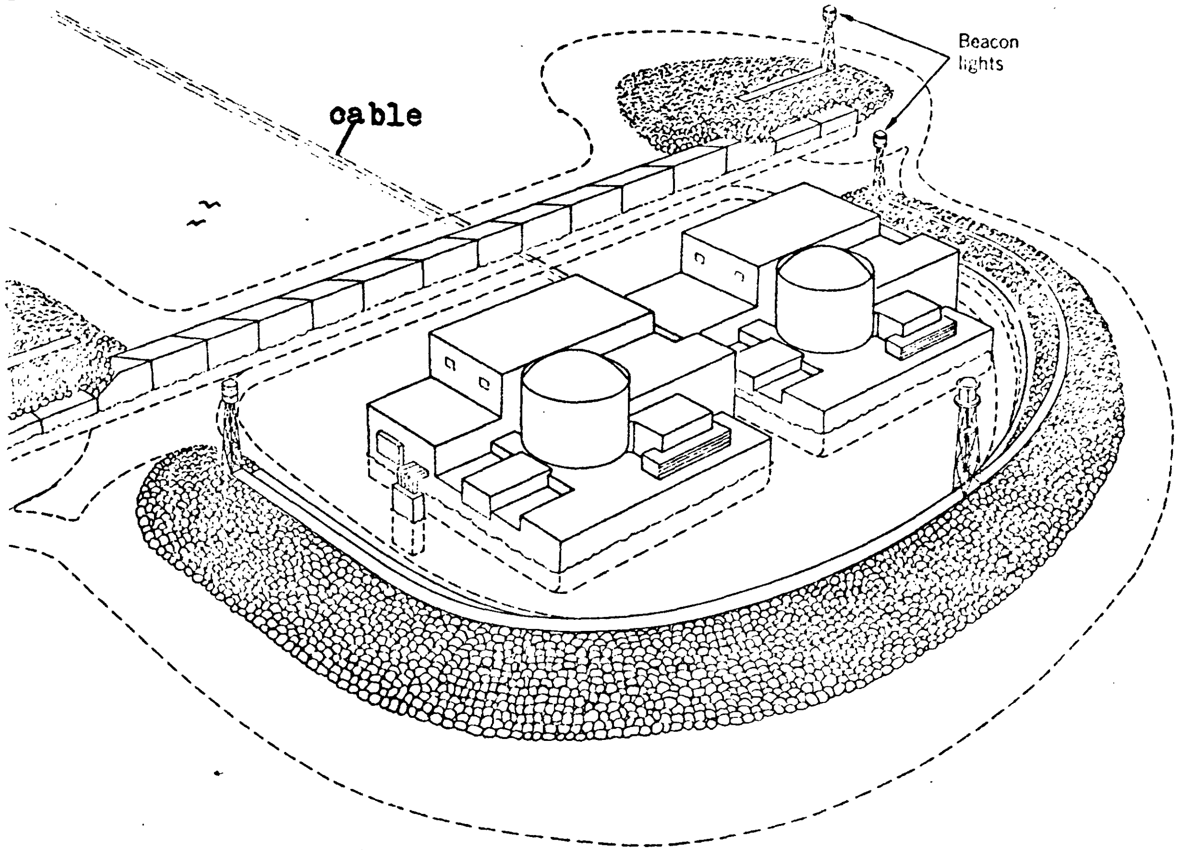
[23] See reference (15).

[24] Expounded further in reference (13), Appendix 10.

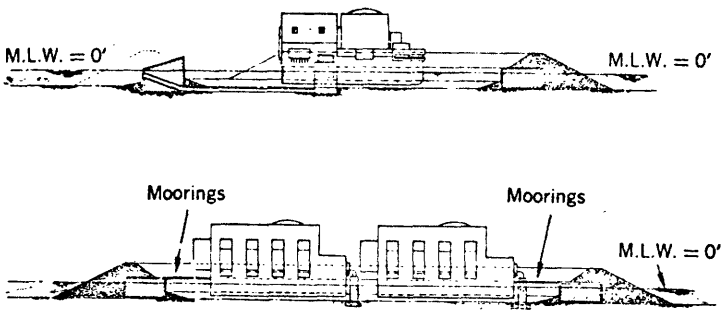
[25] Described in reference (16).

[26] A latest updating of progress is in reference (17).

stages, there are facilities which can be built today which show great promise, if not from an efficiency point of view, at least from an environmental perspective. One of these solutions is the floating, off-shore nuclear reactor, one type pictured below in figure 2.1-3.



Side views:



Note: M.L.W. = mean low water

Figure 2.1-3 Floating nuclear power plant sited 3 miles offshore with cable for power transmission[27]

---

[27] Pictures are from reference (18), page 45.

These offshore reactors will be set approximately three miles out into the ocean in about 50-60 feet of water, where ecological experts[28] predict that they will be beneficial environmentally. In addition these plants require only about 100 acres of ocean, compared with the 500 acres required for a comparable land site, and apparently[29] these ocean sites can provide power to 40% of the U.S. population, that being the percentage of the population living within the 200 mile maximum transmission distance from these sites.

The actual mechanisms involved in the power production process are displayed in figure 2.1-4. Heat is transferred

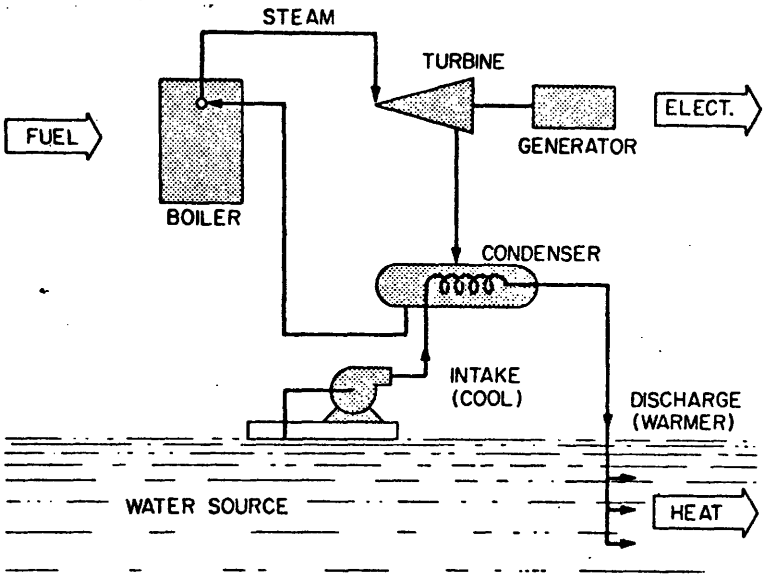


Figure 2.1-4 Energy conversion mechanism of a thermal power plant[30]

---

[28] See reference (18), page 51. The possible change in nearby beach erosion patterns has not yet been tested, but is felt not to be a problem.

[29] From reference (18), originally from (19).

[30] Excerpt from reference (20), page 343.

to the approximately 3 meters^3/minute per megawatt[31] cooling water when it passes through the one inch condenser tubes.

The water temperature differential across the condenser varies considerably depending upon plant type,[32] volume of water used, etc. Figure 2.1-5 shows the range of temperature increases for some purposed nuclear power plants.

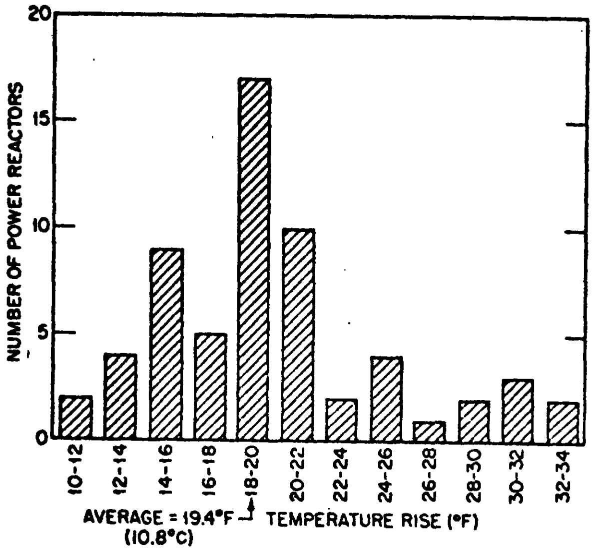


Figure 2.1-5 Water temperature differentials through condensers of 61 purposed nuclear power plants[33]

Assume, for the sake of example, that the average of 10.8° C differential exists during the operation of a particular power facility. If an organism is small enough to have passed through the intake screen it is instructive to examine the temperatures to which it then would be subjected as it passed

---

31. See reference(21).

32. For a generalized mathematical model for predicting the heated outflow rates from different operating conditions see reference (22).

33. Adapted from reference (23).

through the cooling system. Figure 2.1-6 shows such a hypothetical temperature history for an entrained organism as measured with respect to the ambient stream temperature.

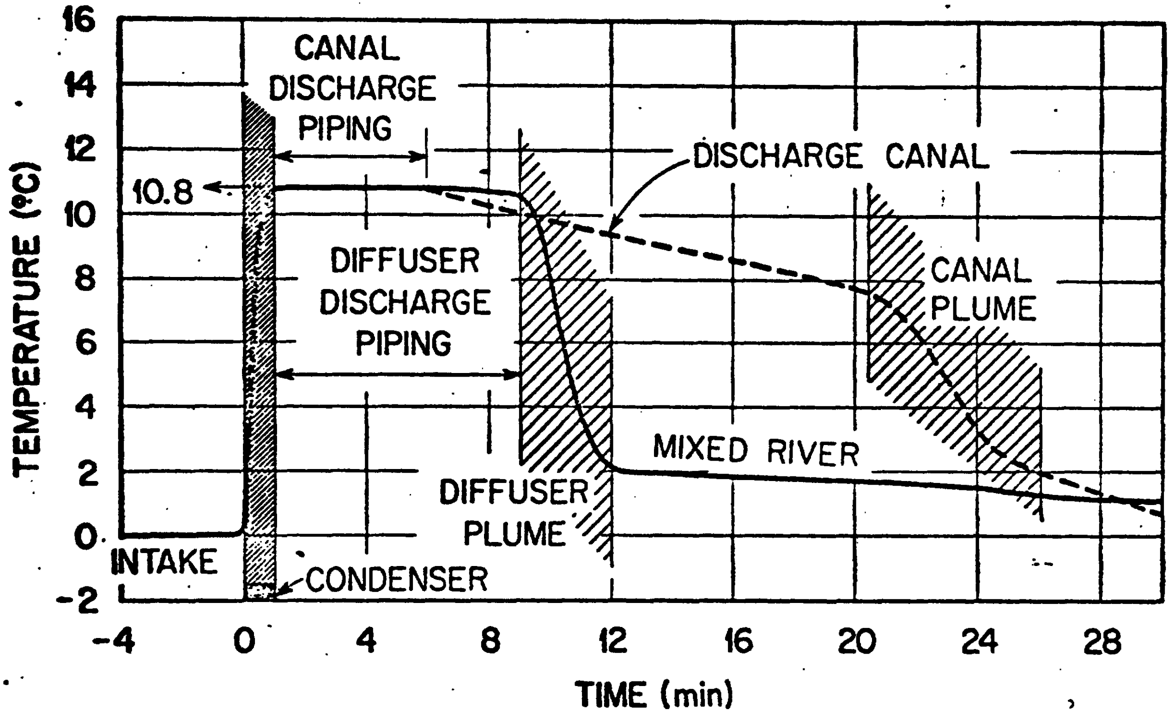


Figure 2.1-6 Temperatures an entrained organism would be experiencing as it passes through the cooling system of a hypothetical power plant. The dotted line shows the temperatures resulting from a plant with a long discharge canal.[34]

It is not difficult to envision times when a discharge canal would effect significantly more damage to an organism entrained in heated effluent for longer time spans.

Once heated water is discharged to the water system its exact temperature distribution will depend not only on the physical and meteorological characteristics at the outlet, but

---

[34] Excerpt from reference (24), page 601. The effects of abrasions and/or noise on entrained organisms have apparently not been studied in any detail. For a list of some pressure problems created by entrainment see reference (3), page 85.

also, again, on the type of discharge equipment used. The complexities and tradeoffs involved are shown by this comparison:

"Two methods are available for discharging heated effluent: surface discharge and submerged discharge. A low velocity surface discharge through an outlet channel has the advantages of

1. more rapid heat transfer to the atmosphere implying there is less heat tied up in the water,
2. close proximity to the condensor, minimizing the travel time for aquatic species caught in the high temperature circulation system,
3. stratification in all but the shallowest receiving waters, (Stratification enhances the flow away of hot water and also leaves bottom regions which are free of heat meaning less obstructed fish passage.)
4. less trubulence reducing scour and other problems associated with high velocity jets, and
5. less cost to construct.

Alternatively, the submerged discharge, either through a single discharge pipe or through a diffusing manifold has the advantages of:

1. location away from the plant preventing severe shore or riverbank pollution and minimizing recirculation of hot water through intakes, and
2. better mixing resulting in a more uniform temperature distribution (particularly in the vertical dimension) with a significantly lower maximum temperature rise above ambient water temperatures."[35]

---

[35] Excerpt from reference (25), pages 2 and 3.

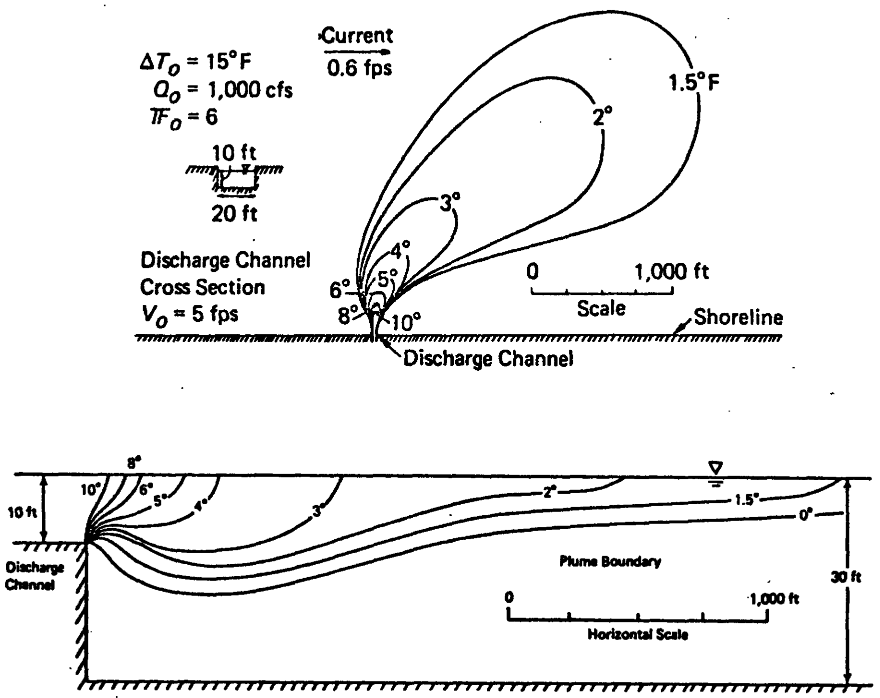


Figure 2.1-7 Surface temperature and vertical section isotherms for a surface discharge.[36]

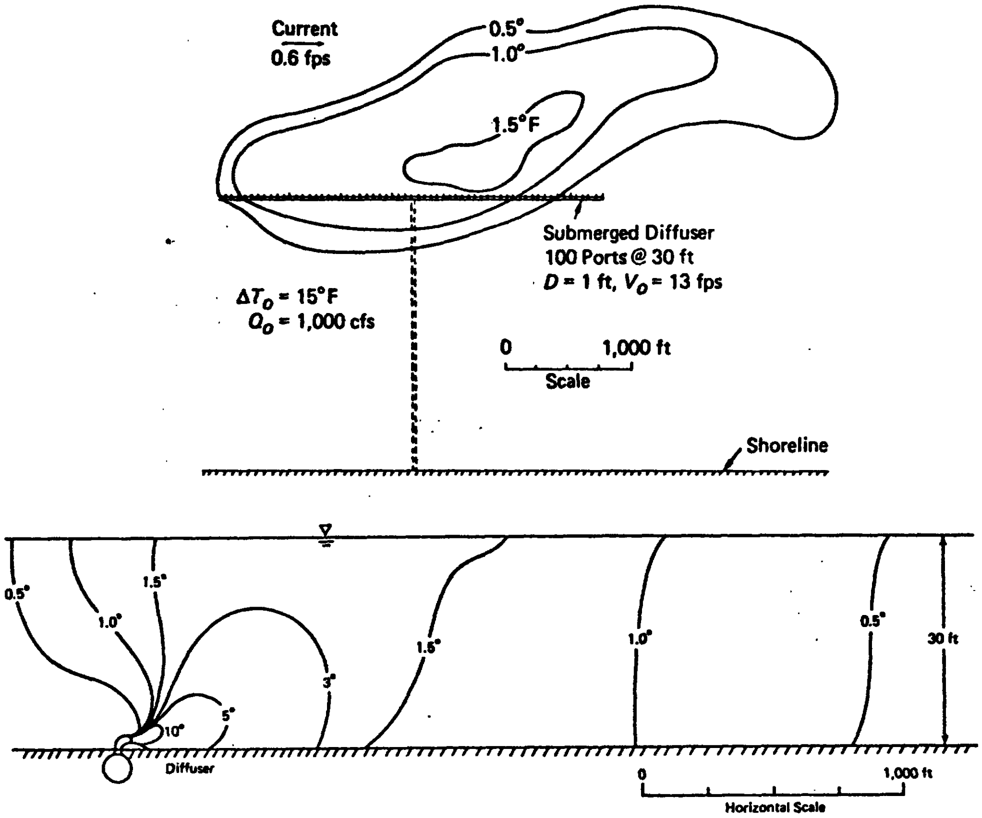


Figure 2.1-8 Surface temperature and vertical section isotherms for a submerged diffusion.[36]

For an idealized environment the temperature isotherms which result from different discharge schemes are shown in figures 2.1-7 and 2.1-8.[36]

As mentioned previously a secondary influence on the temperature gradients in the vicinity of the thermal effluent is the condition of the atmosphere over the mixing water, see figure 2.1-9.

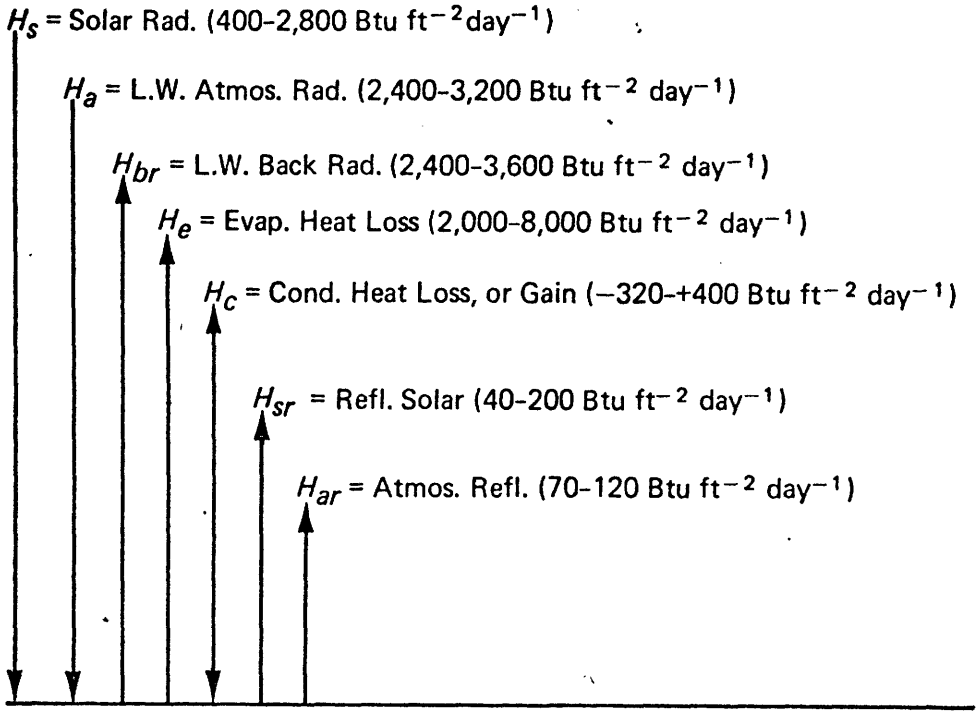


Figure 2.1-9 Mechanisms of heat transfer at the surface of the water body[37]

---

[36] Adapted from reference (26) page 3. It has also been noted that in addition to the ideal mechanisms taking place in the model the discharge designs may effect turbidity at outflows, causing disorientation in fishes, and causing upwellings with consequences to planktonic organisms dependent upon various surface residencies and light intensities, see reference (3) page 86.

[37] From reference (27), finite difference equations are used to calculate these transfers in reference (28).

To summarize these predictive tools, heat diffusion within the sink fluid is predictable from the internal hydrological parameters, whereas exchange of heat to the atmosphere and the resultant equilibrium temperature of the waterbody T_e can be summarized (using figure 2.1-9) as

$$T_e = T_d + \frac{H_s}{K} \qquad 21\text{-}1$$

where T_d is the air dewpoint temperature, H_s the mean daily solar radiation, and K the surface heat exchange coefficient as shown in figure 2.1-10.

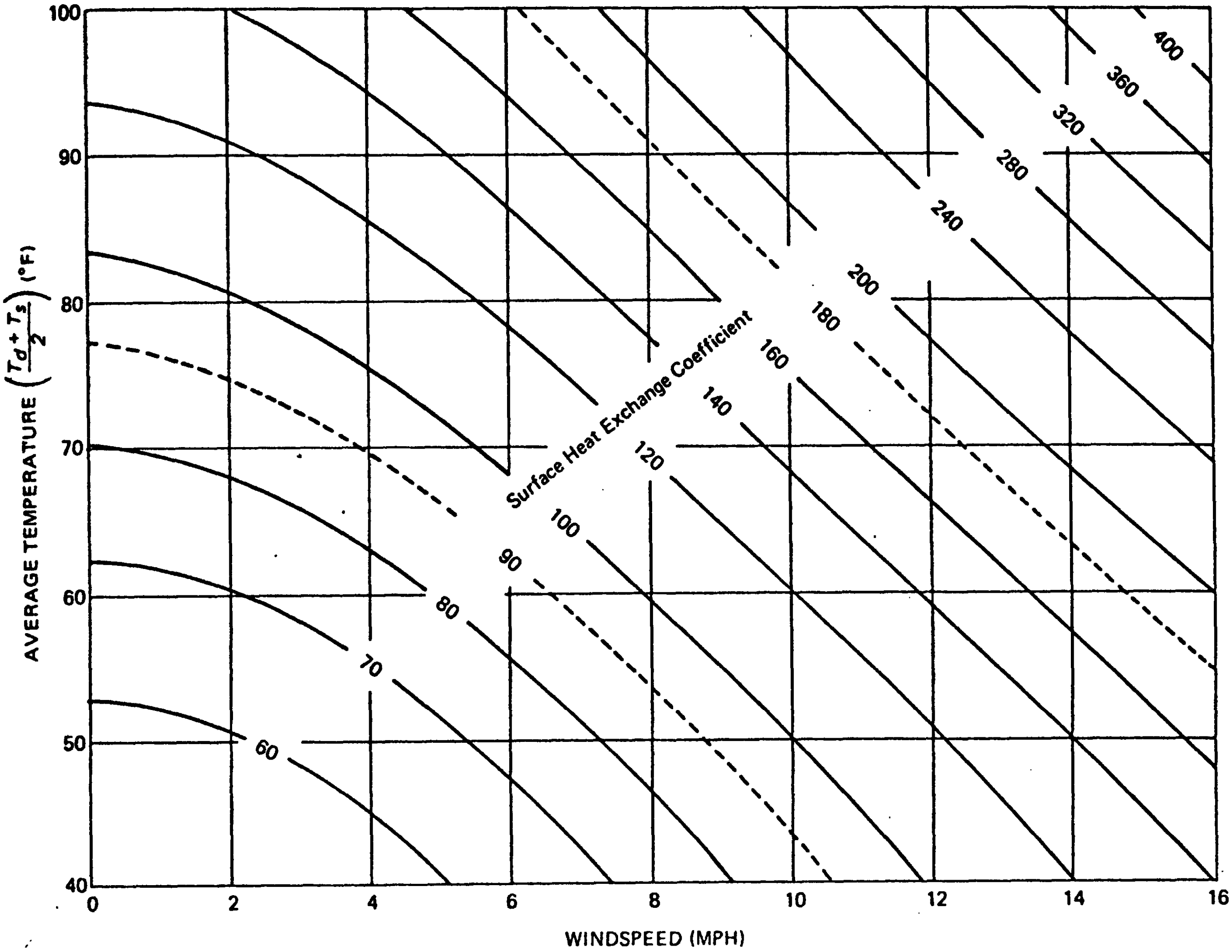


Figure 2.1-10 Chart for surface heat exchange calculation from meteorological parameters and T_s stream surface temperature[38]

---

[38] Excerpt from reference (3), page 115, see reference (29).

As an example of some of the existing techniques for calculating the near field water temperature gradients from the T_e, equilibrium temperature, consider the case of the stream as the dissipation mechanism. The simplest of these computation techniques are presented in table 2.1-1.

Gameson, Gibbs, and Barrett

$$\frac{d\theta}{dt} = -\frac{f}{z}\,\theta$$

where θ = excess of water temperature over natural water temperature, °C
f = exchange coefficient, cm/hr
z = mean river depth, cm

Velz and Gannon

$$\frac{dT_w}{dt} = -\frac{H}{62.4b}$$

where T_w = water temperature, °F
H = rate of heat loss from water surface, $\frac{\text{BTU}}{\text{ft}^2 - \text{day}}$
b = river depth, ft

Duttweiler

$$\frac{dT}{dt} = \frac{1}{\rho c}\,\frac{\lambda}{z}\,(T_E - T)$$

where T = water temperature, °F
λ = parameter dependent on atmospheric conditions,
z = hydraulic depth, ft
T_E = equilibrium temperature, °F

Edinger and Geyer

$$\rho\, C_p U d \frac{\delta T}{\delta x_1} = -K(T - E)$$

where T = water temperature, °F
U = mean stream velocity, ft/hr
d = mean stream depth, ft
K = exchange coefficient, $\frac{\text{BTU}}{\text{ft}^2\,\text{day}}$ °F
E = equilibrium temperature, °F
C_p = specific heat water, $\frac{\text{BTU}}{\text{lb}}$
ρ = density of water, $\frac{\text{lbs}}{\text{ft}^3}$

Table 2.1-1 Some of the simple stream temperature prediction models[39]

---

[39] From reference(27), page 150. More sophisticated models can be found in references (30), (31) and (32), overview in (33).

These are of course highly simplified portrayals of temperature gradients, and they lose accuracy with increasing complexity of the physical situation. If these are deemed inadequate, scale models can be mocked up, or for existing systems, temperatures can be measured directly, or dies can be used, or temperatures can be measured using aerial infrared photographic techniques as is shown in figure 2.1-11.

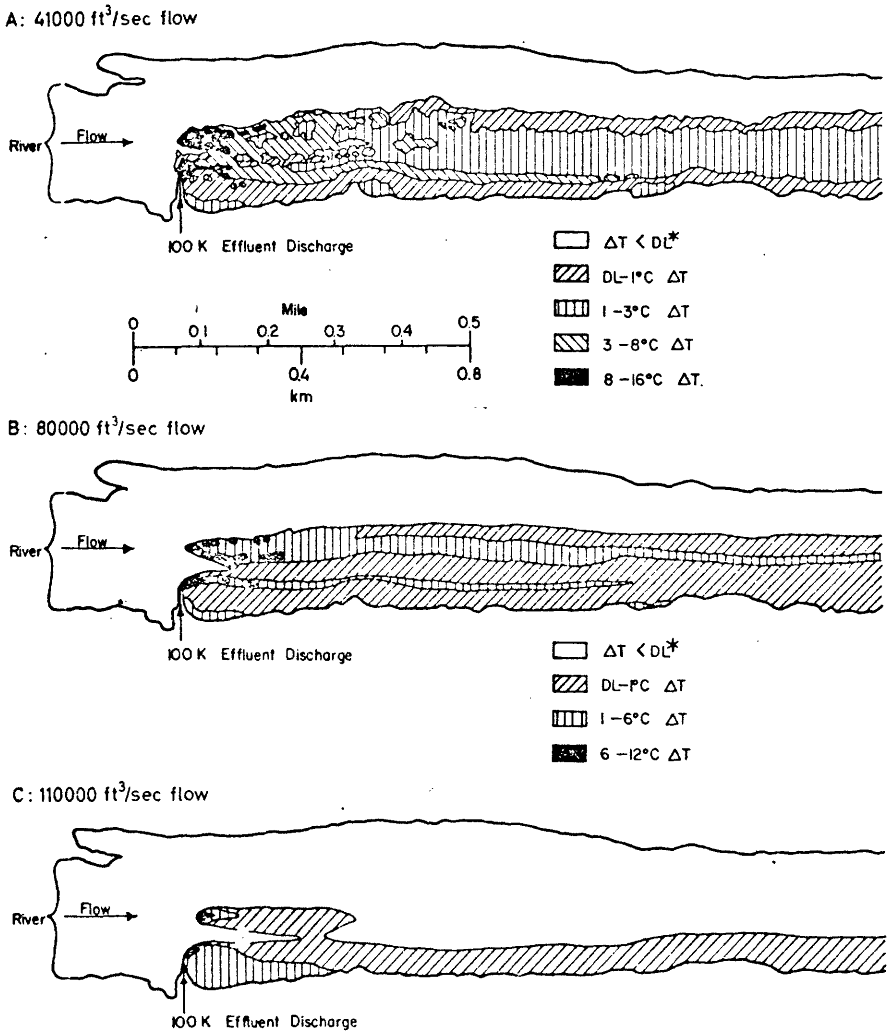


Figure 2.1-11 River isotherms at three different streamflow levels as measured by aerial infrared photography[40]

---

[40] Excerpt from reference (9), page 595.

These techniques are, of course, not limited to temperature prediction in streams[41] nor to specific dissipation mechanisms[42] but this is in many ways the most critical case.

The legal restrictions concerning limitations of allowable heat discharges vary from state to state.[43] The standards of the state of New York are based on the Federal Water Pollution Control Administration guidelines[44] and are paraphrased here because they are more or less typical:[45]

---

41. See for example reference (34) for other site-type models, or an overview, reference (35), of some of the latest lake temperature models, an estuarine temperature model summary is given in reference (36); reference (37) deals with reservoir temperature predictive techniques, and reference (38) with a case study of ocean tidal influences on temperature patterns. The raising and depletion of reservoirs of pumped hydro storage units have environmental impacts peculiar to that type of facility, some of these problems are discussed in reference (39). A description of some of the computer programs available for the prediction of temperature patterns is contained in Appendix K of reference (40). A program also exists, reference (41), which when given power plant and site characteristics and pollution abatement equipment used, not only predicts whether or not specific temperature standards will be met, but it also computes associated capital and operating costs.

42. There are obviously numerous other discharge methods, such as surface jets, modelled e.g. in ref. (42) or (43). Some of the most comprehensive discussions of discharge techniques and their effects can be found in reference (44) and reference (45).

43. Foreign countries tend to set simpler, somewhat more relaxed standards, such as the straight 28° C limit enforced in parts of Germany, see reference (46).

44. See references (47) and (48) for the guidelines of this organization which is now called Environmental Protection Agency Water Quality Office.

45. Some of the legal problems inherent in the definition of a "mixing zone" are discussed in reference (49).

-streams: a passageway allowing for half the stream flow must be provided and the mixing temperature may not exceed 30° C (86° F) or 2.8° C (5° F) beyond the ambient temperature

-lakes: a 1.7° C (3° F) maximum differential is allowable outside as area equivalent to a 300 foot diameter circle

-estuaries: same as for streams except that only a 0.8° C (1.5° F) rise is allowable

-coastal locations: only qualitative recommendations are made.

If environmental considerations are to be ignored except to the extent that they are included in the legal quantities then it would be possible to terminate this project at this point. Any exceeding of the existing legal standards could be granted extravagant environmental costs so as to force other, nonviolating plants to take over the load. However, sentiment is gaining quickly for new, more adaptive controls to overcome some of the limitations[46] of current statutes Efforts have been made to include within the laws both the direct and indirect effects of temperature discharges upon aquatic organisms.[47] The process of adapting laws to be consistent with scientific knowledge is currently in a painful growing process of refinement-challenges-relaxation-refinement

---

[46] Reference(50), page 17 presents the need for flexible judgement decisions rather than legislation. See references (51), (52) and (53) for arguments concerning the need for better legislation, and how that end is being pursued. It has not even been quite clear in the past which bodies of legislation held jurisdiction over the relatively new "thermal pollution" problem, see reference (54).

[47] See reference (55).

etc.[48]

The only clue as to what policies may eventually result comes from the observation that all those concerned appear to favor standards or controls which reflect most accurately the requirements of the particular water habitat in question. The following sections of this chapter relate to the development of those particular requirements.

---

[48] An example of this entire process is the case of the thermal pollution legal actions concerning Lake Michigan. An initial refinement was made to the current legislative policies to limit temperature increases to 0.6° C (reference 56)--a challenge was then entered by the utilities (reference 57)--a relaxation of the suggested increase resulted (reference 58) along with an expression of openness to flexibility (reference 59)--and an entirely new refinement has been presented (reference 60) which is of such a nature as to insure that a challenge will be made.

2.2 General Observations about Aquatic Ecosystems and Temperature

Very few general observations exist concerning the consequences of thermal loadings on aquatic ecosystems. The reason for this rarity arises from the fact that the biologists and ecologists who are qualified to make such generalizations are also cognizant of the incredible complexity of the problem.

As an indication of the complexity of the problem's interrelationships consider the flow of food and heat energies in a typical stream ecosystem, figure 2.2-1. The arrows

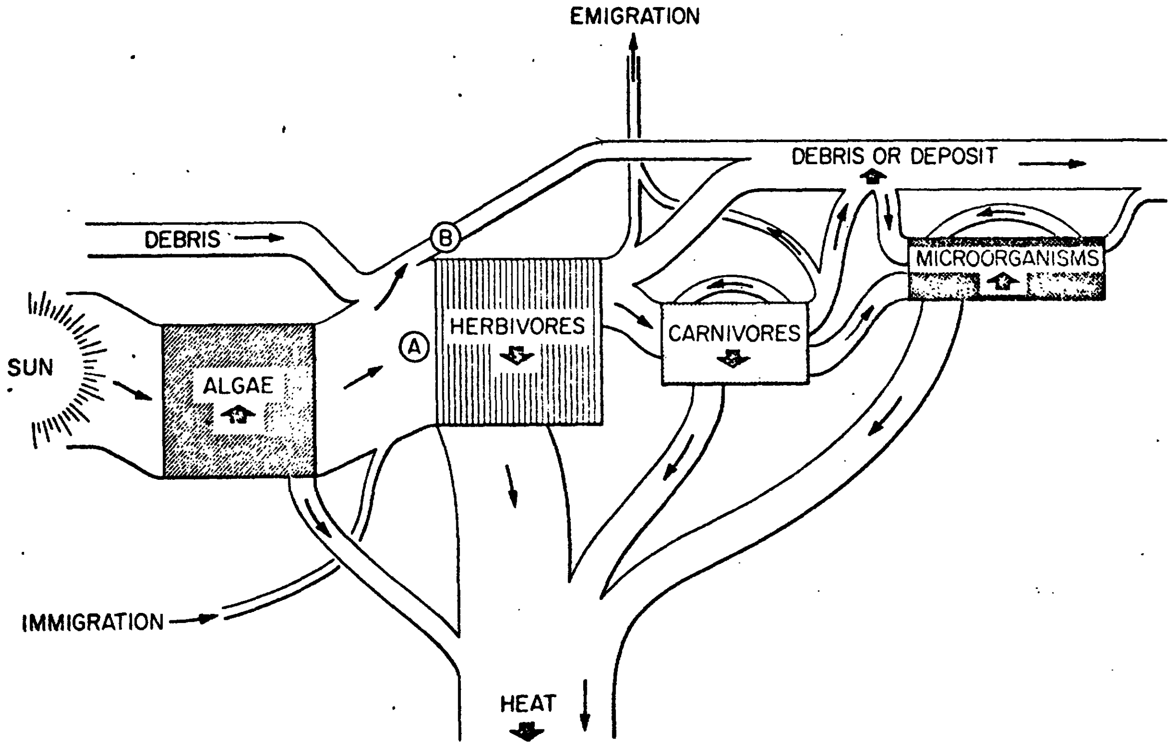


Figure 2.2-1 Pattern of energy flow in a typical aquatic ecosystem[49]

---

[49] Modified slightly from what appears in reference (61) in that carnivores are also subject to succumbing to the actions of some of the microorganisms, viz. disease.

within the boxes show the increase or depletion of populations which occur in the presence of further thermal loadings.

The few rudimentary general studies which have been generated were motivated toward the development of predictive models for calculating the ecological effects of proposed power plants.[50] Some of this work, aimed in particular at the effects of entraining organisms in cooling systems, has been collected by Dr. Charles C. Coutant, who has also been a leading figure in generating mental inertia in this field:

> "If there is a seasonal period of critical high temperatures, power operators should be able to conduct periodic checks of temperature and exposure time for critical species . . . and adjust plant operation accordingly. It is astonishing that such a simple technique has not found wide use. The responsibility probably lies partly with ecologists, who have not clearly explained (or recognized?) the predictive utility of their quantitative data and then made those data readily available to the right people. To date, there is no single document that serves as an adequate handbook of thermal-resistance data. Such a text is sorely needed."[51]

Research on the effects of heated effluents in and beyond the mixing zone is presented by J. A. Mihursky, et al in reference (62). Based on a number of studies documented in source (62) the investigators generated a thermal-biotic predictive model for an estuarine system, see figure 2.2-2. The solid line represents the loss of species due to emigration

---

[50] Fortunately, the biologists making these studies have apparently been unbiased by emotional courtroom battles, and thus their research as a whole can be considered relatively unbiased with respect to the heated utility-conservationist arguments.

[51] Excerpt from reference (24).

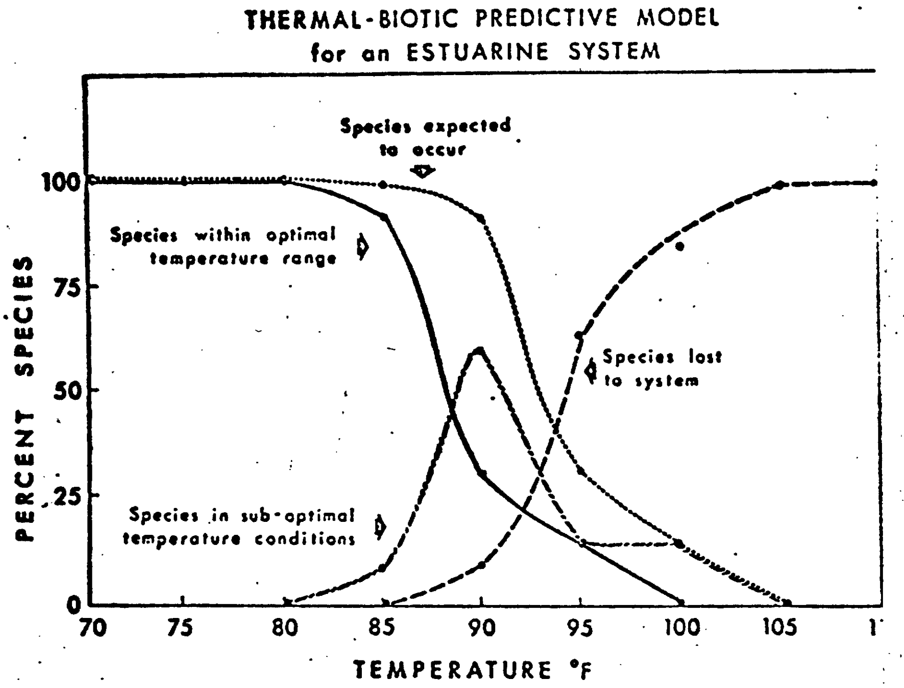


Figure 2.2-2 General model of the health of an entire estuarine system as represented by species diversity (in summer conditions)[52]

or thermal mortalities. The dot-dashed line refers to the number of species existing in those thermally distressing situations which induce for them unnatural physiological conditions, or unusual susceptibility to predators, parasites or diseases.

An extension of complexity of this summer model is necessary to incorporate the seasonal variability in the tolerance of the various species. This incorporation is effected in figure 2.2-3 by demonstrating the range between the most tolerant species (upper diagonal line) and the least tolerant species. The coordinates of this graph are the existing (upstream or predicted) ambient temperature as the abscissa

---

[52] From reference (62), page 351.

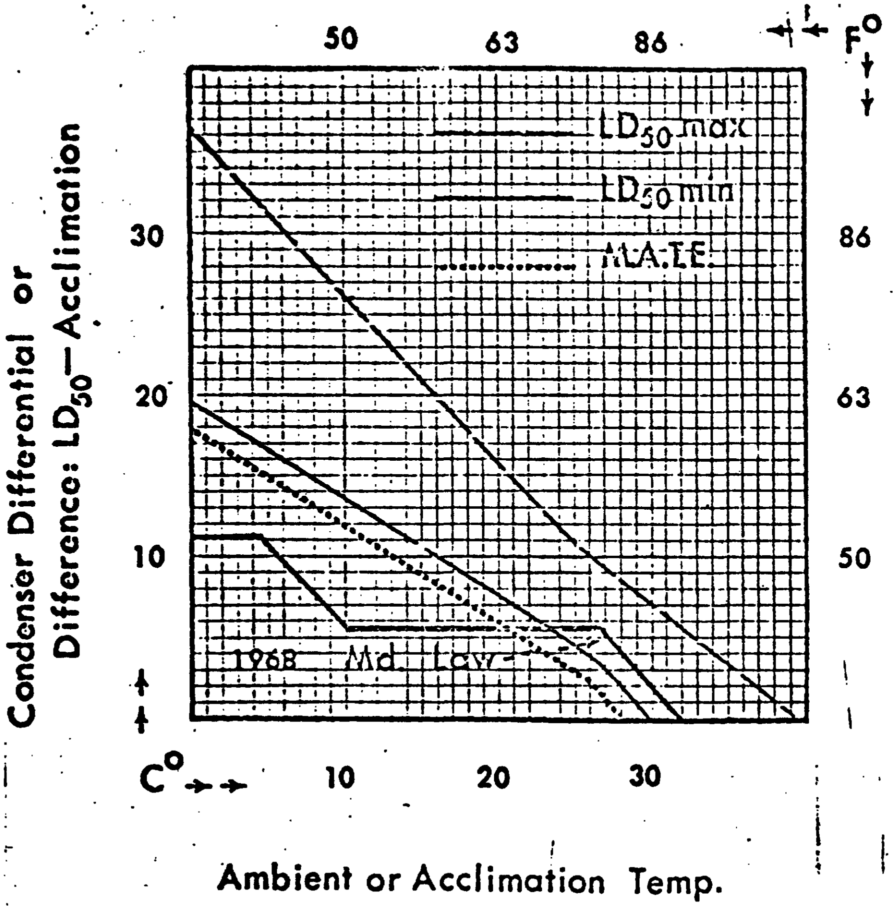


Figure 2.2-3 Lethal temperature tolerances for 50% of a species, LD50, for the most tolerant and the least tolerant organisms, and the maximum allowable temperature elevation (M.A.T.E.) resulting in no appreciable thermal effects, compared with the 1968 Maryland laws.[53]

and the differential temperature addition as the ordinate.

This model indicates that most of the time the 1968 Maryland law is overconservative, except during the summer when the law allows slicing into the diversity of species.

This species diversity,[54] or biotic index,

---

[53] Excerpt from reference (62), page 352.

[54] Another example of the application of species diversity to the thermal discharge problem can be found in ref. (63) & (64). Reference (65) enumerates the deficiencies of this measure and introduces a correcting concept of "evenness," a variance-type measure of the richness and stability of a system. Reference (66) has a more mathematical treatment of this variance measure.

has been frequently used as a kind of measure of the 'health' of an aquatic ecosystem. For example, a water habitat supporting only catfish, bullheads, a couple varieties of invertibrate herbivores, and two or three hot water blue-green algaes would be considered inferior to a system with a large selection of game fish, shellfish, etc. Although the small diversity system may very well be out-producing the larger, it may contain no commercially or recreationally valuable fishes, and may have large algal mats, foul looking and smelling, unswimmable water. Thus, species diversity can be considered a measure, albeit crude, of the total of all the conditions of the aquasphere which affect man and his activities.[55] This relatively coarse detector, unfortunately, is limited in its validity to the measurement of extreme variations. It is thus necessary to proceed with a survey of the effects of thermal increases on a breakdown of the subsections of the aquasystem.[56]

---

55. Reference (67) describes the development of a species diversity mechanism based on actual data collected from a power plant site. Another study concerned with community structure, reference (68), involves a systematic approach to the study of effects of temperature and sewage combinations in an estuary.

56. Some other mathematical models which might be helpful in predicting biological effects of temperature changes can be found in reference (69). The most recent work on this particular project can be found in reference (70), which has apparently assisted regulatory agencies in establishing new standards, and has assisted utilities in finding better operating strategies.

2.3 Direct Thermal Impact on Fishes

Insofar as fish generally constitute the sector of the aquatic ecosphere of major importance to commercial and recreational interests, most of the thermal stress research has been directed toward the welfare of this group.[57] The characteristics of the data and the influencing factors are essentially the same for most organisms and so a detailed study of fish problems can be applied to other life forms, of course with the appropriate seasonal and temperature shifts.

Fishes are poikilothermic animals, that is, their body temperatures rarely differ by more than 1° from that of their environment.[58] Thus, water temperatures suitable to the internal tissue functionalities of fish are necessities. However, any attempt to generalize thermal behavior patterns through the study of cell physiology, that is, thermal limiting processes[59] in the nucleoplasm, cytoplasm or cell wall integrity, seems doomed to fruitlessness. Thermal tolerance is known

---

57. A bibliography of 1220 papers on thermal pollution, most of them concerning fish, is contained in reference (71). A review of 263 of the latest research efforts in this field is contained in reference (72), with a new review available annually in the same journal; and for 1972 reference (73) has a list of available temperature effects studies for species and their stages of reproduction, embryonic development, larval development, morphological aberrations, distributions and thermal tolerances.

58. See reference (74).

59. That is, thermal disruptions of the mechanical, chemical osmotic or electrical workings of the cell.

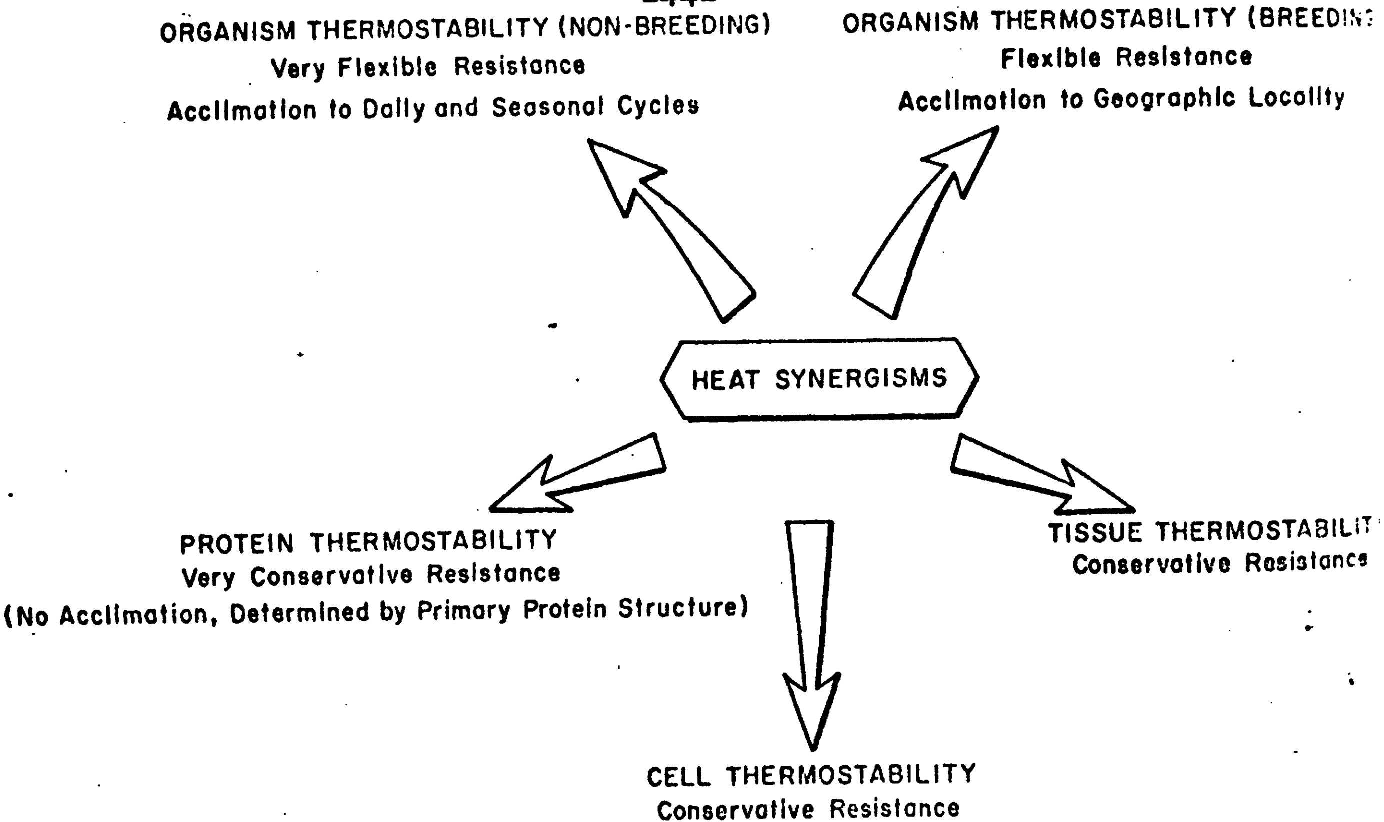


Figure 2.3-1 Effects of heat on different major components of an aquatic organism[64]

to be influenced to a certain extent by acclimations of muscular structures[60] and metabolic systems,[61] by hormonal variations[62] and digestive system processes.[63] Thermal variations are also known to influence the nervous system and the functioning of the reproductive system. For a schematic of the flexibility of various organism parts to variations in temperature see figure 2.3-1.

---

[60] The effect of structural size to thermal tolerance is documented in reference (75).

[61] See reference (76).

[62] The effects on lethal temperatures of sex, day length, season and other hormonal variations have been presented in references (77); (78); (75) and (79); and (80) respectively.

[63] Variation of diet, references (81) and (82) and water quality, references (83), (84) and (85) have profound effects on thermal tolerance levels.

[64] Reference (8), page 180.

The clinching argument against the use of cell physiology or even fundamental body function generalities comes from the information that certain rotifers can exist at -267° C (-448° F) and African midge larvum can withstand 102° C (215° F) temperatures.[65] Cells with basically the same structure have thus withstood an incredible 369° C (663° F) range. With the possibility of cell or function generalities discarded, the study of thermal tolerances necessarily becomes an input-output survey for the various species of concern, without regard for internal states.[66]

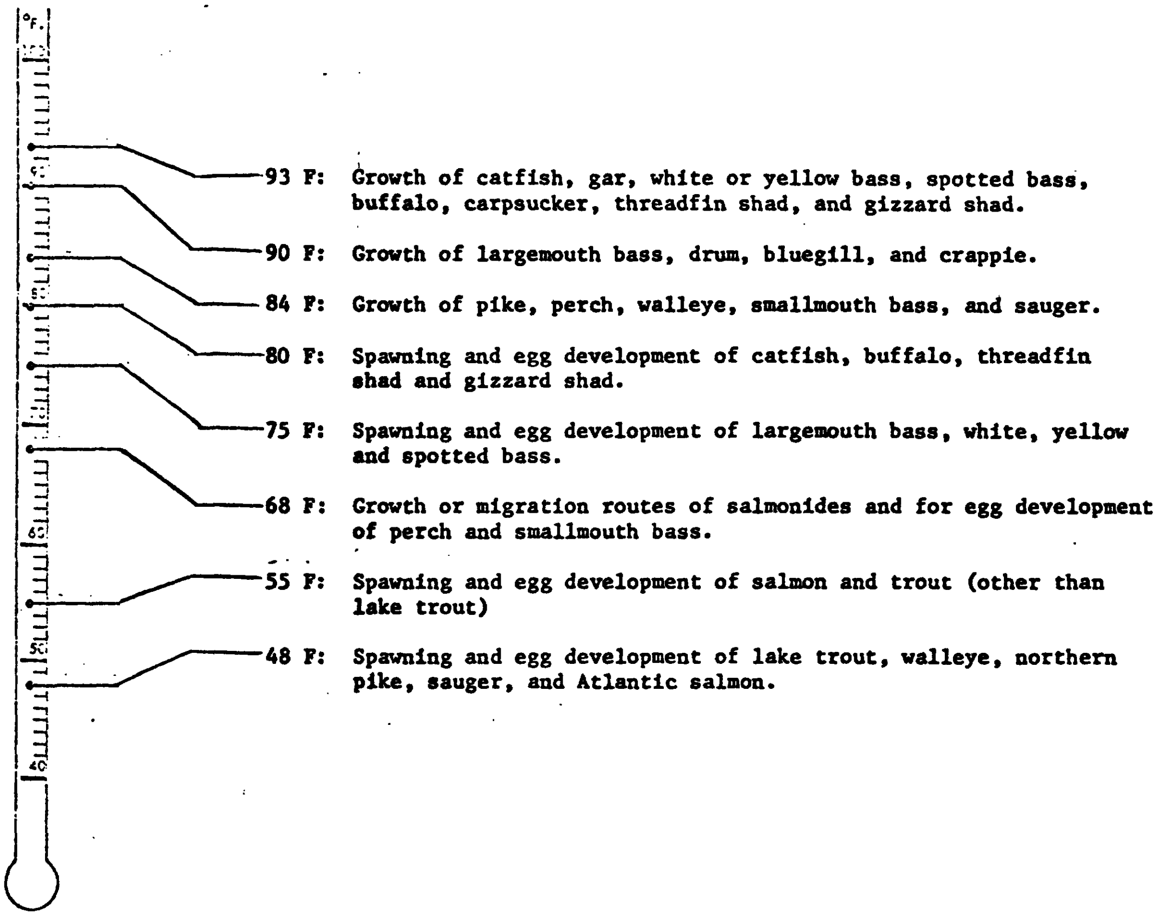
Even the most rudimentary initial studies of the limits of thermal tolerances recognized the existence of differences between the requirements for the satisfactory functioning of developmental processes as opposed to reproductive processes, see figure 2.3-2.

A number of schemes have been created for determining the temperature tolerances of different fishes. One obvious and very accurate method involves the inspection of the geographic distribution of a species, and thus the associated temperature preferences. Another method involves the netting of species

---

65. See reference (86), pages 1 and 2.

66. Even within species apparently identical in all respects except geographic origin, different lethal temperatures (ref. 87) have been recorded. This is apparently a documented case either of canalization, i.e. the setting of certain body parameters in youth according to the environment, or of mutagenetics, i.e. the evolution of a different race of the same species to better adapt to a situation.



93 F: Growth of catfish, gar, white or yellow bass, spotted bass, buffalo, carpsucker, threadfin shad, and gizzard shad.

90 F: Growth of largemouth bass, drum, bluegill, and crappie.

84 F: Growth of pike, perch, walleye, smallmouth bass, and sauger.

80 F: Spawning and egg development of catfish, buffalo, threadfin shad and gizzard shad.

75 F: Spawning and egg development of largemouth bass, white, yellow and spotted bass.

68 F: Growth or migration routes of salmonides and for egg development of perch and smallmouth bass.

55 F: Spawning and egg development of salmon and trout (other than lake trout)

48 F: Spawning and egg development of lake trout, walleye, northern pike, sauger, and Atlantic salmon.

Figure 2.3-2 Maximum temperature recommendations deemed to be compatible with the functioning of the species and their associated biota[67]

at the various thermal gradients created at existing thermal discharge outfalls.[68] These field experiments are superior[69] to laboratory investigations both in use of realistic water quality, and natural habitats, and in the availability of escapes from thermal stress areas for motile organisms,

---

67. The source for this material is reference (88).

68. An experiment of this type is represented in reference (89).

69. The superiority of field experiments over laboratory simulations was made clearly evident when early aquaria experiments resulted in predictions that natural temperature ranges should have extirpated some thriving species (reference (9), page 592). Obviously, adaptation is not as effective in artificial environs.

extrications not being available to animals in screen areas or aquaria studies.[70]

Laboratory investigations of temperature preferendum have revealed that variation in previous acclimation temperatures

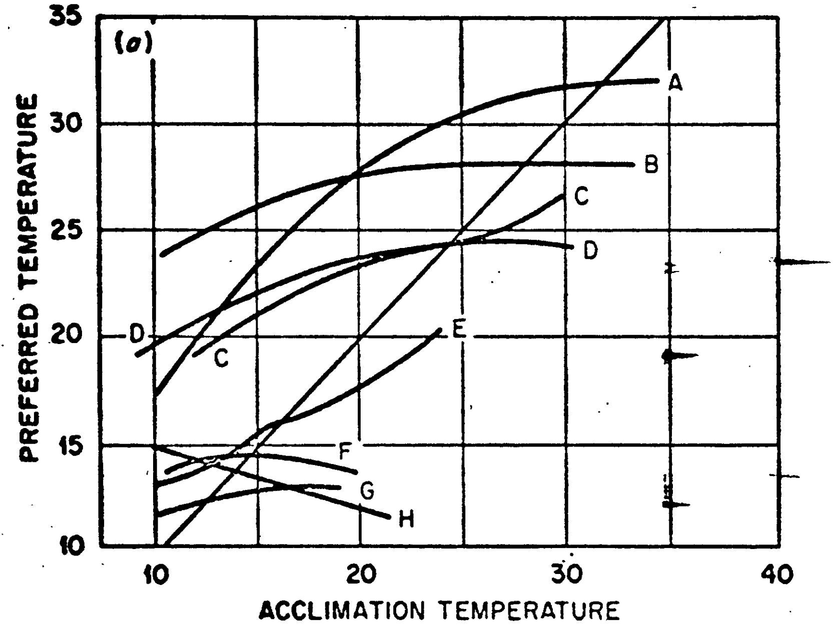


Figure 2.3-3 Thermal preferences of various species of fish in relation to temperature of previous acclimation (eight different species)[71]

results in a variation of the eventual preferred temperature, as is shown in figure 2.3-3.

This recognition that seasonally varying ambient temperatures meant seasonal variation in acclimation temperatures, and thus variations in thermal tolerances, brought about predictive

---

[70] Some empirical equations for the prediction of hot and cold temperatures that fish would avoid, depending on available light, fish length and salinity are given in reference (90).

[71] The source of the research done on these curves is reference (91). Other preference research is in references (90), (92), (93), and (47).

models such as figure 2.3-4. It is crucial to note that as

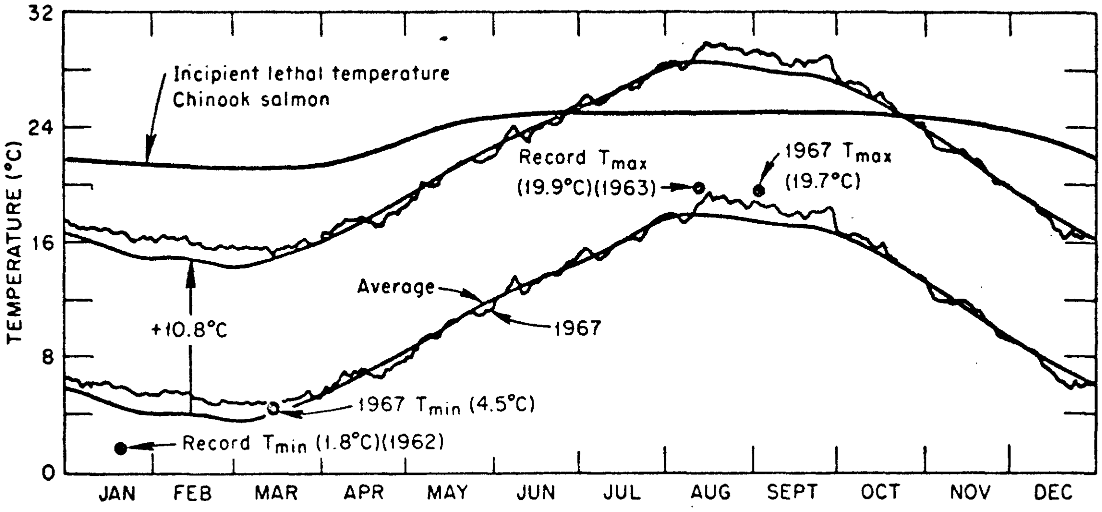


Figure 2.3-4 Seasonal cycle of temperature in the Columbia River and the increase caused by cooling water differential of 10.8° C superimposed on the variable tolerance of a fish species[72]

in almost all studies this is a "one-shot" type of experiment with no account given to any influence except variation in acclimation temperature. As previously mentioned further influences exist that are seasonally varying, among these are length of day effects, and variable tolerances due to size and time of life differences. These, and other as yet unexplained but clearly seasonal effects, all tend to define more sharply the highly seasonal nature of the dangerous operating period. The fact that the juvenile chinook salmon are most abundant from April to August[73] in the operating region represented by figure 2.3-4 can now be used to create a population probability curve relevant to this site.

---

[72] This graph was created for use in source (24), page 602.

[73] Reference (20), page 349.

The probability a fish of species 's' will be lost because of operation in interval k is thus[74]

$$f_s(k) = p_s(k) \otimes e_s(k) \qquad 23\text{-}1$$

where $p_s(k)$ is the affected population probability curve for species 's' at the site and in interval k, and $e_s(k)$ represents the effective mortality probability due to the operation of the facility.[75] This equation 23-1 is obviously an oversimplification, and is presented only to demonstrate the predictive utility inherent in even this very crude quantification effort. It is strange that such a simple technique has not appeared in the literature.

Combining the recognition of acclimation temperature influences and the previously known thermal tolerance variations at various stages of life resulted in the development of a more elaborate data presentation scheme, see figure 2.3-5. The outside polygon represents the temperatures at which the average fish will die (LD_{50}); the inner polygon representing the temperature limitations for a thriving, reproducing community.

This polygon of thermal tolerance can vary considerably from one species to another, see figure 2.3-6. One might despair at being forced to maintain an aquasystem within the

---

[74] The symbol ⊗ represents the convolution operator.

[75] The mortality rate of organisms at temperatures around the lethal dose for 50%, LD_{50}, falls nicely in a normal distribution, see references (94) and (95), with a standard deviation of approximately 1° C (1.5° F), see reference(20), page 350.

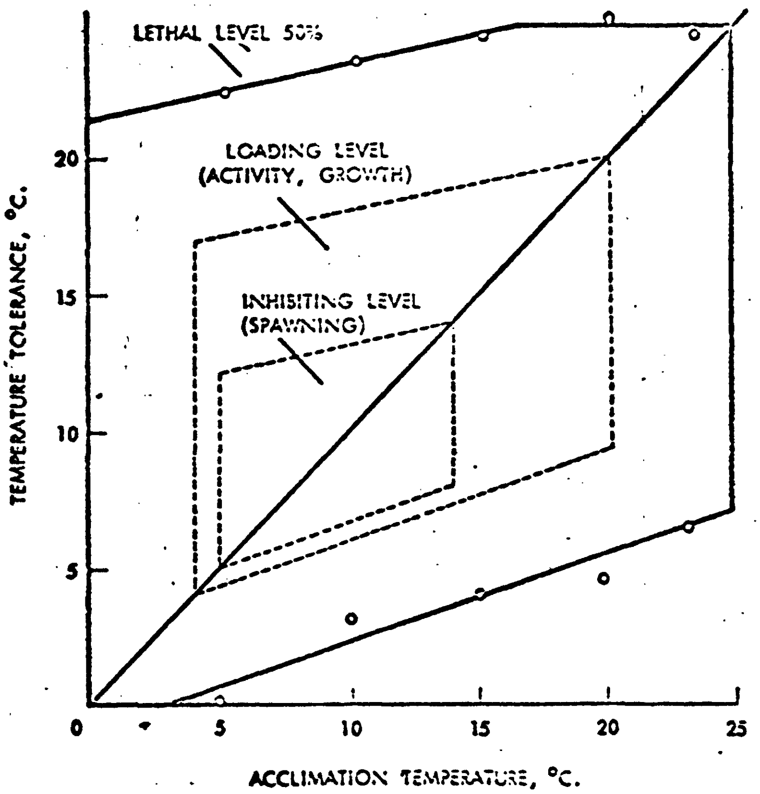


Figure 2.3-5 Representation of the effects of acclimation temperature on 1) lethal temperature, 2) tolerable temperatures, and 3) productive temperatures for young sockeye salmon76

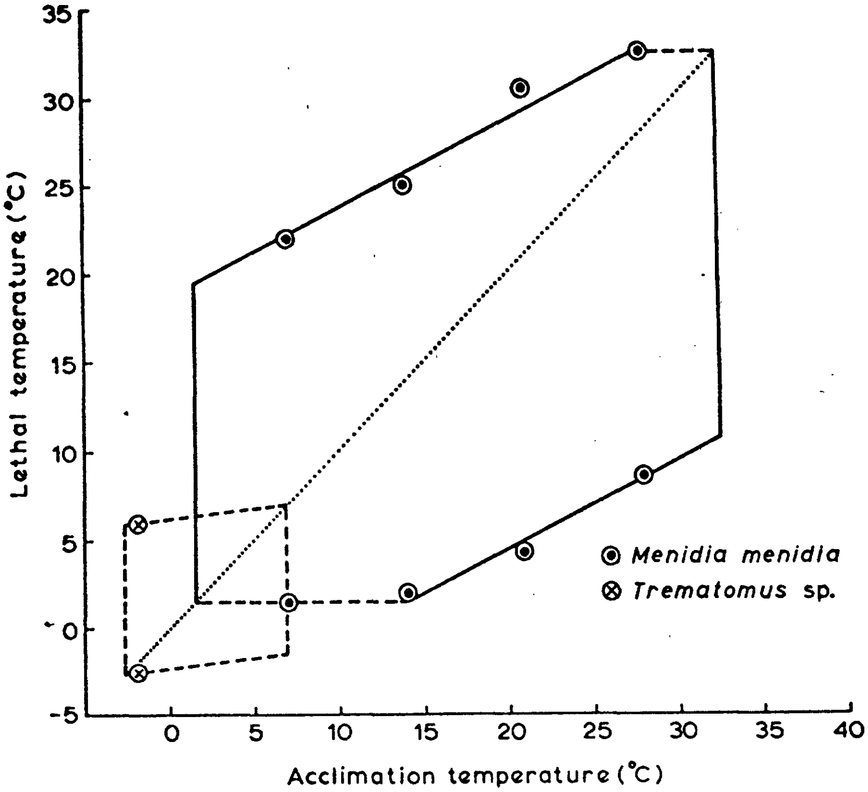


Figure 2.3-6 Temperature tolerances for a temperate species (Menidia) and an Antarctic species (Trematomus)77

small, tight range tolerable to the two species of figure 2.3-6. Fortunately, these two particular species are not found in the same habitat, in fact they are found at quite different latitudes. Fortunately, species found in the same general area can be expected to have generally the same temperature tolerances, see figure 2.3-7.

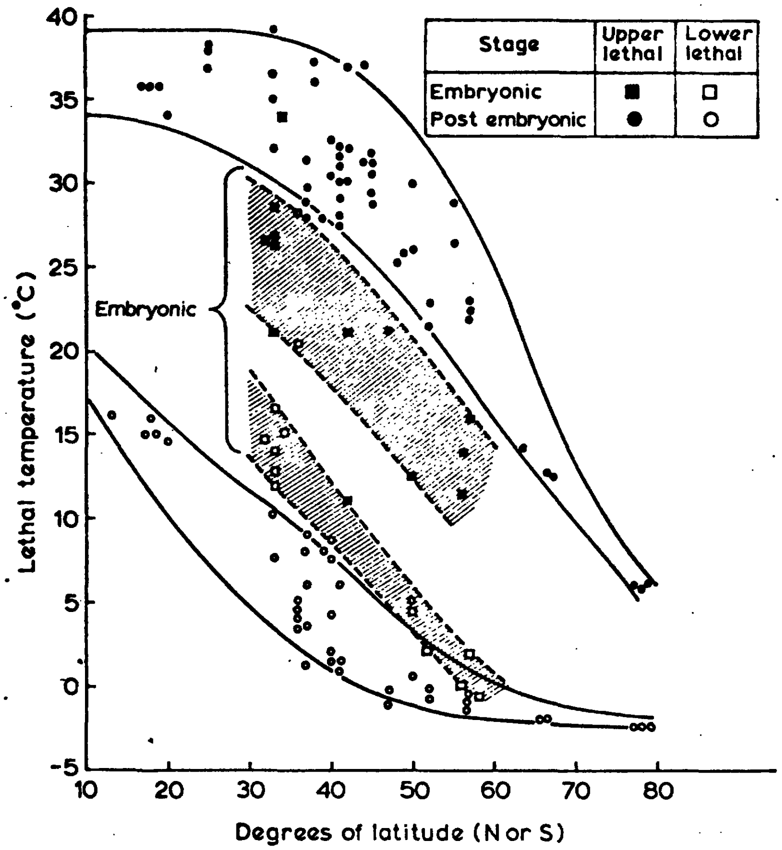


Figure 2.3-7 For natural acclimation temperatures, upper and lower temperature requirements for embryonic and adult species found in various latitudes.[78]

---

76. From reference (96), which also documents one of the few studies on predators' efficiency at hunting in heated water.

77. From ref. (97) originally from references (98) and (99).

78. This graph taken from reference (97) with the original data appearing in a number of other sources.

The introduction of time varying ambient river temperatures, i.e. acclimation temperatures, as well as life stage variations, results in the seasonal implications of the above model, see figure 2.3-6.

The most serious drawback to the use of these predictive models is the fact that thermal death is a function not only of temperature but of <u>duration</u> of exposure as well. An example of the lethal temperature medians for 100 minute and 1000 minute exposures at one particular time of the year for the various fish species is displayed in figure 2.3-9

So one can conceive of a plot like that of figure 2.3-5 but which also includes a time axis. Such a plot has been computed and is given in figure 2.3-10, where time is the amount of time taken to make the change in temperature for these particular bluegills (from reference 100). The upper slice, or regression plane, demonstrates the maximum exposure rates before thermal deaths, the lower slice treating the problem of cold shock, with the following equations:[79]

$$(ult) = 20.9 + 0.62(at) + 0.46(ttti) \qquad 23\text{-}2$$

$$(llt) = -6.93 + 0.58(at) - .016(tttd) \qquad 23\text{-}3$$

where (ult) = upper lethal temperature, (llt) = lower lethal temperature, (at) = acclimatization temperature, (ttti) and (tttd) are the total times for accomplishment of temperature increase and decrease.

---

[79] Equations taken from reference (100), page 1288.

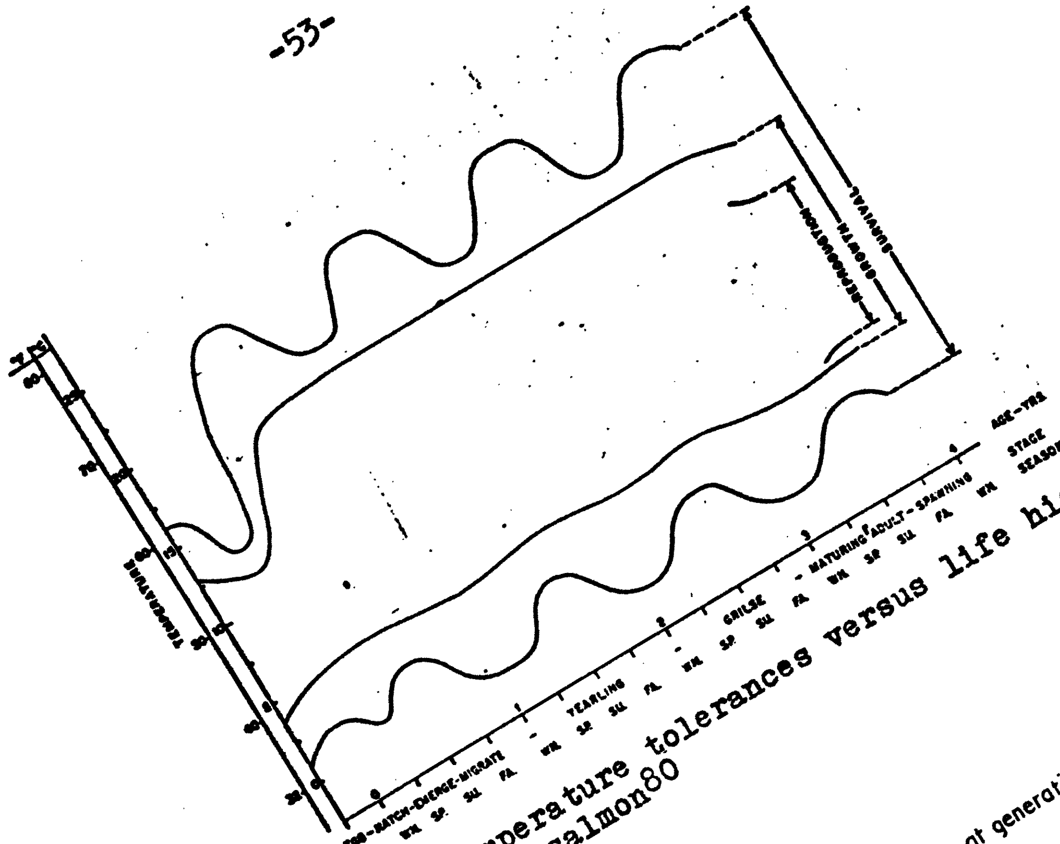


Figure 2.3-8 Temperature tolerances versus life history stages for sockeye salmon[80]

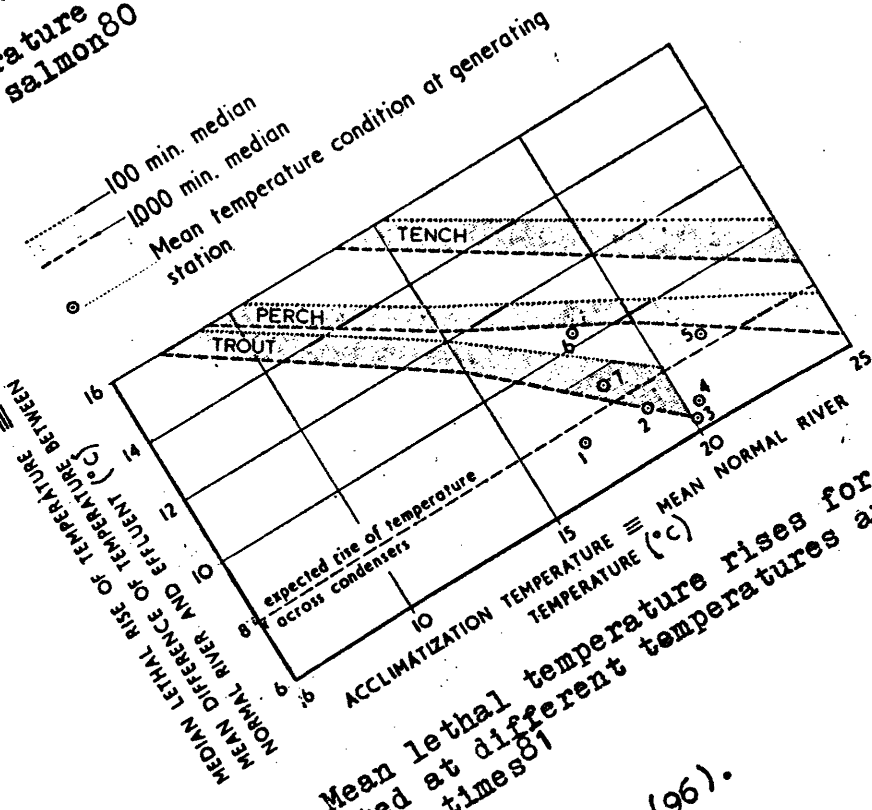


Figure 2.3-9 Mean lethal temperature rises for three fish species acclimated at different temperatures and for two different exposure times[81]

---

80. Excerpt from reference (96).

81. From reference (101), page 59.

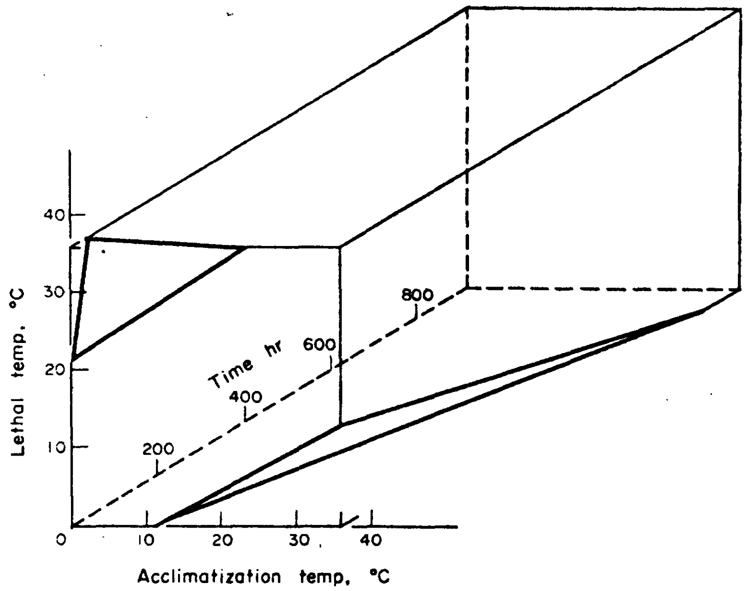


Figure 2.3-10 Three dimensional representation of the rate of temperature tolerance changes with time for bluegills[82]

Since the thermal deaths, rather than the cold shocks, have been the more commonly recognized fish kill problem more refined data has been tabulated for the prediction of this problem. Singling out the thermal death aspect, there is a slightly more sophisticated model which does not address the question of 'how long a time span must a temperature change be made over in order to be survivable' (which is the problem contended with in figure 2.3-10) but it addresses the question of 'how long can a particular temperature be survived?' This more exact, but slightly more complicated, mechanism follows closely the dose methodologies of pharmacy and radiology and it appears to be quite accurate for prediction of 'heat' doses tolerable before there are any thermal mortalities.

---

[82] See reference (100) for the original presentation.

The type of mechanism, presented in figure 2.3-11, uses this accurate[83] dose methodology, and is much better suited than figure 2.3-10 for predicting thermal mortalities for fish either entrained in the cooling system, or near outflows.

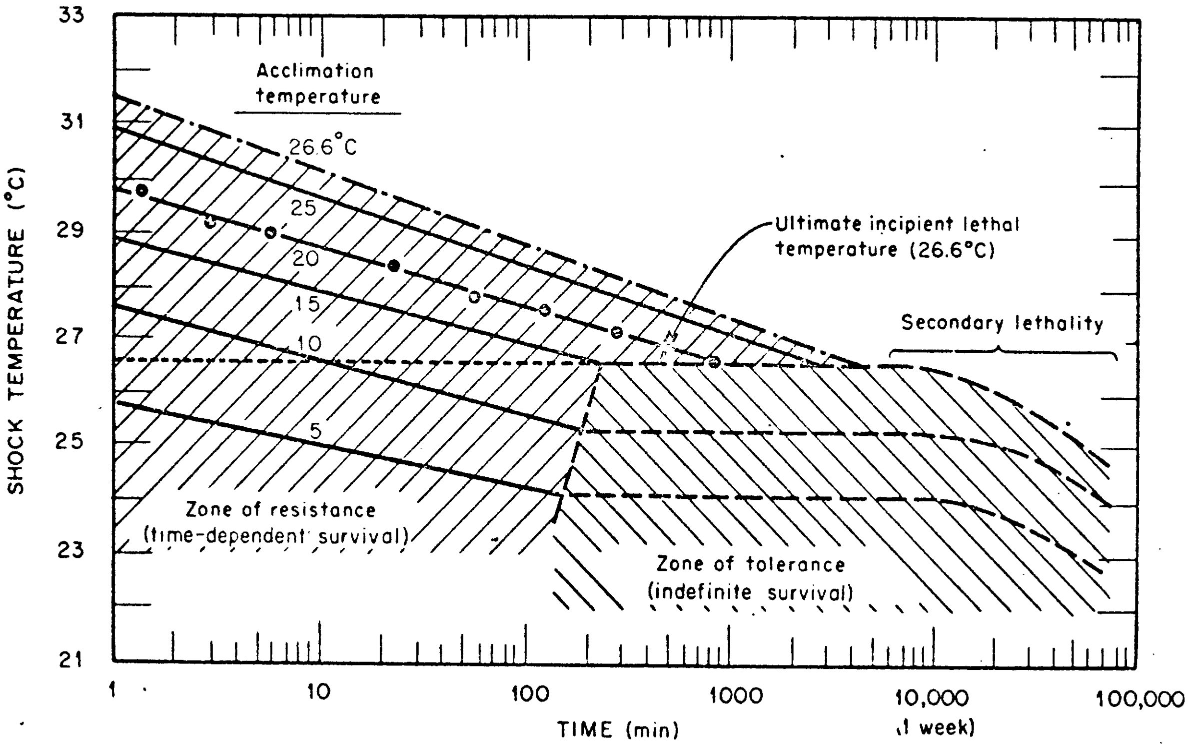


Figure 2.3-11 Lethal temperatures for 50% of a species acclimated to various temperatures, as a function of duration of exposure[84]

In mathematical form, for use in predicting duration-temperature mortalities, these curves may be expressed as

$$T_{LD_{50}} = .22\ T_A - .72 \ln t + 25.4 \qquad 23\text{-}4$$

$$\text{for } 26.6 > T_A > 5$$

where $T_{LD_{50}}$ is the lethal temperature in $^{\circ}C$ for 50% of a population acclimated at T_A $^{\circ}C$ and exposed for t minutes.

A $T_{LD_{50}}$ does not exist if the value computed is less than 26.6° C.

Equation 23-4 represents a very sophisticated and accurate

---

[83] See reference (94).

[84] Adapted from reference (102), for a more complete description see reference (24), page 605.

model for the prediction of direct lethal temperature doses. However, direct mortalities are not the only effect of thermal shocks to fish. There is an indirect mortality evident due to the increased susceptibility to predation in sublethally shocked fish.[85] The relative vulnerability of these fish to predation has been demonstrated to be significant at doses 10% to 20% below those required for visible signs of loss of equilibrium, which were in turn 25% to 50% below lethal doses, see figure 2.3-12

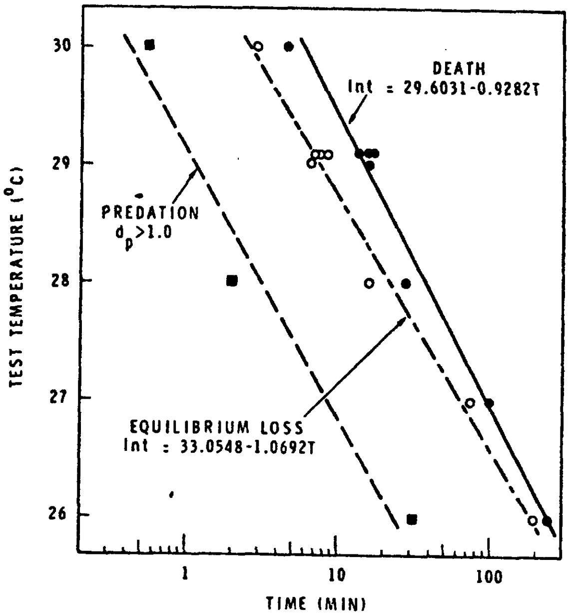


Figure 2.3-12 Doses associated with three types of effects resulting from thermal shock on 15° C acclimated juvenile rainbow trout[86]

Linear semilog models for predicting thermal deaths and equilibrium losses are unfortunately limited in their accuracy to small temperature bands. A model which has proven to be much more accurate, and which is the best presently available

---

[85] See reference(103).

[86] Excerpt from reference (9), page 607, where d_p is the ratio of shocked fish eaten to control fishes eaten.

is a fitting of the information with cubic curves, see figure 2.3-13.

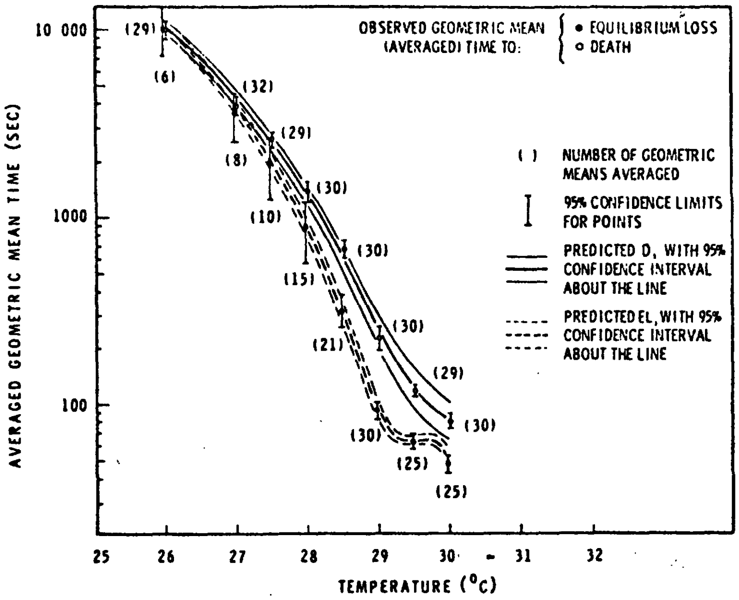


Figure 2.3-13 Cubic models for fish equilibrium loss and lethal doses including variance measures (95% confidence is about two standard deviations)[87]

This type of information, though, must receive careful treatment before it can be used in a quantification of impact. It is possible that increased susceptibility to predation may not reduce a species' population, if the numbers consumed by the predators remains constant. Even if greater consumption results, it is therefore probable that the predator species will increase in size and/or in number, and it is in fact these carnivores which are usually the most desirable of all the species.[88]

---

87. Excerpt from reference (9), page 604. Generally, a decrease in temperature of 2° C below the lethal temperature results in no losses, either from predation, or from fluke, highly sensitive individuals, substantiated in (104) to (108).

88. An example of a temperature change significantly affecting predator-prey interactions (coho-sockeye) is in ref. (109).

Unfortunately, for these best available models little data is available. Some transformation of the less sophisticated data[89] is possible, but a thorough understanding of the model from which this data has come is necessary so as to recognize the limits of that data's meaningfulness.

There are, of course, other so-called 'indirect' lethalities caused by thermal loadings, these occuring via the mechanisms of parasitic diseases and food stock limitations, and these will be discussed in sections 3.1 and 2.5, respectively. However, leaving behind for the moment any lethal effects, temperature also effects the general activity of fish, see figure 2.3-14.

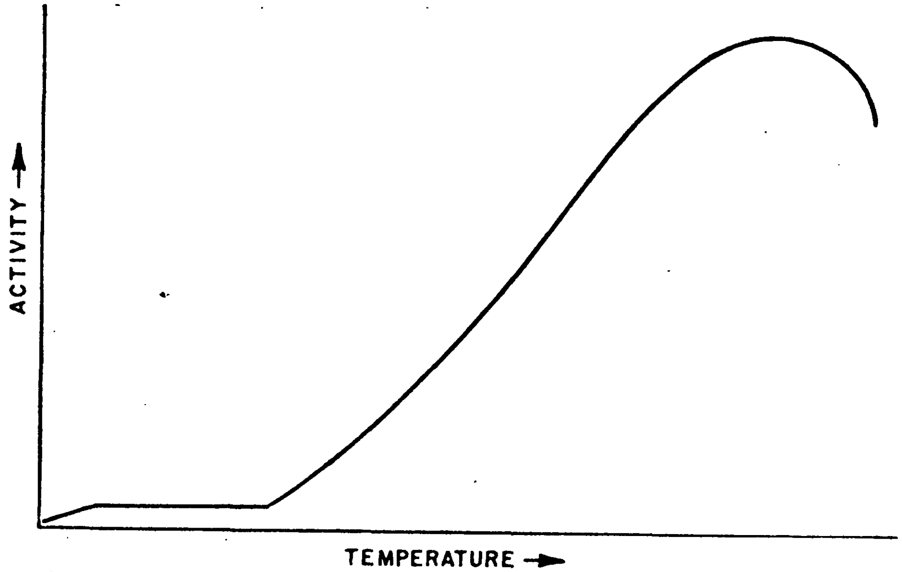


Figure 2.3-14 General effect of temperature upon the activity of fish[90]

---

[89] Tables of some of this 'less sophisticated' data, including maximum temperatures, minimum temperatures, optimum temp. ranges, maximum temperature changes, all for various life stages and acclimation temperatures can be found in references (13), (47), (73), (110), (97) and (107).

[90] From reference (111), page 206.

The consequences of the temperature versus activity plot presented in figure 2.3-14 are quite apparent. There is a point on this curve which then represents maximum activity, but to translate this into more tangible terms the graph of figure 2.3-14 must be broken down into the very specific types of activity which summed together to make this composite index. Such a breakdown is represented in figure 2.3-15.

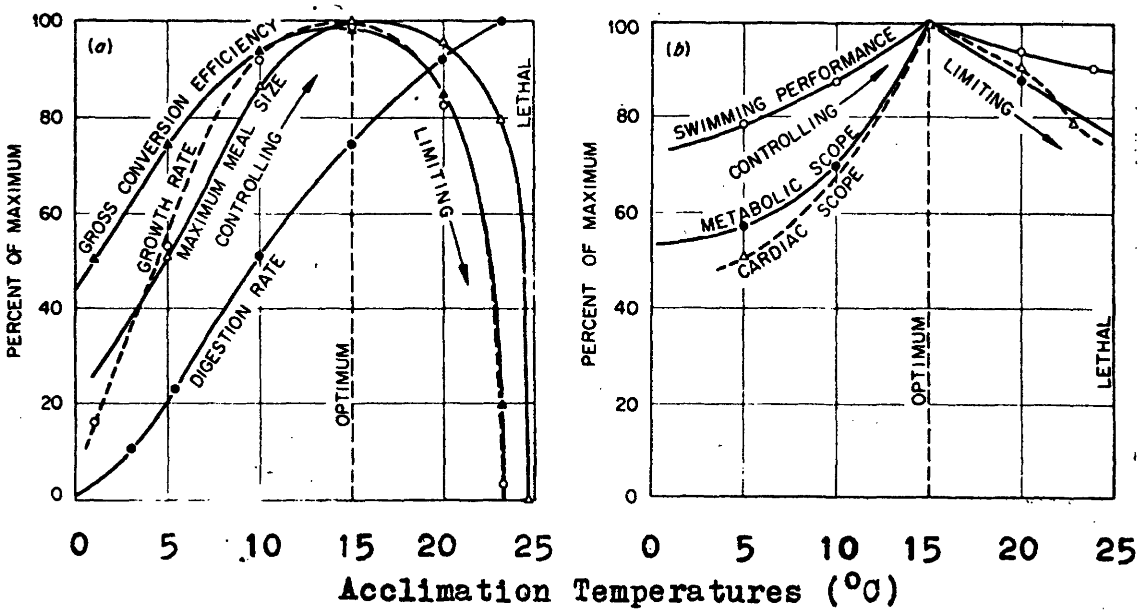


Figure 2.3-15 Relative performances of various sockeye salmon activities at different acclimation temperatures[91]

The "optimum" temperature is then found by examining the various factors and their importance. The coincidence of several maximum performances at a single "optimum" temperature is testimony to the evolutionary fine tuning of the species to its environment.

These growth rate measures cannot really be made

---

[91] From reference (112).

independent of knowledge of food availability. In fact, a graph of growth rate versus temperature at different food availability levels, as shown in figure 2.3-16, can be made up from input-output type of experiments without requiring information on swimming speed, digestion rate, etc. These plots are ideal for predicting productivity.

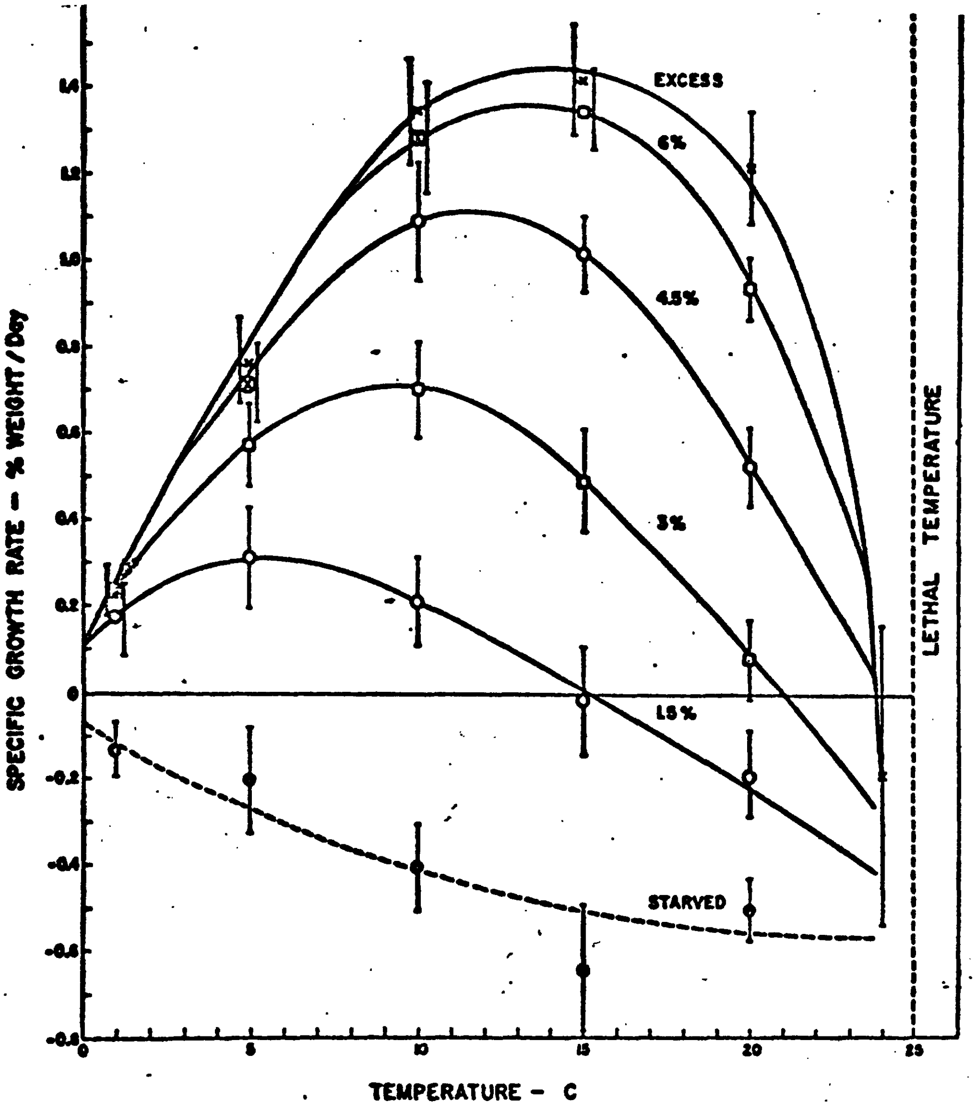


Figure 2.3-16 Growth rates of migrating anadromous fish as a function of temperature and food availability[93]

---

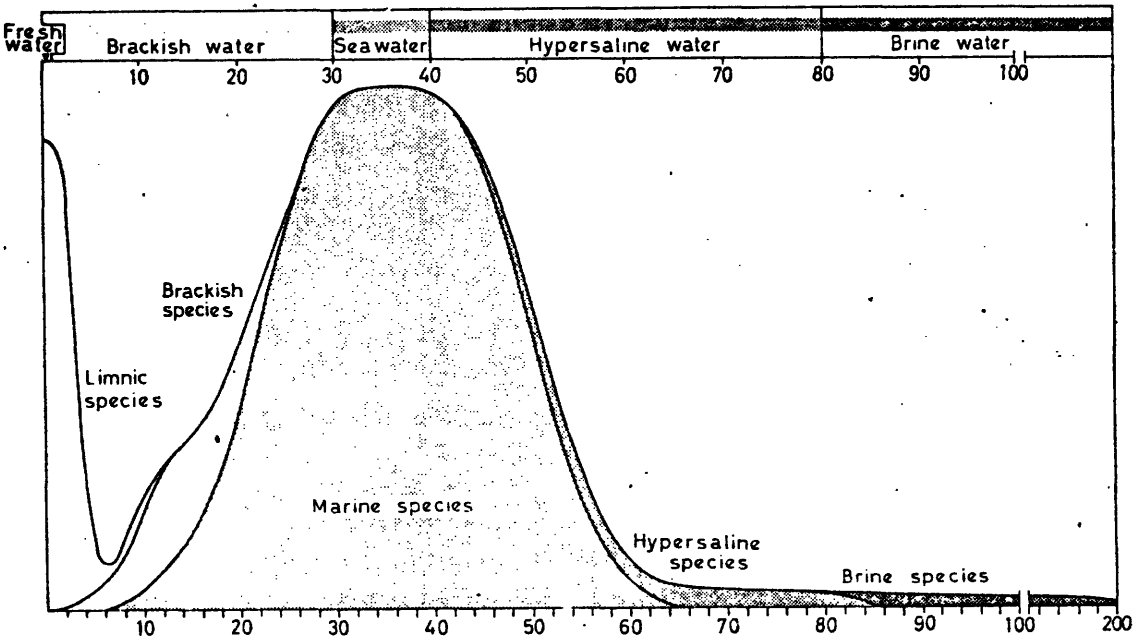
[93] From reference (113), with subsequent efforts to take advantage of controlling the environment to realize optimal growth rates being presented in reference (114).

Treated thus far has been the effect of temperature on fish lives and on fish productivity, however, there are many other temperature related fish problems. Many of these are peculiar to particular sites, and will not be discussed here,[94] but some are quite general and will be mentioned briefly, such as temperature-salinity[95] effects on fishes.

---

[94] For example, overfishing due to attraction of game fish and game fishermen to heated effluents, small mixing fields that nevertheless block the upstream migration of anadromous fish (see ref. (115)), higher metabolic rates and subsequent fuel depletion due to higher temperatures on upstream migrations during fastings (see reference (116)).

[95] Salinity is measured in o/oo, i.e. parts per thousand, and generally varies from 32o/oo near the Arctic to 38o/oo near the rain forests at the equator (as would be expected considering the amount of water that dissolves minerals and then runs off the land), see reference (117), page 31. There are many exceptions to this range, in particular, near icebergs and near rivers ocean salinities may drop below 20o/oo and in semi-trapped secondary seas, such as the Red Sea, salinities can be as high as 41o/oo, see reference (118), page 688. Most marine species are distributed naturally in the more typical ranges of salinity, as is shown in the accompanying plot from reference (119), page 824.



The concern over temperature-salinity effects upon fish functions stems not only from the temperature side of the problem, but also from the increased salinity which surrounds ocean sited power plants. With wet cooling towers, or cooling ponds at ocean sites, a great deal of pure water is lost to the air via evaporation, increasing the salt content of the surrounding waters. Whereas waste heat has many, see figure 2.1-6, mechanisms for going to the atmosphere and dispersing in water, 'waste salt' obviously cannot disperse into the air and thus only the dilution mechanism can keep the concentration down. After years of operation gradients of salinity will build up around the outlet, and these increases in salinity can have profound impacts upon the local aquatic life, see e.g. figure 2.3-17.

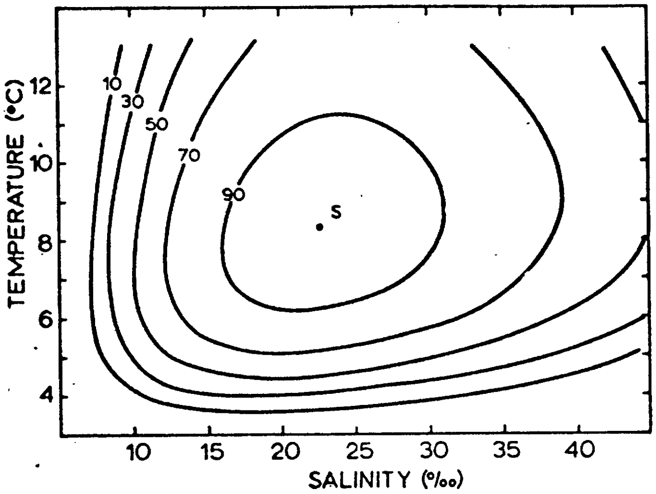


Figure 2.3-17 Percentage hatching of the eggs of a particular species (English sole) as a function of temperature and salinity[96]

---

[96] From reference (120), originally based on data presented in reference (121).

2.4 Shellfish Populations within Thermal Plumes

Shellfish is a term used to describe the various aquatic species of the mollusca and arthropod invertebrates. These include, among others, oysters, clams, mussels, scallops, snails, and crustaceans such as shrimp, crabs, crawfish and lobsters; a very desirable group both as food and as stabilizers of aquasystems.

The magnitude of the effects of thermal effluents on these shellfish populations is reduced due to the fact that most of these organisms are benthic, i.e. live on or very near the floor of the waterbody, whereas the warmer water being less dense rises to the surface of the waterbody. This condition is in many instances[97] unfortunate insofar as most shellfish, particularly ocean dwellers, thrive and are more productive in warmer habitats, where food availability is not the limiting factor.

Consider for example the growth of a clam species in figure 2.4-1. Those points well within the bell-shaped curve are restricted by limiting factors other than temperature, such as food. The average yearly temperatures at these American and European sites is well below the 21°C (70°F)

---

[97] A incident of destructive effects does exist and is well known. This is the case of the Mya genus of clams in the Chesapeake Bay. Extensive mortalities of this soft shelled mollusk have been attributed to excess heat ever since 1965. This condition might almost have been expected insofar as the Mya is a strictly northern genus and was at the very limits of its heat tolerance as far south as it was in the Chesapeake estuarine system (see reference (3), page 141 or reference (62) page 351).

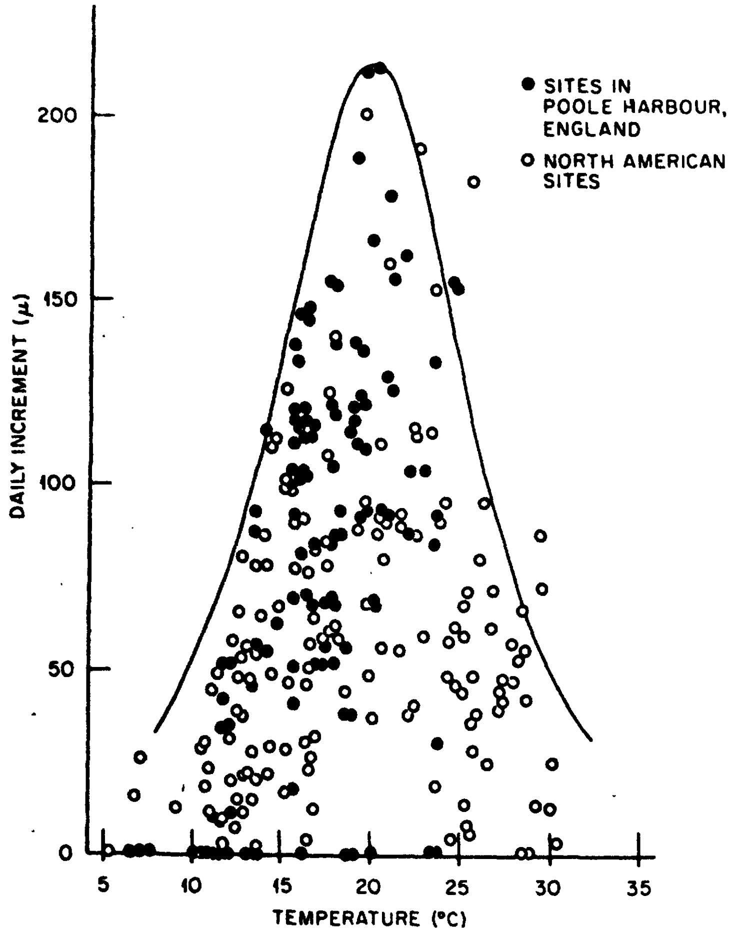


Figure 2.4-1 Relationship between temperature and rate of shell growth of a species of clam at two sites[98]

for optimum growth of these clams, and thus, thermal effluents could be quite beneficial to the extent that they were able to raise these bottom temperatures.

The heating of ocean shorelines is still significant enough to have prompted plans, and in some cases operations already exist, for oyster beds (in New York, Delaware and on the Gulf Coast[99]), and shrimp (in Texas) and lobster production (in Maine).

---

98. From reference (107), originally in reference (122).

99. See reference (86), page 6.

The major obstacles in these operations appear to be water quality,[100] i.e. control of the use of anti-foulants, anti-corrosives and the presence of dissolved copper; increasing the amount of available food;[101] the unpredictability of species' dependence upon warmth from effluents (and their subsequent possible losses at shutdowns[102]); and the possibility of unusually great sensitivity to temperature at critical times of the year. One example of this critical time is breeding time for which there is evidence of very specific temperature requirements for the spawning of molluscs,[103] oysters,[104] and crab.[105] Obviously, temperature increases at this time could be avoided by scheduling power plant maintenance then. This is another example of the need for the use of plant operation criteria which include awareness of specific ecosystem problems.

Because many valuable shellfish live exclusively in salt water, the problem of increased salinity of waste water must be considered in combination with the temperature increases. These temperature-salinity requirements can be

---

[100] Refer to source (123).

[101] See reference (124).

[102] One such loss of fish due to cold shock is documented in reference (125) and others possibly due to shutdown are described in references (126) and (127).

[103] See reference (128).

[104] Refer to reference (129).

[105] Described in reference (130).

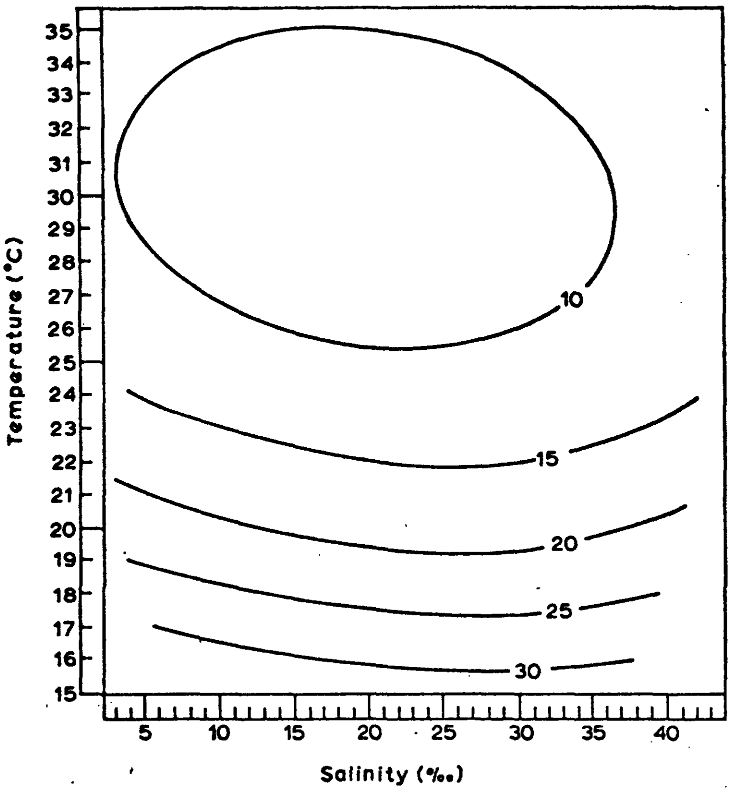


Figure 2.4-2 Estimated days for complete larval development of a crab species (from reference (119)).

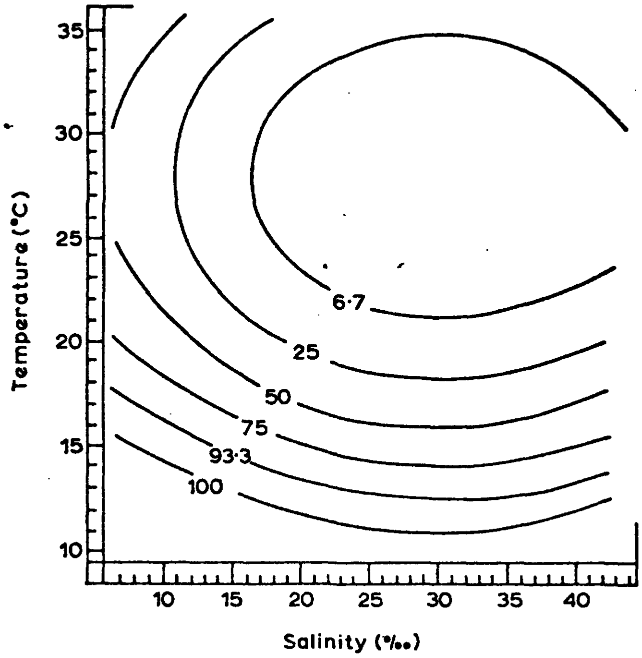


Figure 2.4-3 Percentage mortalities of megalops larvae of blue crabs under different temperature-salinity conditions (from reference (119), originally from reference (131)).

quite different for different stages of development and different species. Figure 2.4-2 represents the length of time for larval development of a species of crab, while figure 2.4-3 shows the mortality rates of one larval stage of a different crab species. Here again the best temperature for development of these embryonic shellfish is well above ambient temperatures (30°C is nearly 90°F which is well above usual ocean temperatures).

A better known, and more valuable (currently $2.85/lb.) shellfish, the American lobster has been much studied under many different water conditions. One study, figure 2.4-4, shows an incredible tolerance to wide ranges of

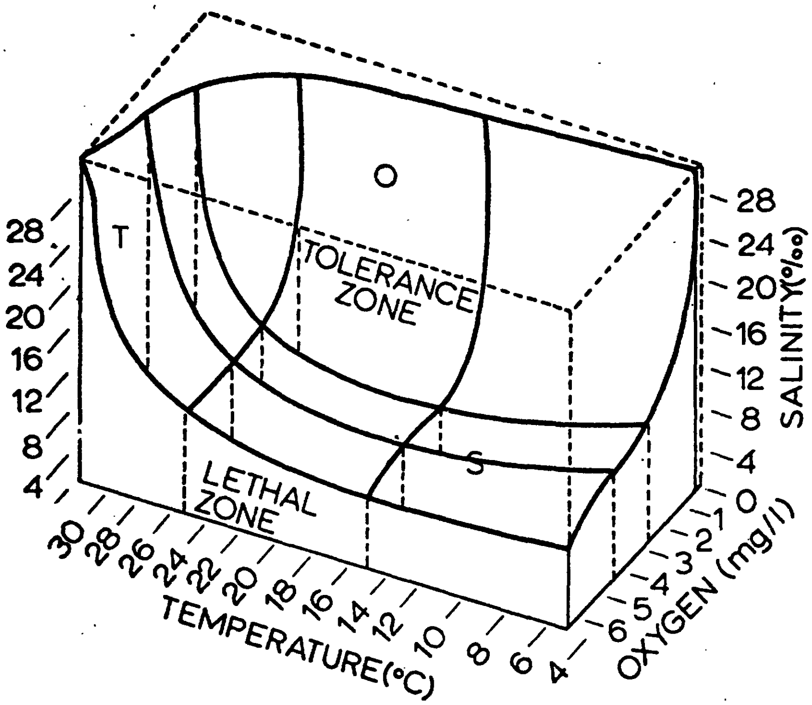


Figure 2.4-4 Boundaries of lethal conditions of temperature, salinity and dissolved oxygen for lobster[106]

---

[106] From reference (120), originally in reference (132).

temperature, salinity and dissolved oxygen.[107] Of course, there can be a significant difference between what is tolerable to a species and what is within limits of productivity. Figure 2.4-5 represents the temperature tolerance in terms of acclimation temperatures, and also thereon superimposed shows the rate of activity of the lobster measured in terms of its walking rate. For the

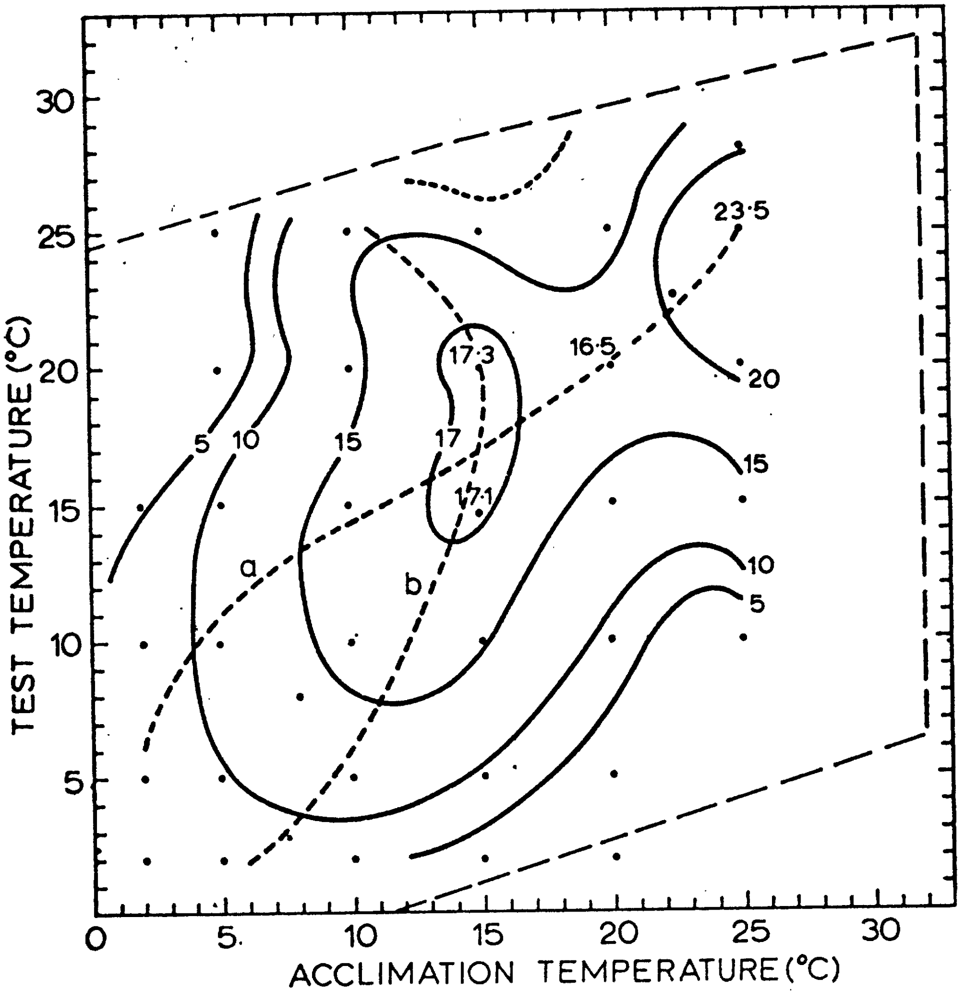


Figure 2.4-5 Thermal tolerances and walking rates of the American lobster[108]

---

[107] Dissolved oxygen generally varies in ocean water from about 4 to 6 ml/l, see reference (117), page 31.

[108] From reference (120), based on reference (133).

lobster this walking rate is an excellent overall measure of activity. Because of the small, drifting material upon which the lobster feeds, the amount of area it covers is nearly proportional to the amount of food the lobster intakes. Thus, the walking rate is a good indication of growth rate. In addition, this walking rate is a good measure of the 'catchability' of the lobster,[109] because it is proportional to the probability that they will come across a lobster trap.

Beneficial aspects of thermal enrichment to shellfish must, of course, be included in the final assessment of the desirability of operating procedures, as should any other beneficial results from aquatic farming.

2.5 Disturbance of Food Chains

> "The natural foods of a fish probably will not be affected if the fish itself is not affected. This may be a controversial point, but is a matter of deducing that organisms that live together naturally have a somewhat similar environment in their evolutionary history and consequently have similar tolerances."[110]

As a generalization this statement is apparently valid,[111] however, there are numerous specific cases of food limitations which show a careful examination of this problem is in fact needed.

---

[109] See reference (133).

[110] Excerpt from reference (134), page 12.

[111] For a statement of opinion on the relative insensitivity of invertebrates see reference (135), page 5.

Food obviously means different things to different species. To carnivores, or tertiary consumers, food means secondary consumers. Secondary consumers use primary consumers as food and they in turn eat the primary producers, such as algae. Generally, algae is a source of food for some non-carnivorous fish, but the topic of algae growth will be covered in section 2.6. Considered here will be the main source of food for those non-carnivorous fish,[112] specifically the invertebrate herbivore population or zooplankton.

Although the availability of zooplankton[113] populations seem to vary greatly with temperature and can be a major factor in indirect thermal effects on desirable fish, relatively few temperature studies have been performed on these species. Fortunately, many of the observations made concerning fishes seem to be, in essence, applicable to zooplankton populations.

There is apparently a mechanical destruction of many zooplankton species entrained in cooling system waters which makes collection and counting of outflow carcasses unreconcilable with the inflow-outflow statistics. A means of circumventing this difficulty for the observation of temperature effects on these herbivore invertebrates has been the collection of population samples above and below power plants on rivers, see figure 2.5-1. High reproduction

---

[112] Only food for non-carnivorous fish is considered here, for carnivores eat other fish and their populations and problems have already been treated.

[113] Meroplankton can be treated within this zooplankton grouping.

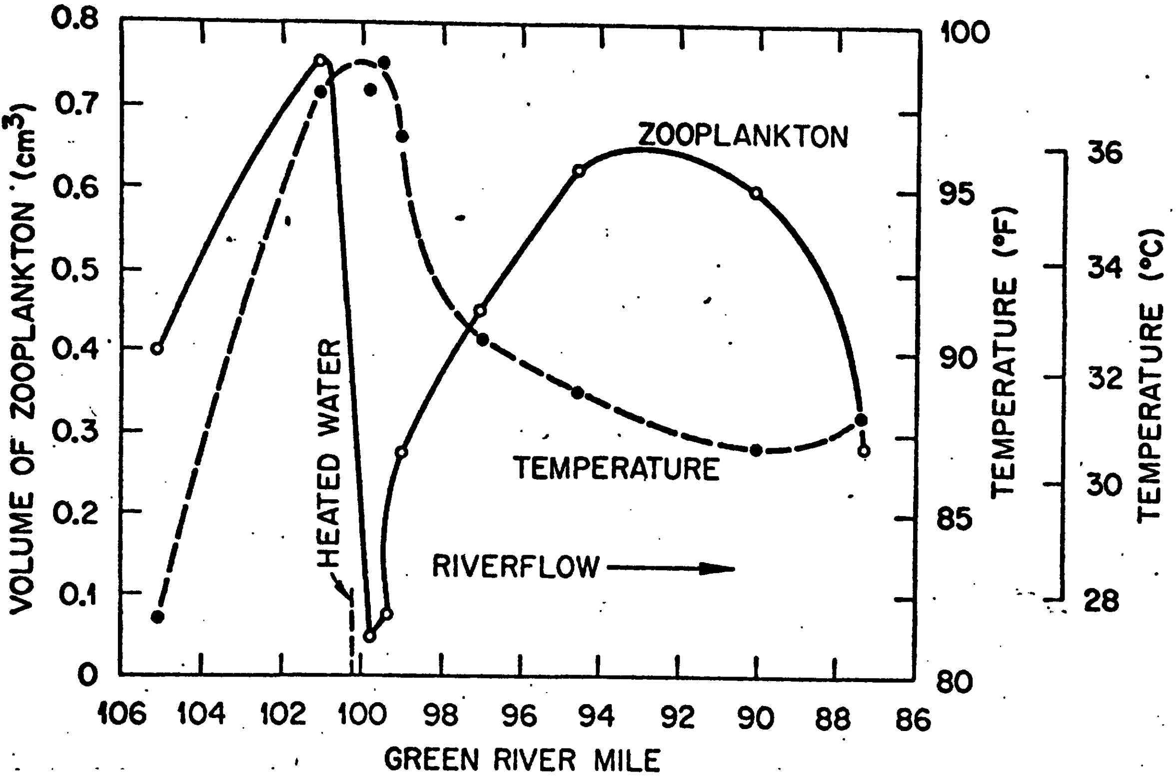


Figure 2.5-1 Zooplankton and water temperatures around a power plant on a river[114]

rates in the warmed, mixed river accounts for the increases in populations just upstream and downstream from the heated outflow. The deficiencies in the immediate area of the outfall must thus be balanced against the increased productivity in the neighborhood of the facility.

These "one-shot" studies are not as informative as research efforts which address themselves to the seasonal variation characteristics inherent in this problem, see figure 2.5-2. Thus, if thermal tolerances are the limiting factor for a particular zooplankton species of major value in the biocoenosis,

---

[114] See reference (136).

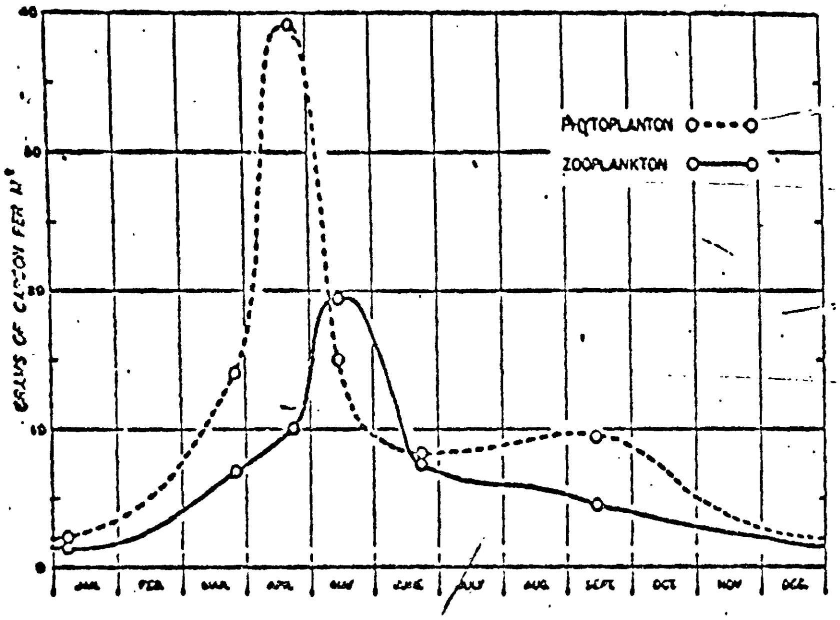


Figure 2.5-2 Annual cyclic variations in zooplankton and phytoplankton populations[115]

that is, the interlocked community of organisms, the seasonal population curves and temperature resistance ranges can be used to develop a predictive tool.

It is possible, although apparently unlikely, that primary food availability could be a limiting factor to important species of zooplankton. If this is the case these populations can be predicted using measures of primary food availability and grazing rates of zooplankton, see figure 2.5-3. In the vicinity of the heat source there are possible ramifications associated with the accumulation of algal forms, particularly those which are normally grazed upon by some of these zooplankton herbivores. The studies of this phenomenon, and the availability of primary food, are presented in the following section.

---

115. Excerpt from reference (137).

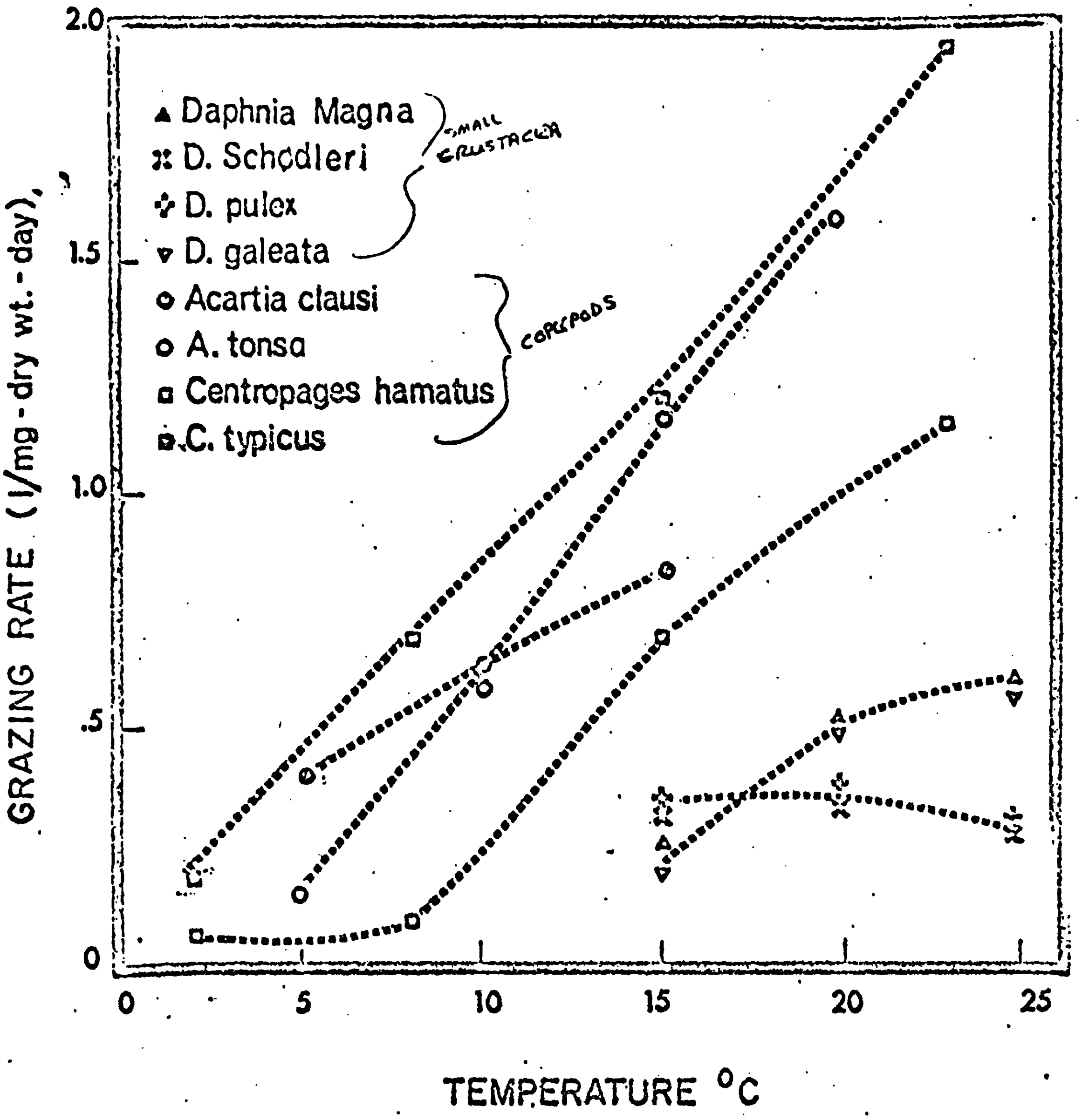


Figure 2.5-3 Grazing rates of various species of zooplankton versus temperature[116]

2.6 Algal Successions

The importance of algae blooms extends beyond their effect as a possible limiting factor in the food-consumer homeostasis. In the presence of the proper nutrients and within specific temperature bands, algal communities can

---

[116] From reference(138), page 13.

become so overabundant as to form large mats and putrefy the water.[117] These algae blooms are predictable[118] from information on light availability, water quality, turbidity and temperatures.[119] As is shown in figure 2.5-2 the accumulation of phytoplankton is a very seasonal problem. Great populations are most likely to build up in the spring before the herbivore populations arise to devour the enormous supply. Thus, although temperature is probably most important in the prediction of algae populations, there are a number of other important factors. Some of the seasonal factors, such as the herbivore populations, can be seen to be at work in the graph of figure 2.6-1.

In addition to the complexity of influences, prediction of algal populations can be further complicated by the great variety of species. Even at a single location[120] the variety of algae with different food value, composition, characteristics, eutrophication potential, etc., may be substantial, as is demonstrated in the temperature performances of various species in figure 2.6-2.

---

117. See reference (88) for some nutrient requirements of algae.

118. A cyclomorphic phenomenon exists for some phytoplankton but it is rare and to a certain extent predictable.

119. An extensive treatment of the correlation of algae and light is contained in reference (139) or (140).

120. Some algae temperature acclimations are described in (141).

121. From reference (140), originally in (142).

122. From reference (138).

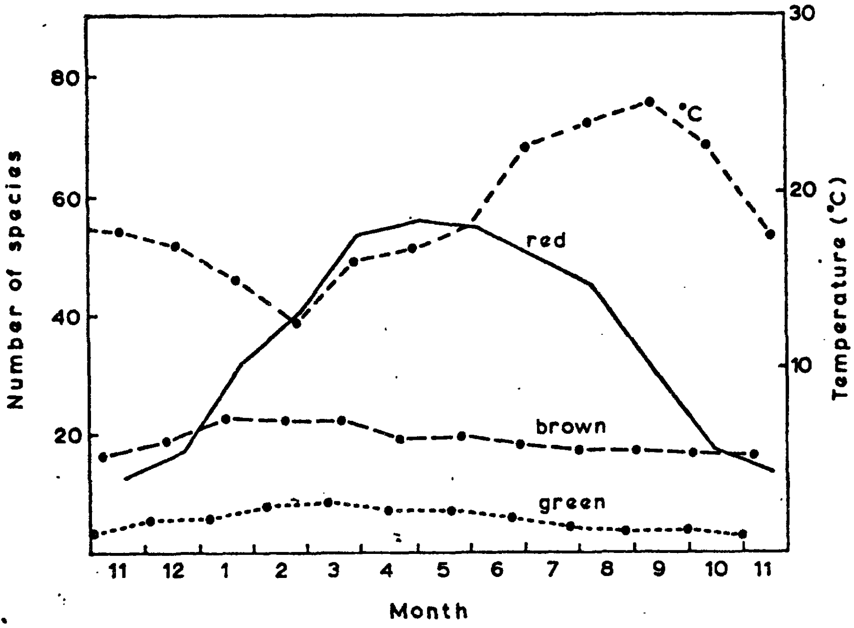


Figure 2.6-1 Seasonal variations in populations of red, brown and green algae in relation to temperature changes[121]

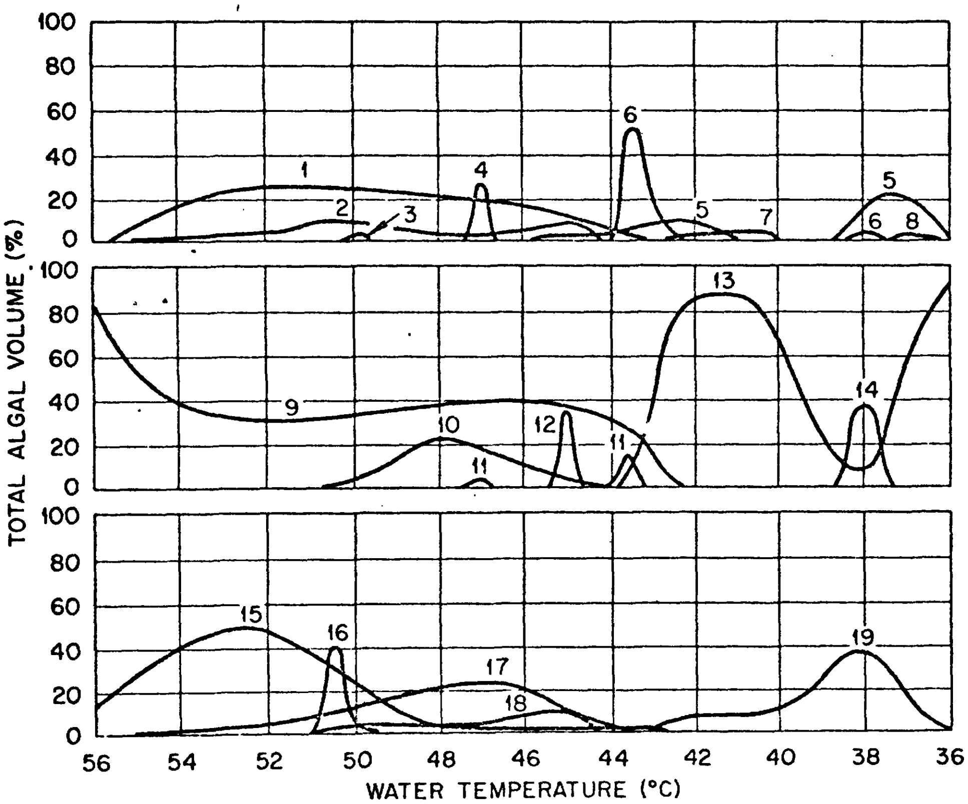


Figure 2.6-2 Percent volume of various algae populations versus temperature[122]

One might despair at the tremendous variety of algal species, however, for the sake of a predictive model algae can be grouped neatly into three catagories; diatoms, green and blue-green. Once a sample of the water quality[123] and available populations have been analyzed, a much simplified diagram of population shifts may be determinable, see figure 2.6-3.

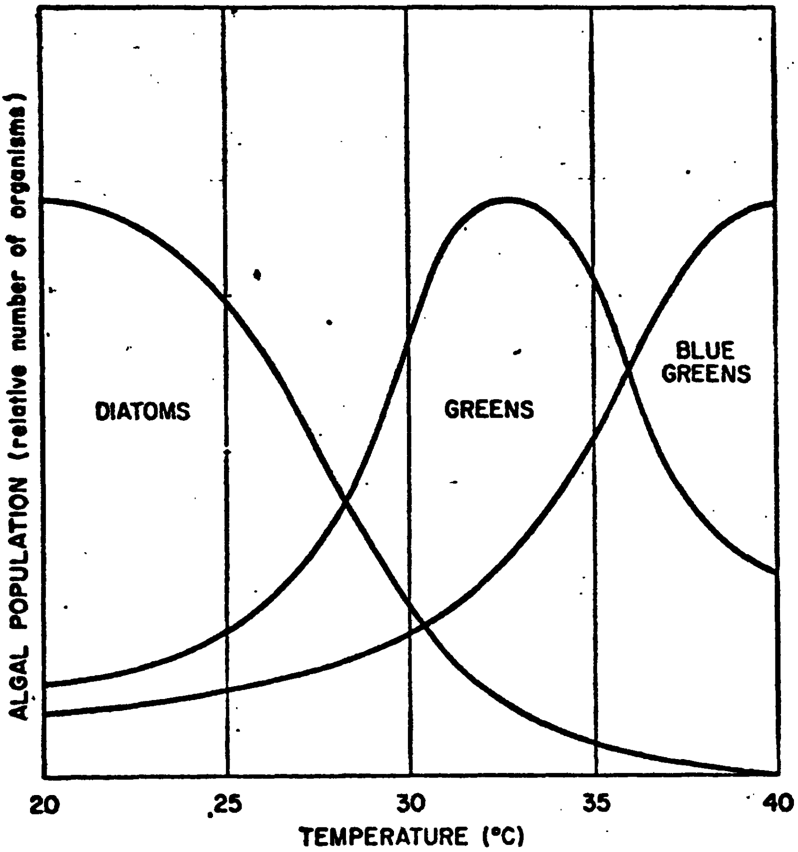


Figure 2.6- 3 Temperature effects on changes in algal groups[124]

And fortunately a quite accurate generalization can be made concerning the desirability of the different algal groups. As food sources the diatoms, and to a lesser extent the green

---

[123] Water quality determines to a great extent whether or not certain algal forms will accumulate. Some studies have shown that algae populations actually decrease in certain waters as temperature rises, see reference (143). Heated discharges have even been considered as a means of checking overgrowths of algal flora at some sites.

[124] From reference (144).

algaes, are almost[125] universally more suitable as food for higher organisms. On the other hand, blue-green algae are usually poor food and can sometimes even be toxic to herbivores.[126]

To see which group of algae is responsible for the possible buildup of stifling mats is also an important consideration. This huge accumulation of algae, and thus putridity, is a natural end state in the eutrophication, or maturing process, of water bodies. For aesthetic, recreational and commercial reasons, however, man has intervened in this natural process to make dying water bodies usable.[127] The acceleration of this eutrophication process is thus deemed undesirable. The algal forms which contribute to this eutrophication are those which consume nitrogen and fix them into nutrients. These nitrogen fixing, nutrient producing algae are generally[128] easily identifiable by heterocysts, which look like large holes, in their structures. The major[129] families of these nutrient

---

[125] A particular species which is an exception to this principle is treated in reference (145).

[126] See reference (146).

[127] For example, the blue harbor of Green Bay, Wisconsin was given that name by the first settlers because they found the bay clogged with green algae. A nearby clear lake at one time was badly stagnant and still bares the Indian name for "stinking waters."

[128] Minor exceptions are reported in references(147) and (148).

[129] Three nitrogen fixing microorganisms have been discovered, reference(149) as well as one nitrogen fixing non-planktonic organism, reference(150). So nutrient buildup can not always be attributed to algal populations, even if it is known to be produced by some organism with the ecosystem.

producers are two of the several orders of the blue-green algae.

Any study of the potential for significant putrification from algal groups can and must be quantitative, and should be coordinated with the collection of data on background sources of nutrients, such as fertilizer runoff.

2.7 Major Fish Kill Incidents

Having covered the thermobiology of the major components of the predator-food chain, i.e. fish, shellfish, zooplankton and algal groups, it is now necessary to consider what minor organisms may have a significant influence on the problem, minor being worms and insects (outside of their zooplankton type stage) and microorganisms. Rather than go into each of these groups in laborious detail, a survey will be presented of fish kill incidents and in this way it can be seen if any of these minor groups is in fact causing a significant problem.

A detailed study of fish kill incidents is also worthwhile from the standpoint of recognizing and, if possible, avoiding the substantial intangible economic effects of such occurrences. For example, fish kills were in part responsible for tipping to the unlikely side the "$36,000 adventive trout fishing" versus "$6,500,000 cooling tower" controversy on the Connecticut River.[130]

---

[130] See reference (86), page 4.

Because there is so much publicity given to fish kills, one might think that they are a common occurrence, especially those caused by power plants. And when graphs of losses are presented they are usually in an alarming looking, <u>cumulative</u> plot, such as is shown in figure 2.7-1. Actually, however, there were 22.8 million fish killed in 1970, and of these only .058 million were estimated to be caused by power plants.[131]

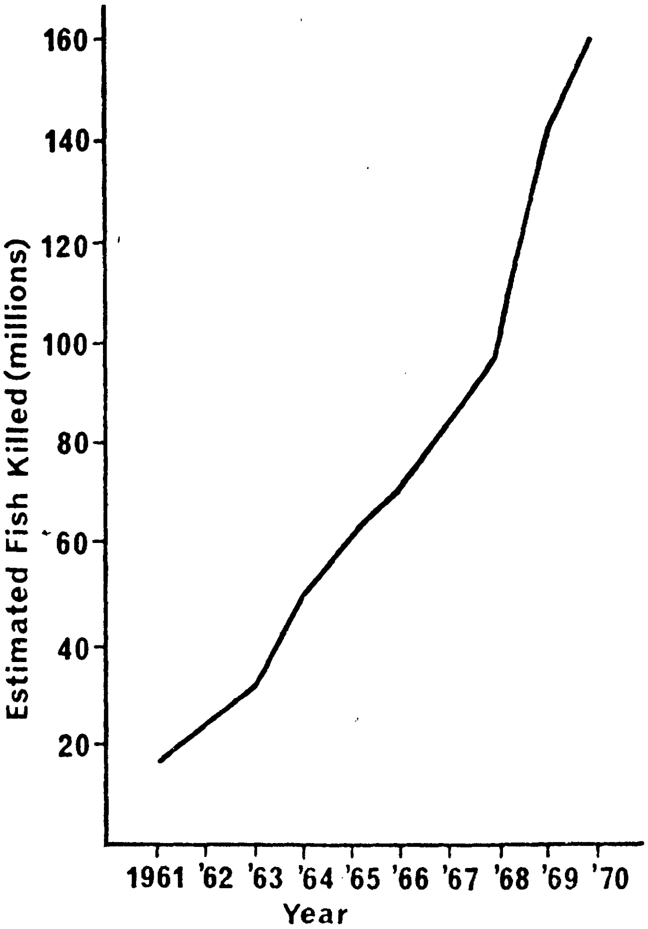


Figure 2.7-1 Cumulative number of estimated fish killed, beginning in 1960[132]

---

[131] This and other data on this subject in reference (151).

[132] From reference (151), page 100.

2.7.1 Intake Impingement

The three critical components of environmental concern at the intake of the power plant are the intake configuration and positioning, the intake screening mechanism and the preparatory treatment given the intaken water.

Water treatment depends directly upon its intended use.[133] Boiler water makeup undergoes the most rigorous treatment, including ion exchange procedures. Not so rigorous, but still involving the loss of nearly all entrained organisms, is the preparation of water for cooling towers. Once-through cooling water requires just a cursory settling time and the addition of some anti-fouling and anti-corrosion chemicals. Ecological losses incurred during these procedures are readily quantifiable.

Intakes may be single-leveled, or fixed or variable multi-leveled and depending upon their positioning will have a profound effect on the types and quantities of entrained organisms.[134] This (as well as the intake screen) is an engineering problem which should be optimized at the construction planning stage.

Some poor intake screen designs are responsible for major fish kill problems. Because of the colonialistic characteristics of fish they are likely to be lost in great numbers once they start becoming impinged upon intake screens.

---

133. Descriptions of different preparatory procedures for intake water is contained in reference (88).

134. Depth has also been shown to slightly affect the tolerance of a fish with respect to thermal stress, see reference (152), page 26, extensive pressure studies are contained in (153)&(154).

The Indian Point reactors have apparently been plagued by this type of fish kill, and the solution seems to be an engineering problem. Travelling screen designs have been used at some facilities to solve this problem, see figure 2.7.1.

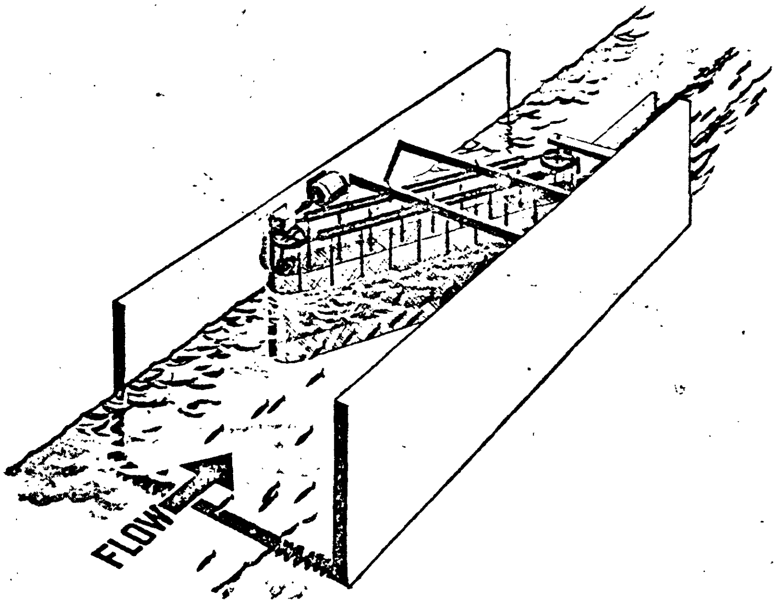


Figure 2.7.1 Travelling screen for the prevention of impingement of fish at intakes[135]

Obviously, the size of an intake screen of this type must be calculated to allow slow enough current through it so that injury is not prominent before fish are deposited back into the stream.

Bubble screens and other devices have been tested and it appears that fish kills due to impingement will in the future not dictate significant environmental impacts upon various operating schemes, although if this is an existing problem it can be easily considered.

---

[135] From reference (155), page 234.

2.7.2 Entrainment in Cooling Systems

Direct thermal deaths, or indirect deaths caused by food chain disruptions, are not likely to be of the magnitude of major fish kills. This in no way is meant to imply that these should not be accounted, and the methods of the earlier sections of this chapter deal with the formulation of these "probability of affected population" convolved with "probability of impact" methods. This technique is equally appropriately used in the prediction and operation of the system to avoid major biological incidents resultant from entrainment damage.

2.7.3 Discharge Canal Traps

Perhaps the best understood and most th^{er}oughly documented fish kill incidents result from the unfortunate designs of discharge canals.

Figure 2.1-6 has shown how discharge canals can add considerably to duration of thermal stress upon entrained

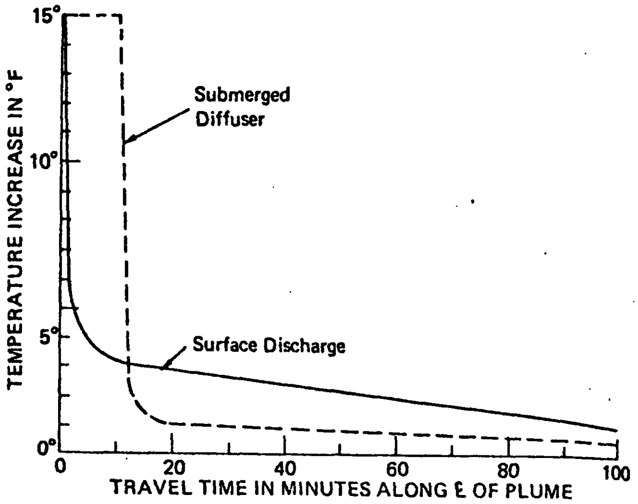


Figure 2.7.3-1 Comparison of temperature versus travel time along the centerline of the effluent plumes for surface and submerged discharges[136]

---

[136] Excerpt from reference (3), page 112.

organisms. Also the use of submerged diffusers, generally being farther from power plants, can result in similar extended excursions in hot water, as is shown in figure 2.7.3-1.

These are not, however, the causes of major kills, which are instead due to faulty discharge designs that create traps, see figure 2.7.3-2. Attracted by the warmth and abundance of thriving food the fish swim up the discharge canals when the power plants are shut off. Upon later startup the canal becomes lethally hot and the pond soon also is intolerable.

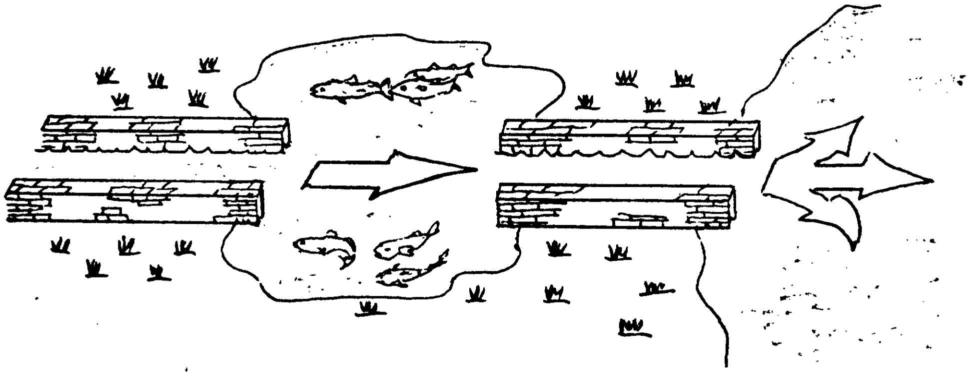


Figure 2.7.3-2 Type of discharge canal trap that causes major fish kills

Despite the apparent predictability of these poor designs, such as at a Pennsylvania power plant which used an old river bed as an extension to the middle of its discharge canal,[137] these problems are fairly common causes of major fish kills. Other incidents have occurred on Cape Cod Canal in 1968, Hudson River,[138] and in Great Britian.[139]

---

[137] See reference(156) for more details.

[138] Refer to reference (157).

[139] See reference (158).

Outflow screens, screened discharge canal walls at ponds, or outfalls, where possible, are some potential solutions for this discharge trap situation which is primarily an engineering problem.

2.7.4 Thermotoxic Synergisms

In mixing zones and nearby thermally loaded waters fish kills due to thermal stress are rare occurrences because being motile organisms fish tend to seek out food sources in thermally pleasant surroundings. Fish will not stay unaware in thermally stressing situations, and when given an entire range have been known to be particular in their temperature choice to within 0.03° C.

Problems do arise, however, when there is no escape from the heat, and this is primarily an engineering problem with respect to the size or flow of the water body adjacent to a generating facility. Sessile, i.e. relatively stationary, organisms are also not capable of escape, but since these animals are benthic (i.e. on the floor) they are subjected to very little heat, and thus massive kills are rare. However, any organism very near to their limits of thermal tolerance, especially noticeable from geographic distribution studies, which is in the mixing area or nearby will very likely by lost. This is a problem which can and should be included in the plant licensing bioassay, and must be considered a fixed ecological loss associated with that particular site selection.

To conclude this survey of fish kills, there is one last type of extreme biological incident which does occur in and adjacent to the mixing zones. This is a phenomon which will here be called the thermotoxic synergism: the possibility of a lethal situation resulting from combined non-lethal thermal stresses and non-lethal chemical or microorganism concentrations.[140]

There are several types of these thermotoxic synergisms. Thermal stress and chemical concentrations may be directly lethal to an organism, or may cause the organism to make unsatisfiable food or nutrient demands of his environment, thus causing indirect mortalities. Also, these synergisms may be in the form of increased susceptibility of an organism to bacterial or virulent concentrations when under thermal stress, or they could involve the accelerated growth of pathogens at higher temperatures, see figure 2.7.4.

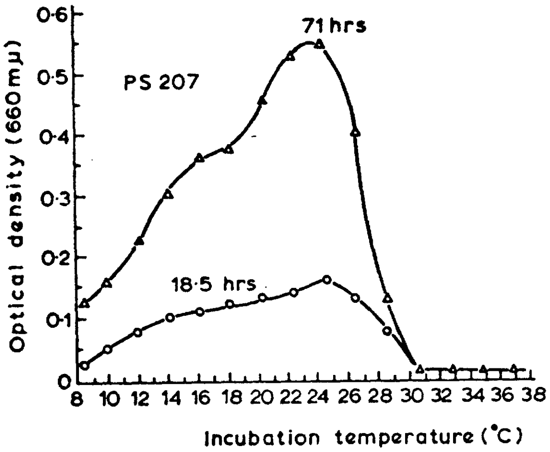


Figure 2.7.4 Temperature influence on marine bacteria growth[141]

---

[140] For example, a 10°C temperature increase doubles the toxic effect of potassium cyanide and an 8°C temperature increase triples the toxic effect of O-xylene, see further examples in reference (159).

[141] Originally in reference (160), after data in reference (161).

And finally, chemical and microorganism combinations along with sublethal thermal stress may cause mortalities.[142]

The thermotoxic problem is not as complicated as it might at first appear to be; some simplifications are possible. Instances of research[143] indicating insignificant differences in susceptibility, of fish in and out of thermal stress, to certain diseases, indicates that there may also be only a few troublesome combinations among the other types of thermotoxic combinations. Some of the troublesome bacterial-temperature combinations have already been listed.[144] Further research has shown that the thermotoxic problem may exist only at certain predictable times of the year.[145]

Prevention of mortalities caused by thermotoxic synergisms would require several steps. First, the very thorough water quality test used for plant licensing procedures must be

---

142. Microbial compositions of an ecosystem also change with temperature, and some of this little researched area is covered in reference (162).

143. See references (163), (164), (165), and (9) page 609. Some cases have been demonstrated, see e.g. reference (166), that show disease control mechanisms are more active at higher temperatures, but the reverse appears to be generally the case, see e.g. references (167), (168), (169) page 48. Another case of increased virulence of fish pathogens at higher temperatures is described in reference (170).

144. See ref. (171) page 152, also refs. (172) to (176). Saprophytic bacteria, living on preformed organic matter, prefer 22 to 28°C, while parasitic prefer about 37°C, (reference (47), page 47). Also to be considered is the desirability of different bacteria, which can range from deadly pathogenics to stream purifying or organically necessary.

145. Ref. (177) indicates the seasonal variations of antibody production and immune responses, ref. (178) discusses seasonal variation in bacterial growth which has more or less an independence to temperature.

studied for thermotoxic danger levels. Second, spot checks of water quality (discussed in section 3.1) must be collected periodically (preferably both upstream and downstream) to help anticipate problems. Finally, either a governmental agency, or the utility, should collect information on inadvertant spillages from all the industries on the waterbody, for use in determining emergency situations. If these steps are carried out, production scheduling and generation unit commitment can be coordinated with the quantified predictions of mortalities due to thermotoxic synergisms, and major fish kills averted (equation 31-1 proposes a method for such a quantification)

An example of an as yet unsolved fish kill incident is presented on the following page.[146] Although this incident would seem to be clearly a case of thermotoxic mortalities, apparently no effort has been made to ascribe the cause to the combination of some of the stresses. One could speculate that the three steps previously mentioned might have prevented this episode, or at the very least the nuclear plant could have been spared the incident. if it had not operated during that week of incredibly poor water quality.

The operation of the power plant itself may result in some loading of the water bodies with chemicals (as pointed out in the following article). Apparently, on Long Island, chemicals used during plant maintenance are discharged directly to the waterbody and when plants begin operating some large fish

---

[146] Excerpt from reference (179), page 84.

84 Boston Sunday Globe May 7, 1972

Conn. N-plant, fish kill linked

By John Peterson
Globe Correspondent

WATERFORD, Conn.— Water discharge from a nuclear reactor has been labeled as the tentative cause for a fish kill off this southeastern Connecticut community. But there is debate about other possible causes.

Scientists working for Northeast Utilities which operates the Millstone Point nuclear power complex where thousands of fish began dying a week ago, attributed the mortality to a shock syndrome.

They said gradual temperature changes do not affect most fish but the quick 23-degree difference of water discharge from the plant's steam condensers caused stress conditions for the menhaden species which succumbed throughout the week.

Estimates of the death toll by the Connecticut Department of Environmental Protection (DTP) stopped after the second day of the kill with at least 10,000 to 15,000, affecting only the menhaden species. With fish still dying at a rapid rate, spokesmen for the agency said, "in excess of 10,000."

Northeast officials said late this week they were working on the design of a large netlike device which will keep fish out of the region.

The kill was the second for the species in southeastern Connecticut in a month. Last fall officials estimated millions died in the Thames River in nearby New London. State officials said the apparent cause was a lack of oxygen, but a positive conclusion could only be drawn after years of study.

Samples of the fish taken by Northeast were analyzed by Dr. Richard Wiike of the University of Rhode Island.

Acording to Wilke, the quick rise in temperature near the plant was too much too soon. Massive hemorhage was found in the menhaden gills, liver, and body cavities of the analyzed samples.

Wilke also said he found evidence of bacteria isolated in the kidney and liver tissue which might produce a poisonous toxin, but those tests would take weeks to complete.

Theodore B. Bampton, chief of the DEP's Preservation and Conservation Division, said preliminary findings by his section concur with Wilke's.

Local ecologists and marine biologists who took water samples at the onset of the kill, however, privately refute the tentative cause.

One of theme, Dr. Robert DeSanto, a zoology profesor at Connecticut College and president of the Thames Science Center, said he flatly disagrees.

DeSanto and some of his students said they found acetone, or some closely related substance in water samples they took Monday.

Before and after the announcement of the Rhode Island tests, DeSanto said he believed the fish died of a chemical pollutant.

The stage of construction on a second atomic plant adjacent to the existing unit suggests the use of that chemical which DeSanto said was used mostly as a cleansing agent.

The area of the kill is slightly more than a mile away from the scene of a assive oil spill Mar. 21.

In that incident more than 80,000 gallons of highly toxic home fuel oil were spewed throughout the region, claiming many lower forms of marine life.

Scientists are still assessing its damage. However, at this point, state officials do not think the spill and the fish kill are linked.

kills are reported (although these have apparently not been documented).

The constant use of anti-fouling chemicals such as chlorine may effect some mortalities due to thermotoxic synergisms. There are experiments being conducted to test the relative effectiveness of, and impact associated with, replacing these chemicals with periodic backwashes of hotter (10°C additional) water. Constant use of corrosion inhibitors, such as hexavalent chromium, is also known to be lethal in combination with heat.[147] These constant small toxin concentrations in effluents undoubtedly affect some fish, but probably are not responsible for any major fish kills.

---

147. River water mixed with 4% of the normally heated, corrosion inhibited effluent right from the outlet resulted in some mortalities, see reference (180).

3. Operating Considerations

The essential and obvious environmental consequences of operating generators must be the thermal related mortalities. Elements for the prediction of these consequences are developed in chapter 2 and quantified in chapter 4. The periodic sampling of water quality required for the modelling of these inputs, as well as the operating consequences on the environment from other than thermal problems are stressed in this chapter.

3.1 Water Quality and Radiation

Sampling of water quality is an essential input to even the crudest modelling of aquatic ecological impacts.

First, nutrient concentrations and availability of foods must be quantified. These will then enable predictions of eutrophication, algae, herbivore and carnivore population growths, and desirability of various temperature levels for optimal beneficial productivity in the aquasphere. There are obvious chemical tests for the determination of nutrient levels, as well as some simpler transparency[148] and color tests which can be automated. These simple color and clarity tests can be useful, but chemical tests, especially for the nitrogens: organic, ammonia, nitrate, nitrite, and phosphoruses: total and soluble, would be much better measures of the nutrient level.[149]

A controversial water quality topic is whether or not

---

[148] See for example reference (181).

[149] See for this opinion reference (182).

measures of dissolved oxygen, DO, and biochemical oxygen demands, BOD, are useful. The problem of thermal pollution is often presented as the following argument:

> as temperature increases the ability of water to hold oxygen is decreased, BUT as temperature increases the activity of aquatic organisms increases and thus their needed for dissolved oxygen increases.

Elaborate methods for computing DO and BOD levels are available[150] including some partial differential equation models for optimizing DO levels around power plants.[151] The need for DO is definitely a real need in fish,[152] but the consideration of this parameter in the case of thermal pollution is not necessary,[153] except in waterbodies with very extremely deficient dissolved oxygen levels (for example cooling ponds, or areas full of sludge). This should be a consideration of the siting of a facility, and probably need never be considered

---

[150] See, e.g. for energy balance techniques reference (183), stochastic filtering methods applied (184), BOD curves (185), state estimation (186), forecasting techniques (187), simulations (188) and DO strategies in the presence of other pollutants (189).

[151] Contained in reference (190).

[152] See for example, reference (191)

[153] The argument follows the course that within the temperature range of interest DO concentration changes little, also, poikilotherms have evolved a metabolically regulated system which demands almost identical quantities of DO within its temperature range of existence, see reference (192) and refer to the curves of metabolic rates in the adjacent Figure 3.1-1.

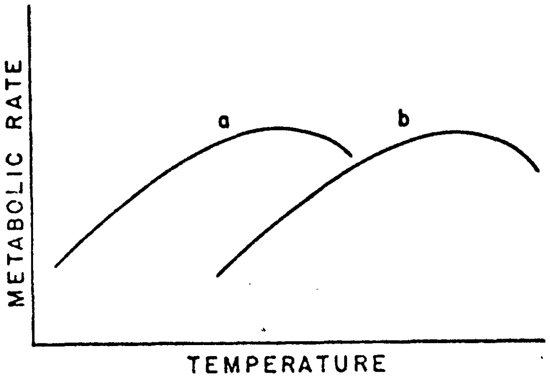


Figure 3.1-1 Metabolic rates at various temperatures for polar (a) and tropic (b) animals (from reference 192).

further.

At sites where dissolved oxygen should be considered there are a complexity of factors which must then be examined. Obviously, the cooling water during its turbulent mixing and air entrapping journey will add oxygen to the water,[154] and this can make a particularly important difference if the intake structure is arranged to take in the cold, oxygen-short, bottom water. An addition of dissolved oxygen will also occur if a warming effluent reduces the ice cover of a waterbody. Increased levels of dissolved oxygen are not always beneficial, for example, if the appropriate nutrients and algae are present, dissolved oxygen can lead to speeded up eutrophication.[155]

A third water quality consideration requires that cultures be taken to test for existence of certain infectious microorganisms, including, possibly, coliform bacteria (which in itself is not harmful, but is an indicator of the presence of very harmful pathogens).

Other variables of interest are sediment rates, and concentrations of suspended and dissolved solids,[156] alkalinities, chlorides and mineral substances. Increases in temperature can beneficially effect the cleaning of muddy rivers,[157] because sediment rates, or settling

---

[154] See reference (11), page IX-24.

[155] See reference (193).

[156] Copper losses from corrosion of heat exchange surfaces have had a significant impact on nearby shellfish, see ref. (194).

[157] See page 14 of reference (47).

velocities, are inversely proportional to the water viscosity, and water density. And, although density changes very little with temperature (about 1% for 100°F), the viscosity decreases about 1% for every 1°F temperature increase.[158] As for the problem of dissolved solids, obviously, hotter water dissolves more minerals, and it evaporates faster, further increasing mineral concentrations, such as salinity, which can increase significantly the corrosion of bridges, ships and other structures. However, not all thermal-chemical combinations are bad, e.g. chlorine disinfects much faster at higher temperatures,[159] and thus an intensive study of total chemical impact must include positive and negative factors of effects near the plant, as well as those displaced downstream.[160]

Water quality changes occurring because of damming of water in a reservoir[161] is still a little understood problem, but there are indications[162] that such impoundment has significant effect on reducing turbidity, lowering dissolved solid concentrations, and reducing seasonal

---

158. See reference (195).

159. See reference (195).

160. Downstream aggravations are unfortunately quite typical, particularly because temperature naturally increases downstream thus displacing some possible consequences.

161. A complex model of chemical transfers in an estuarine benthal system is contained in reference (196).

162. See reference (197).

temperature changes.[163]

Some of the toxins which affect water quality are arsenicals, alkylbenzene sulfonates, alkylate sulfonates, carbamate, chlorinated hydrocarbons, fluorides, phenols, sulfides, cyanides, ammonias, defoliants, detergents, algicides, fungicides, herbicides, insecticides and pesticides. Lethal levels of these toxins[164] have been developed for fish (in general). For example, consider the pesticides in Table 3.1-1

Organochloride pesticides			
Aldrin	0.04	DDT	0.6
BHC	2.0	Dieldrin	0.3
Chlordane	2.0	Endosulfan	0.2
Endrin	0.2	Methoxychlor	4.0
Heptachlor	0.2	Perthane	3.0
Lindane	0.2	TDE	3.0
		Toxaphene	3.0
Organophosphorous pesticides			
Coumaphos	2.0	Naled	3.0
Dursban	3.0	Parathion	1.0
Fenthion	0.03	Ronnel	5.0

Table 3.1-1 Example of 48 hour median lethal doses, LD_{50}, for fish, of some common pesticide toxins as measured in micrograms per liter[164]

The synergistic effects[165] of these toxins have long been recognized, and the very conservative formula for the consideration of these effects has been proposed:

---

[163] Water quality changes in estuaries, in terms of salinity, temperature, bio-chemical oxygen demand, and dissolved oxygen is the topic of the estuarine modeling effort in ref. (198).

[164] See reference (88), or for a more detailed analysis (199).

[165] The heightened sensitivity of aquatic organisms to toxins when temperatures increase, as well as the increases in toxins caused by temperature increases are discussed in reference (200).

$$\frac{C_1}{L_1} + \frac{C_2}{L_2} + \ldots \frac{C_n}{L_n} + \frac{C_t}{L_t} \angle 1 \qquad 31\text{-}1$$

where C_i is the measure of concentration of toxic material and L_i is the respective toxic limit, and where there seems to be no reason why a similar term for temperature could not be introduced, i.e. the dose C_t over the limit L_t. Of course, ideally, rather than just adding these expected values, measures of variance should also be manipulated (this then provides the precise probabilistic treatment if the curves are Gaussian, i.e. normal, distributions).

It would be unreasonable to make frequent measurements of all these suggested parameters. A number of these water quality variables are monitored by governmental agencies, and many of the rest can be measured once, i.e. before plant construction, or perhaps annually. An information service on emergency situations, e.g. inadvertent spillages upstream, could provide the bulk of this data required for quantifying thermotoxic environmental impacts due to plant operation.

A certain number of automatic monitoring devices are available if it is felt they are required. These include measures of magnetic flow, total oxygen demand, total organic carbon, dissolved oxygen, oxidation reduction potential, temperature, pH and conductivity.[166]

The most complicated problem to be dealt with in water quality concerns the study of barely detectable, harmful,

---

[166] From reference (201), page 33.

trace materials, of which some organisms are capable of accumulating levels greatly in excess of their concentrations in the environment.[167] Existing concentrations of such metals as manganese, copper, nickel, zinc and lead evidently are significantly reducing productivity of some ecosystems.[168] Those and other metals such as mercury, cadmium and arsenic have accumulated concentrations in some marine organisms[169] which have caused concern, and in some cases illnesses, to man because of their use as foods.

Detrimental radiation effects of normal reactor operation to surrounding aquatic life has not been observed, even in highly polluting early reactor models.[170] Even though these organisms live directly in the water from reactor effluents they are lower forms of life than man, and thus are much less sensitive to radioactivity.[171] A graph of the approximate tolerances of different animals is presented on the following page in figure 3.1-2 And there is considerable evidence to support the claim that waterbound radioactive wastes from nuclear reactors will not cause harmful problems to man.[173] Background radiations

---

[167] For example, reference (202) documents ^{90}Sr in bones of perch at concentrations up to 3,500 that of the radioactive wastewater in which they lived.

[168] See reference (203).

[169] For some current data on these concentrations see ref. (204), or ref. (205) for radioactive concentration factors.

[170] Reference (3), page 185.

[171] Radiosensitivity is apparently proportional to the amount of DNA in the nucleus of the animals cells.

[173] See for example reference (208) or reference (180).

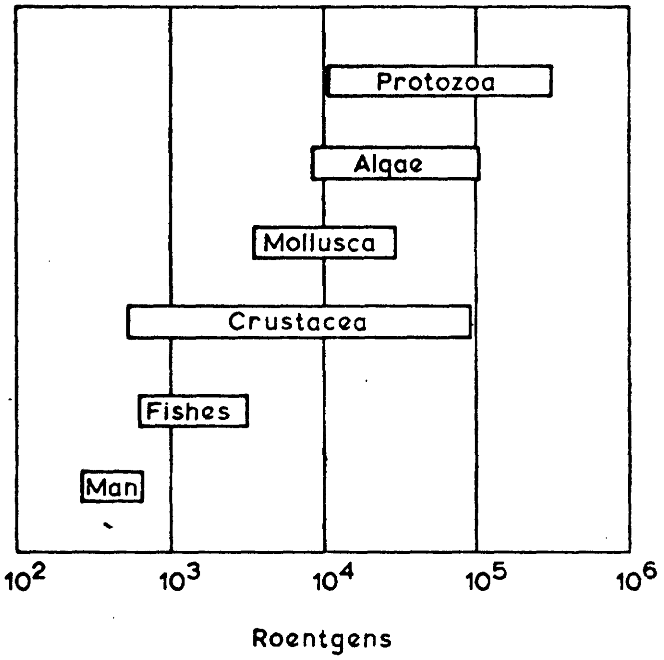


Figure 3.1-2 Relative radiation tolerance of different aquatic organisms in relation to man[172]

in nature far exceed those of reactors under normal operating conditions,[174] and "in actuality, the reactor designs in many cases are such that even in the event of loss of coolant accidents, the dose to the surrounding population would be no greater than those permitted during normal operation."[175]

The numerous pathways available for the transfer of radiation to man via the aquasystem are shown on the following page in figure 3.1-3. The problem of determining impact to man is further complicated by the fact that the different

---

[172] From reference (206) originally in reference (207).

[174] See reference (3), page 181.

[175] Excerpt from reference (3), page 213.

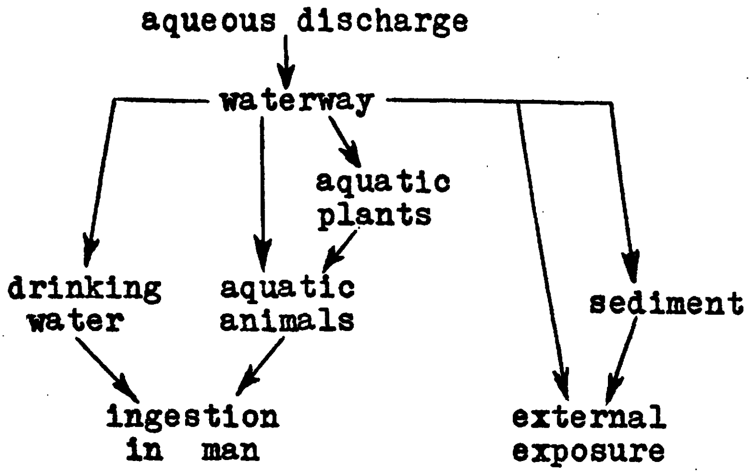


Figure 3.1-3 Aquatic critical exposure pathways of radioactive materials to man[176]

radionuclides tend to follow different, but characteristic, paths through the aquasphere. Some, e.g. the insolubles, tend to dilute and disperse by the mechanisms of currents, turbulence, isotope dilution and biological transport. Other isotopes tend to be concentrated, either in the biota or through various physical or chemical processes.[177] Adding together the highest possible dosages to man from all the possible pathways, and including also all airborne pathways, results in numbers such as those given in figure 3.1-4 for a 210 megawatt boiling water reactor.[178]

In terms of possible genetic mutations due to public exposure to radiation, it has been estimated that the per capita dose from radiation for medical purposes (100 mrem/yr) is ten thousand times that from nuclear facilities

---

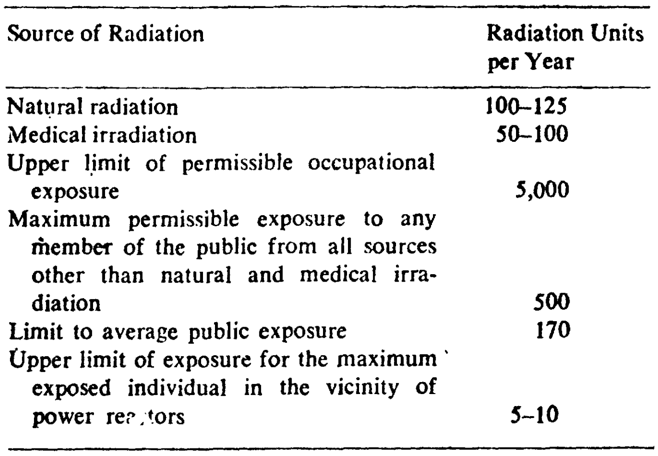
176. Adapted from reference (3), page 180.

177. For example, adsorption, ion exchange, coprecipitation, flocculation or sedimentation.

178. Reference (3), page 197.

Critical Organ	Nuclides	Dose mrem/yr	Fraction of Radiation Protection Guidelines
External whole body	gaseous fusion products	14.0	8×10^{-2}
Thyroid	^{131}I	0.74	1×10^{-3}
Bone	^{89}Sr, ^{90}Sr	0.026	2×10^{-4}
Gastro-intestinal	^{58}Co, ^{60}Co, ^{140}Ba	0.0027	5×10^{-6}
Internal whole body	^{134}Cs, ^{137}Cs, ^{3}H	0.011	6×10^{-5}

Figure 3.1-4 Estimated total dose rate to critical organs (0.01 mrem/yr).[179] These figures are slightly misleading in that populations around facilities might receive closer to 1 mrem/yr — and people right next to reactors upwards to 10 mrem/yr. However, figure 3.1-5 shows how insignificant even these figures are compared to other radiation sources.



Source of Radiation	Radiation Units per Year
Natural radiation	100–125
Medical irradiation	50–100
Upper limit of permissible occupational exposure	5,000
Maximum permissible exposure to any member of the public from all sources other than natural and medical irradiation	500
Limit to average public exposure	170
Upper limit of exposure for the maximum exposed individual in the vicinity of power reactors	5–10

Figure 3.1-5 Population radiation dose from all sources[180]

The rationale behind the radiation concern, and

---

179. From reference (259), for more information see (199).

180. From reference (3), page 212.

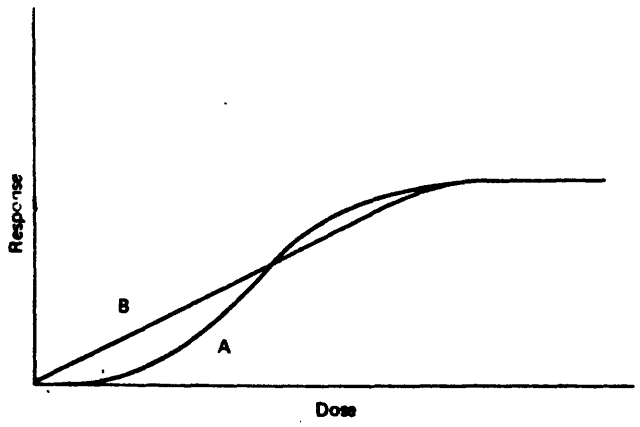


Figure 3.1-6 Types of dose curves, (A) conventional dose threshold curve, (B) linear response curve[180]

extremely strict standards, lies in the curves in figure 3.1-6. There are theoretical, experimental and epidemiological evidences which possibly support the contention that radiation follows the linear curve, thus whatever radiation is added will add proportional effects. And thus, the nuclear safety research will continue, and the radiation standards for nuclear power plants will continue to tighten to be as strict as is practicable until there is evidence against the linear curve. Such evidence may never come, however, because these levels are so far below significant experimental radiation levels (100,000 mrem/yr) as to make statistical studies inconclusive.[181]

---

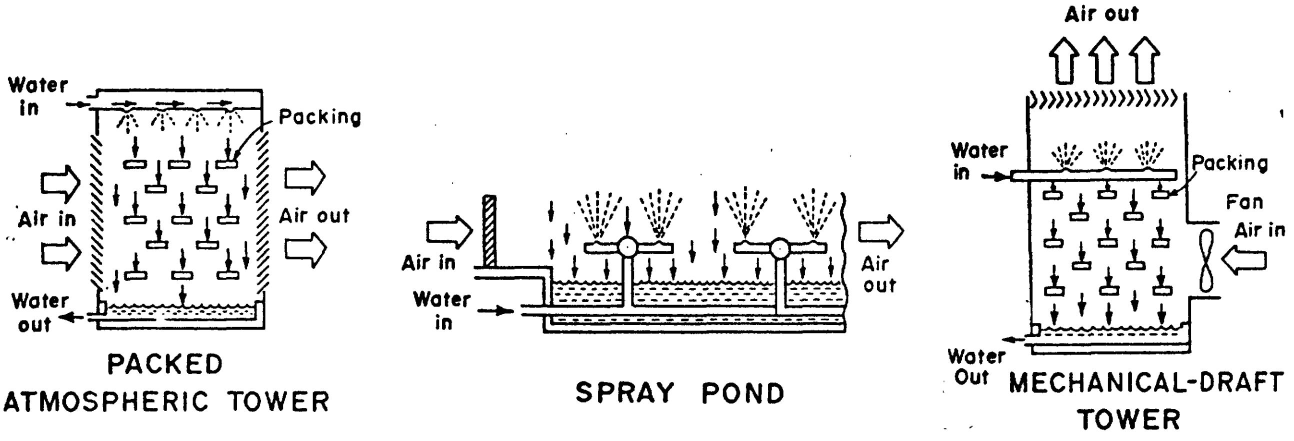
180. From reference (3), page 212.

181. Some of the other problems of radioactive waste, such as eventual disposal of collected materials and the release of radioactivity at refueling and reprocessing of used fuels are discussed in references (209), (210) and (211), or for a very thorough treatment of biological effects of radiation see reference (206) or reference (199), Chapter 11.

3.2 Water Cooling Mechanisms[182]

Considering cooling towers as the panacea for the ecological impacts from nuclear power plants is a quite erroneous, but unfortunately fairly common, concept, especially among those with intense water systems interests.[183]

Most cooling towers are not only immensely large[184] but involve a certain amount of complex equipment which is vulnerable to the elements, see figures 3.2-1 and 3.2-2.[185] This combination



PACKED ATMOSPHERIC TOWER

SPRAY POND

MECHANICAL-DRAFT TOWER

Figure 3.2-1 . Schematics of some water cooling mechanisms[186]

---

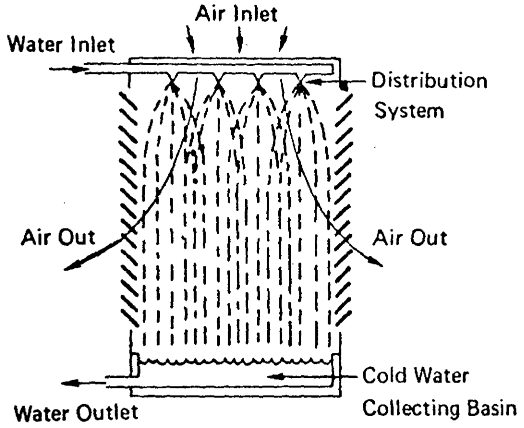
[182] For an extensive overview of this topic consult reference (45), Chapters 12 and 13.

[183] Even if the only consequence of the cooling tower is the release of heat to the atmosphere, the impact of this heat is not inconsequential. Reference (260), page 41 predicts a 5 to 7°F temperature rise in 20 years for the Los Angeles Basin, and temperature can have a significant impact on the incidence of human health problems see ref. (212).

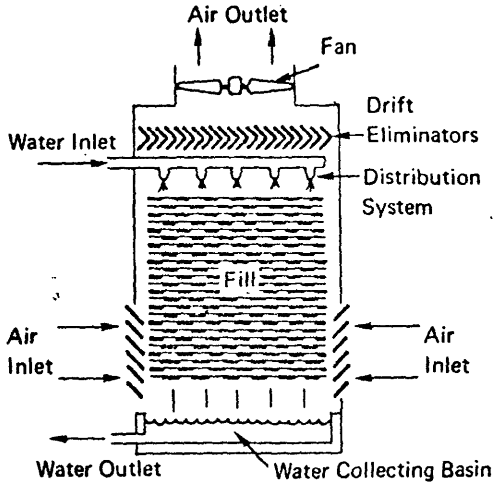
[184] The aesthetic appeal of some of the natural draft hyperbolic cooling towers, 500 feet high and 400 feet in diameter, is also a consideration.

[185] From reference (3), page 118.

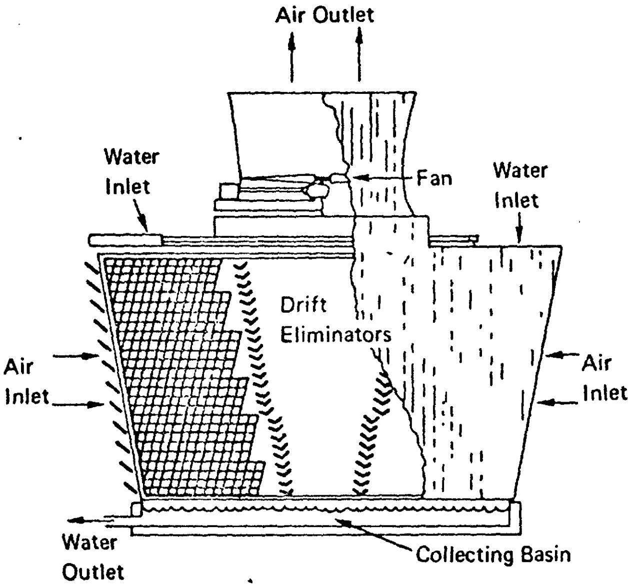
[186] From reference (213), page 45.



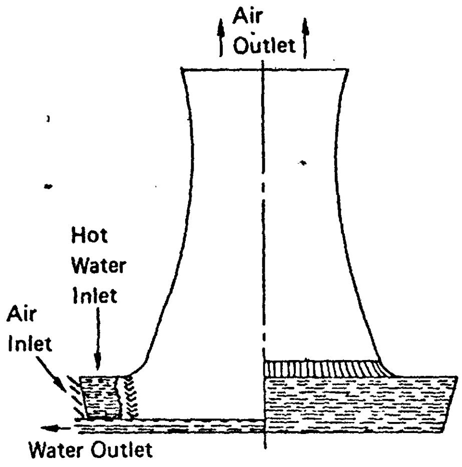
ATMOSPHERIC SPRAY TOWER



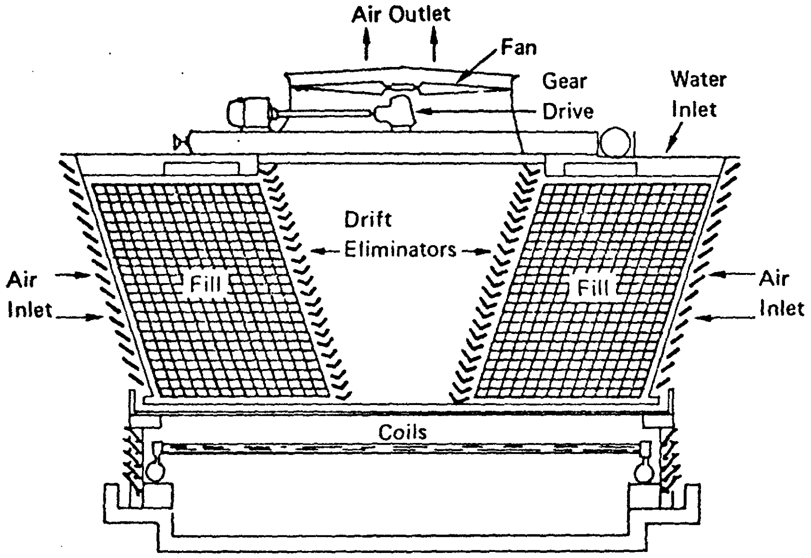
COUNTERFLOW TOWER



CROSSFLOW TOWER



HYPERBOLIC NATURAL DRAFT TOWER



COIL SHED TOWER

Figure 3.2-2 Schematics of different types of cooling towers[185] results in a considerable cost, well over $4.00 per kilowatt, which can be considered to be their primary disadvantage. Although prices will vary significantly for different sites and different plants, the results given in figure 3.2-3 are representative. Some of the factors which can effect these costs are land prices, power plant size, fuel costs, water quality and cost, capital charges, climatic conditions at site, local labor

Type of Cooling System (Fresh Water Systems)	Incremental Capital Cost Associated with Cooling, in $/KW	Incremental Power Costs due to fuel, operating, capital charges, mills/KWhr
Fossil Fuel		
Cooling Pond	2.6	.08
Wet Tower Mech. Draft	5.8	.14
Wet Tower Natural Draft	8.0	.18
Dry Tower Mech. Draft	25.1	.81
Dry Tower Natural Draft	29.3	.99
Nuclear Fuel		
Cooling Pond	3.9	.07
Wet Tower Mech. Draft	6.5	.12
Wet Tower Natural Draft	8.6	.18
Dry Tower Mech. Draft	35.8	.98
Dry Tower Natural Draft	44.0	1.06

Figure 3.2-3 Incremental costs above those of once-through cooling[187]

---

[187] Costs adapted from average of six sources listed in reference (11), page IX-37, additional tables can be found in reference (214), page 415, references (215), (216), (217) and additional information is available in ref. (47).

costs (labor accounting for nearly 40% of the total tower cost.[188]), load factors, etc.[189]

Wet cooling towers and other evaporative cooling mechanisms such as cooling ponds[190] use up a considerable amount of water, as much as one million gallons per hour,[191] which could be a considerable portion of a small stream. The chloride, sodium, sulphate, and other dissolved solids will naturally increase in concentration at each recycling, and may be hazardous when eventually discarded. Oceanside sites have additional problems contending with the hundreds of tons of blowdown salt, and this cannot always be dumped directly into the ocean because some aquatic organisms are particularly sensitive to changes in salinity.

Essentially all organisms in this million gallons per hour of makeup water will be lost, which at some sites could be far more significant ecologically than once-through cooling.

Potential effects to the weather in the vicinity from the large thermal and humid emissions of cooling towers may include:[192]

---

188. See reference (218), page S.11.

189. Another comparative table can be found in (218), p. S-16.

190. A cooling canal, with approximately 168 miles of accumulated length, has been built as one type of cooling 'pond,' see reference (219), but in general not enough land is available for this solution (12,000 acres at Turkey Point in Florida).

191. See reference (220).

192. A further description is in ref. (221) or (218), p. S-24.

1. increased rainfall for a considerable distance downwind

2. clouds most of the time downwind[193]

3. in unstable weather, severe thunderstorms or even tornadoes may be induced

4. fog and ice in the vicinity of the tower[194]

5. increased winds, in fact it has been estimated that a 2000 megawatt nuclear plant with dry cooling towers might induce a 20 mile an hour wind at ¼ mile radius from the tower.[195]

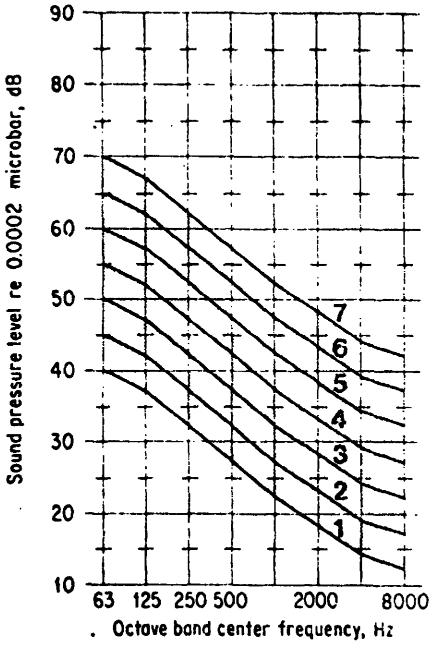
Another cooling tower problem is noise pollution. The concern over noise pollution is further increased due to the high cost of after-the-fact sound attenuation, making it essential to formulate a noise pollution predictor so that these sensitive problems may be avoided in the planning stage. The first step in building a predictor involves the definition of an acceptable noise level for the tower, depending upon existing typical background noises. The curves in figure 3.2-4 on the following page represent the levels of noise for the various areas that might be within earshot of the tower. Obviously, trees, buildings or other obstructions, and wind conditions (directions and speeds), will effect these criteria, and on-the-site measurements should definitely be taken,

---

[193] Models to simulate the extent and shape of plumes from cooling towers for prediction and prevention of possible problems are considered in reference (222).

[194] See references(223) and (224).

[195] A full description of this prediction is contained in reference (225) on page 93.



Condition	Curve no.
Nighttime, rural*	1
Daytime, rural*	2
Nighttime, suburban*	2
Daytime, suburban*	3
Nighttime, urban*	3
Daytime, urban*	4
Nighttime, business area	4
Daytime, business area	5
Nighttime, industrial area	5
Daytime, industrial area	6
Within 300 ft of A	4
Within 300 ft of B	5
Within 300 ft of C	7
300 to 1000 ft from A	3
300 to 1000 ft from B	4
300 to 1000 ft from C	6
1000 to 2000 ft from A	2
1000 to 2000 ft from B	3
1000 to 2000 ft from C	5
2000 to 4000 ft from A	1
2000 to 4000 ft from B	2
2000 to 4000 ft from C	4

No nearby traffic of concern
A = intermittent light traffic
B - continuous light traffic
C - continuous heavy traffic

Figure 3.2-4 Typical outdoor noises measured in sound pressure levels[196]

but these curves do present informative approximate guidelines. The extent to which the noises predicted from the cooling towers rise above these background levels, will be the extent to which the towers will be heard. Sound attenuation possibilities for the towers include, depending upon the severity and frequencies of the problem, "centrifugal fans instead of propeller fans, fans with two-speed motors to cut loads at critical times (if possible), barrier walls, discharge baffles, acoustically-lined plenums,[197] and tower discharge directed away from noise-sensitive neighbors."[196]

---

[196] Reference (218), page S-23.

[197] A plenum is an enclosed space in which the pressure of the air is greater than that of the outside atmosphere.

Cooling towers are not only considerable noise polluters,[198] but they may greatly change the makeup water chemistry[199] and add to the water considerable amounts of fungicides, algicides, chromates (specifically Na_2CrO_4 which may be in concentrations of 200 ppm[200]), and many other chemicals used in fouling and corrosion control.

These and the other air problems are considered in the atmospheric counterpart to this study, reference (212), specifically: chemical discharges to ambient air (affecting odor and chemical properties of air quality), salt discharged from cooling towers (affecting people, plants and property resources), radionuclides discharged to ambient air (both from the points of external contact and ingestion by humans, other animals and plants), fogging and icing (affecting ground, air and water transportation as well as plants), combination of airborne water vapor with SO_2 to form sulfuric acid aerosol, and the ambient noise problems.[201]

It does seem obvious that if a cooling mechanism is available in a system that its schedule of operation must be considered both from economic and ecological grounds.

---

[198] Noise pollution is further discussed in reference (226).

[199] Specifically, CO_2, suspended solids are removed, ammonia converts to nitrate, air is inserted, and generally pH and hardness are changed—see reference (227).

[200] See reference (3), page 127.

[201] Part of this list was orginally given in reference (228).

3.3 Other Consequences

Some of these other operating consequences might include some of the rewards for the beneficial uses of the discharged heat. For example, thermal effluents could be used to help alleviate some of the natural, relatively common, cold spell fish kills such as those which occur in the Gulf of Mexico.[202] Or, for example, coastal plants could pump their effluent miles offshore and release it near the bottom, thus driving nutrients up to the surface, increasing plankton and fish productions. "It is estimated that large scale operations of this upwelling process could have a significant effect on the world fish protein supply."[202] Some other general societal benefits could be in the form of warmed beaches, ice free navigable rivers, etc.

Any beneficial uses which can be translated directly into dollar profits, such as aquaculture, irrigation, radiator heating, etc. must be introduced into the dollar operating costs and not in the beneficial environmental impacts. Working examples of some profitable ventures include pumping effluents through greenhouses,[203] or through irrigation ditches for frost protection or to

---

202. See reference (11), page IX-42.

203. See reference (229) for a description of an operating example.

extend growing seasons.[204] Articles on fish cultivation, including catfish farming, optimum egg temperatures via thermal discharges, and general articles on mariculture, agriculture, and silvaculture (tree farming) are contained in reference (230). These direct dollar costs of plant operation might also include various detrimental effects, such as decreased efficiency of the downstream plants which are forced to use warmer water.

Obviously, it is necessary to make this clear distinction between dollar costs and ecological impacts if any meaningful tradeoffs are to be explored.

---

204. See reference (231) or reference (232) for a working example of these agricultural uses. Reference (233) contains 77 references which deal with this and related issues.

4. Quantification Procedure

From talks with both ecologists and biologists, and from reading the related literature, it is easy to deduce the tremendous respect held for the complexities and uncertainties of nature. To immediately wrap up the entire thermal pollution problem in a computer program and let it turn out a quantity would cause considerable suspicion, and it would probably be very well-founded suspicion. So what must be created is a logical, systematic procedure which does not depart from the real world at any state, thus being verifiable and correctable, and which eventually results in an evaluation of social benefits.

There are numerous benefits from this type of formalization of environmental impacts, in particular the benefits from quantitative impact figures which can be used in the entire power plant operation decision-making process.

> "Formal analysis stimulates insightful thinking about the interactions of various parts of the problem and the interrelationships between the problem and proposed alternatives. It forces an explicit consideration of the entire problem, and this process can be a catalyst for generating new alternatives to be considered, and helps pinpoint where additional information is needed for decision making purposes. This facilitates the gathering, compiling, and organizing of the data in a form useful to the decision maker. In addition, decision analysis can help promote more efficient interaction among group members working on a problem. Discussion can be raised above the level of just mentioning pros and cons of each alternative, and the substantive issues of balancing pros and cons can be attacked."[205]

---

205. Excerpt from reference (234), page 9.

4.1 General Systematic Representation

To approach the problem from a systems analysis point of view means essentially the formulation of the problem as an input-output system, see figure 4.1-1.

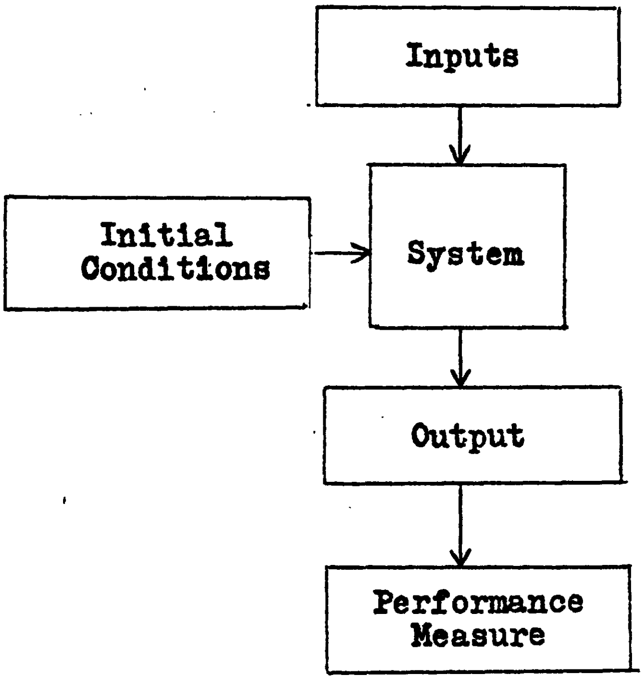


Figure 4.1-1 General approach of systems analytic techniques

Translating into this form the problem of assessing impact to water systems from electric power generation has been hypothesized, see figure 4.1-2.[206] Here the block diagram shows a feedback mechanism[207] resulting from a study of performance measures eventually changing operating procedures. For the purpose of this study consider the somewhat similar block diagram in figure 4.1-3.

---

[206] See reference(134), page 4.

[207] Such a feedback mechanism is in fact inherent in an operating scheme which has been developed specifically for using this impact quantifier, see reference (5).

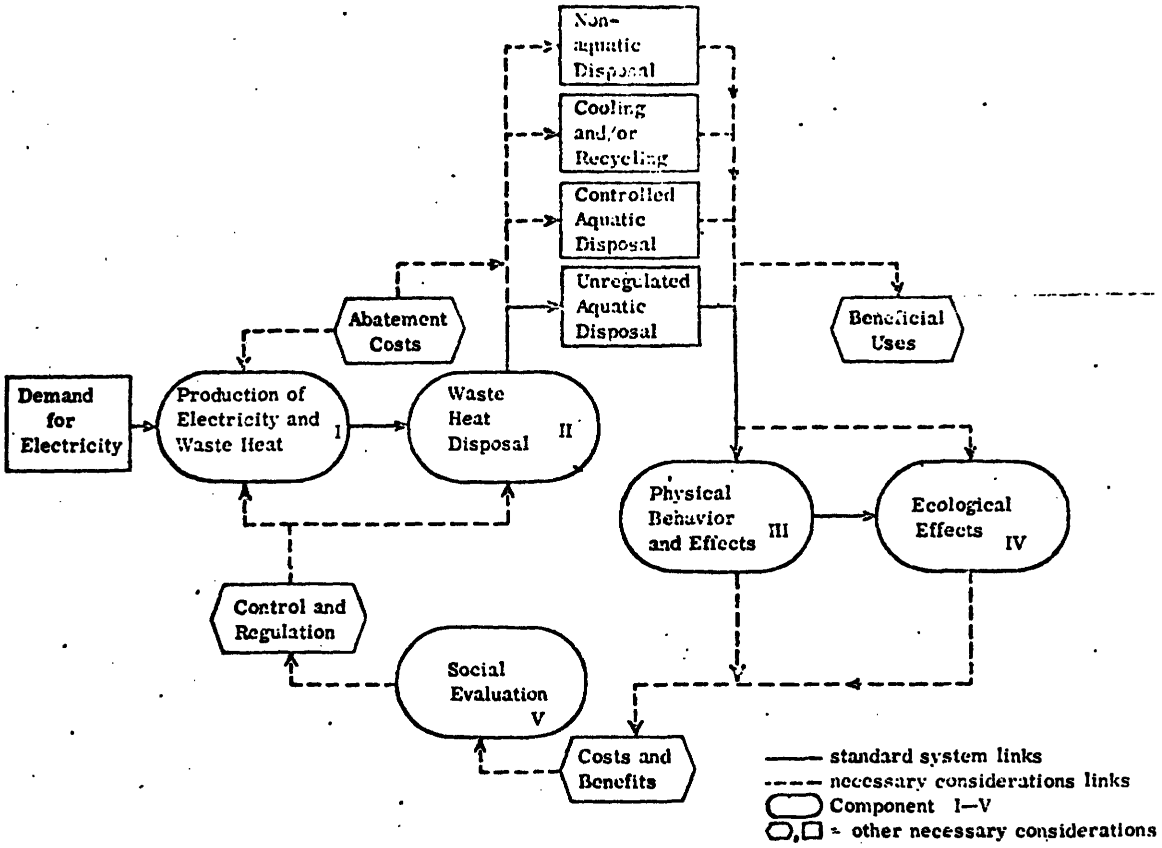


Figure 4.1-2 Hypothesized feedback mechanism for power system evaluation[206]

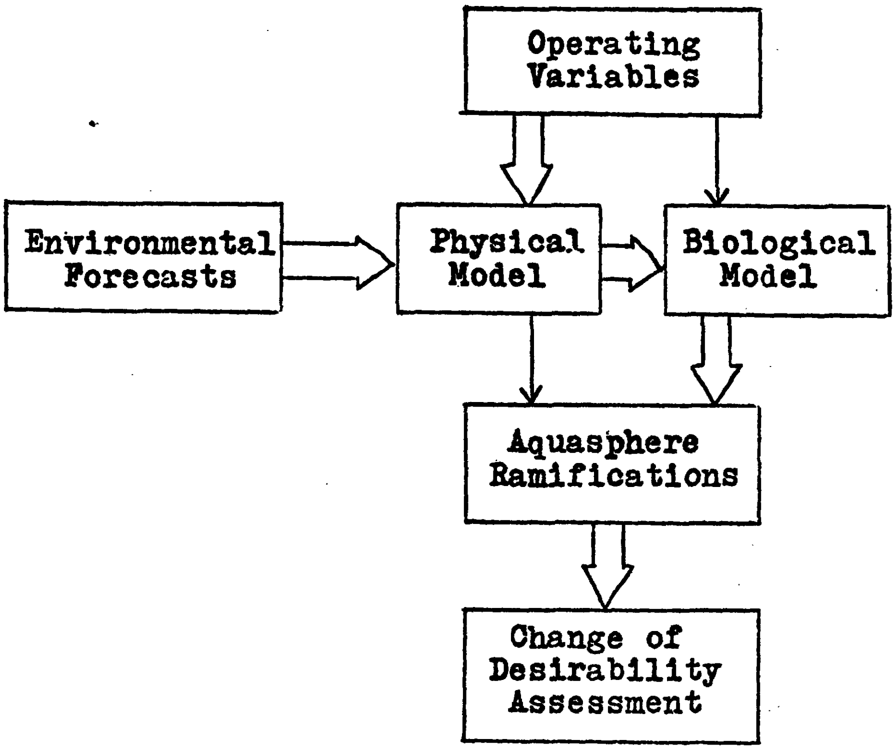


Figure 4.1-3 General systematic representation of aquatic impact

The operating variables in figure 4.1-3 include the time interval selected for study, operation modes such as base loaded or cycling, thermal outputs, and cooling tower or cooling pond operation possibilities. These quantities are input to the physical model. The time interval (to key seasonal variations) and makeup water requirements (i.e. total loss of organisms) go directly to the mortality assessments in the biological model.

Forecasts of environmental factors include river temperatures, river flows, turbulence, stratification, ambient water quality measures and relevant weather information.

The physical model then predicts, as best it can, the probabilistic space-time temperature distributions which might be expected during the interval of concern (an hour or a week) for the different modes of operation as compared with non-operation. Some of these results feed directly into the aquasphere ramifications, e.g. consumption of water (i.e. hydrological budgets), water quality changes, raising or lowering of ground water levels, and the purely physical aesthetic considerations such as heating of beaches, etc.

So as not to become distracted from this quick overview of the solution procedure, the complex biological model will be treated in the next section. It will generate probabilistic loss of population curves for the several critical species of that particular time period.

Assessing aquasphere ramifications amounts to a determination of the disconcerting changes or imbalances of species' populations.

This stage of the formulation converts an essentially dynamic process into something which can be measured in a static way. What must thus be performed is an assessment of the future ramifications inherent in the different modes of operation <u>compared</u> with the non-operation of the facility.[208] It is only in this differential sense that meaningful measures can be gotten. One must essentially know what is in fact desirable so this differential ramification assessment can be quickly performed and well directed toward the next module of the analysis. Basically, a measure of any resultant change in the 'health' of the community must be assessed, this including a general assessment of the critical species' abnormal doses and immunity buildups. Any residual temperature increases must be assessed. Contribution to the long range extirpation of commercially or recreationally valuable species must be assessed in view of the speed with which they might reestablish themselves. And finally, the effects of operating modes on the long range aesthetic values inherent in the ecosystem must be measured, for example, additions or subtractions from eutrophication or putrification processes caused by changes in nutrient budgets.

Calculation of social benefits or relative desirabilities associated with the different operating modes is discussed in section 4.3.

---

[208] As an example see reference(235).

4.2 Physical and Biological Models and Example

The work on a physical model can either follow the lines of predictive techniques described in section 2.1 or, for existing plants, can be collected in a probabilistic manner from experiments using dyes or from several infrared aerial photographic records of water temperatures.

The biological model can be formulated from the various components described in the bulk of chapter 2. The coordination of these predictive models is depicted in figure 4.2-1.

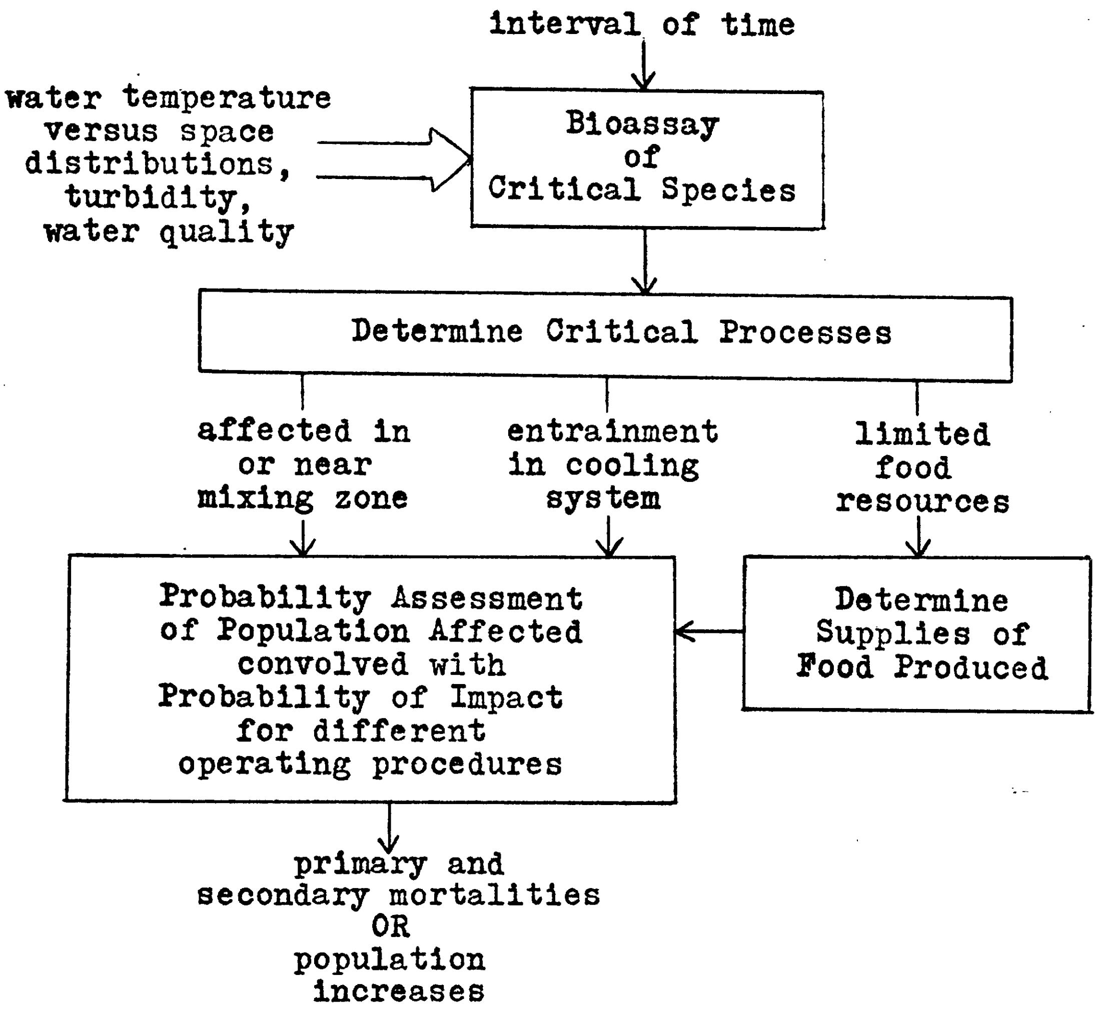


Figure 4.2-1 Block diagram of biological model

The bioassay of critical species is generally available from the licensing formalities required for new power plants. Consider, as an example, the information available concerning critical species' sensitivity to toxins in the water. Licensing forms require the assessment:

> Total chemical effect on aquatic biota should be estimated. Biota in dilution water should be considered in calculations if applicable as well as biota affected by discharge. Supporting documentation should include reference to applicable standards, chemicals discharged, and their lethality for the aquatic populations affected. [209]

For the species which are critically affected by plant operation, and this would include depletion or increases in game fish, large productions or declines in algal populations, etc., there will be specific operation processes causing these changes. These processes might include direct entrainment in cooling systems, effects of being in or around the mixing area, ~~or~~ and limitations of food sources.

With these limiting processes defined, the predictive techniques of chapter 2 can be used to create probabilistic estimates of population depletions or increases.

As an example of this procedure consider the simple case where there is only a single critically affected species at any time of the year, then treatments of two or more species[210] is a trivial extension. Suppose for a hypothetical

---

[209] From Table 3, article 3.2 of reference (228).

[210] Occasionally the figure 10% arises in the literature as a general sampling measurement error for aquatic species, see e.g. reference(20), page 348, and thus this may be a possible level at which a species depleted or increased by this number could be considered to be critically affected.

power plant the affected species are represented in table 4.2-1.

January	possible premature hatching of eggs of species X
February	no species critical
March	food and warmth increasing growth of fish X
April	food and warmth increasing growth of fish X
May	entrainment of fingerlings of fish X
June	algal accumulations
July	algal accumulations
August	entrainment of migrating fish Y
September	no species critical
October	spawning of fish X
November	eggs of fish X colder than optimal
December	eggs of fish X colder than optimal

Table 4.2-1 Example of most significant consequences of operating at various times of the year[211]

Of course, at some times, for example May, the consequences of plant operation might be insignificantly smaller than at other times, say August. That is to say, the magnitudes of benefits or detriments over the year can be expected to change greatly.

To follow this example in table 4.2-1, consider the

---

[211] According to reference (107), reference (236), which the author has been unable to obtain, uses the bioassay to plot the temperature requirements of the various species and their life stages over the course of the year. When these curves are superimposed it becomes clear which are the critical species at each time of the year.

operation of the facility in August[212] when the critical species is fish Y and the critical process is entrainment in the cooling system. From the convolution of the probability of affected population with the probability of impact, the probability of different levels of mortalities of this species can be determined. Because in this example this is the only species affected by plant operation in August then this extent of population loss alone is carried to the assessment of aquasphere ramifications, see figure 4.1-3. Suppose there is no predicted rise in Y's foodstocks and no starving of its predators, then the loss to society of this number of fish Y, perhaps affecting slightly commercial and recreational fishing, is the total environmental impact associated with plant operation in August. This calculation of loss, or benefit, to society is contained in the next section.

Now that the method for connecting together the physical and biological quantifiers has been outlined, examples will be presented of some existing quantifiers which have very specific tasks.

A vast number of studies have been preformed to contribute to the finding of an index of water quality. Although temperature is not usually included in these indices, thermal pollution will definitely affect their values. The indices will change to show the obvious

---

[212] Quantification of impacts over weekly or even hourly discrete time intervals would require essentially the same process. It is all a matter of initially determining the cycles of the ecosystem, even within the course of a day.

thermal effects in water quality, such as decreasing amounts of dissolved gases — but they also show subtle changes, such as increased microbial biochemical reactions (doubling with 10°C increases).

It has long been realized that the water's use must be reflected in the factors influencing its quality index. For example, water acceptable for drinking may not be acceptable for irrigation (too much dissolved copper, for example), and water acceptable for irrigation may have a bad odor or taste and thus would be unacceptable for drinking. Besides being use oriented, these indices must also take on such difficult tasks as reflecting external diseconomics, that is, social costs borne by persons other than the polluters.

As more analysis is concentrated on obtaining measures of water quality, the indices are becoming more complex, e.g. the U.S. Public Health Service in 1946 had only 7 items to be considered in measuring drinkability of water, in 1962 this grew to 21 items, 50 items in 1968, and current revisions promise more.[213]

In 1970, the National Sanitation Foundation collected a panel of 74 experts in water quality, and the WQI (Water Quality Index) was developed. Included in the index are the categories:

---

[213] 213. See reference (237), page 389.

dissolved oxygen
fecal coliforms
pH
5-day BOD
nitrate
phosphate
temperature
turbidity
total solids
toxic elements
pesticides

Threshold requirements were developed for toxic elements and pesticides, otherwise each variable, q_i, contributed to the WQI via a weighting factor, w_i, as in the equation:

$$WQI = \sum_{i=1}^{9} w_i q_i \qquad 42\text{-}1$$

where the q_i are chosen on the basis of the quality curves developed by the experts, see figure 4.2-2.

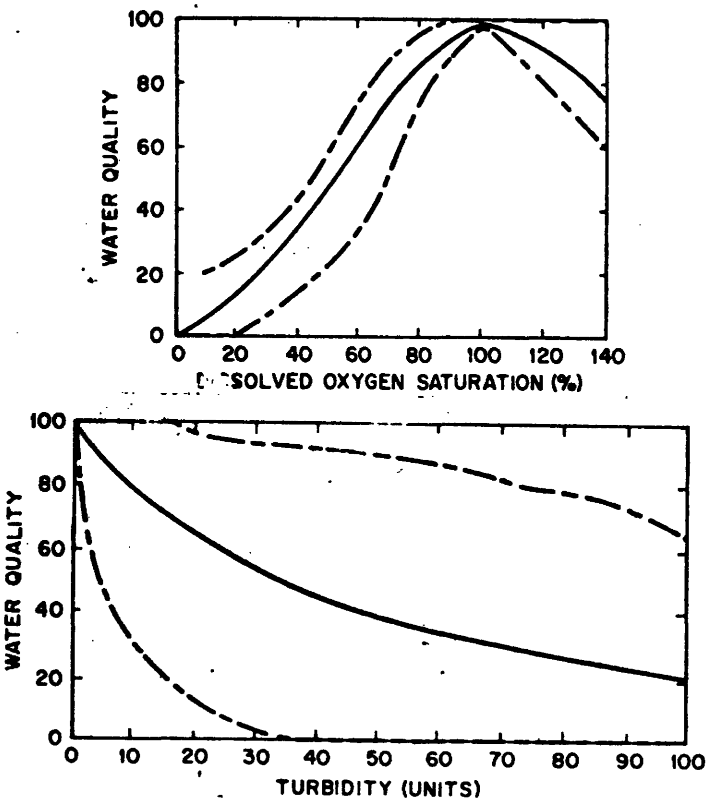


Figure 4.2-2 Mean qualities and 80% confidence limits from panel of experts on two water quality parameters[214]

---

[214] From (238), page 176.

Of course, of specific importance to this study is the curve developed for the rating of temperature, see figure 4.2-3.

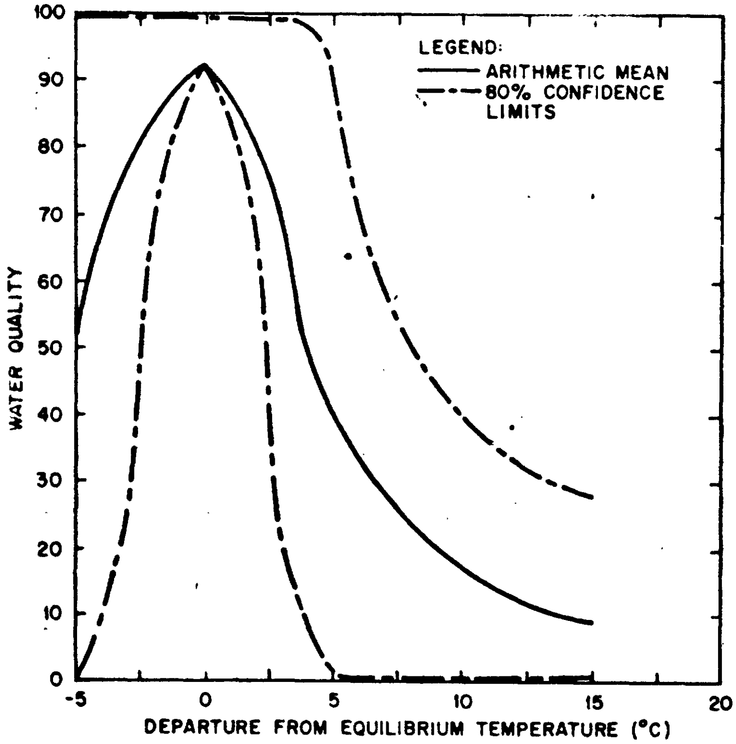


Figure 4.2-3 Mean and 80% confidence limits for the value of the temperature parameter in the water quality index[215]

Further work has been done on the field evaluations of these parameter values, and on the development of specific use oriented water quality indices, parameters of which are shown on the following page in Table 4.2-2.

The temperature curve of figure 4.2-3 is really just a crude method of incorporating within the WQI a measure of the effect to the biological community of thermal increases. There are, however, measures specifically

---

215. Reference (238), page 180.

Fish and Wildlife Water Quality Index	Public Water Supply Water Quality Index
Dissolved oxygen	Dissolved oxygen
Nitrate	Nitrate
Turbidity	Turbidity
pH	pH
Temperature	Fluoride
Phosphate	Hardness
Ammonia	Fecal coliforms
Phenols	Phenols
Dissolved solids	Dissolved solids
	Chloride
	Alkalinity
	Color
	Sulfate

Table 4.2-2 Index parameters used for determining water quality for two specific water uses[216]

designed for calculating the 'health' of these perturbed aquasystems. Most of these measures are glorifications of the species diversity measures described in section 2.2. Perhaps the most accurate of these species diversity measures gives not only a measure of compositional richness

$$\bar{d} = -\sum (n_i/n) \log_2(n_i/n) \tag{42-2}$$

but also a measure of the dominance of one or more species

$$r = \frac{\bar{d}_{max} - \bar{d}}{\bar{d}_{max} - \bar{d}_{min}} \tag{42-3}$$

where

$$\bar{d}_{max} = (1/n)\left[\log_2 n! - s \log_2(n/s)!\right] \tag{42-4}$$

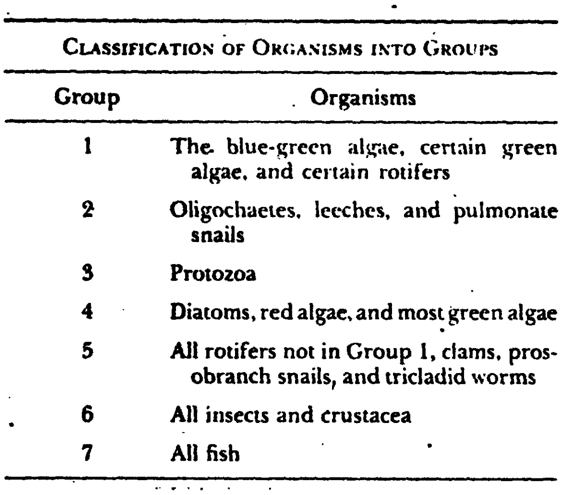
$$\bar{d}_{min} = (1/n)\left\{\log_2 n! - \log_2 [n-(s-1)]\,!\right\} \tag{42-5}$$

---

[216] Reference (238), page 179.

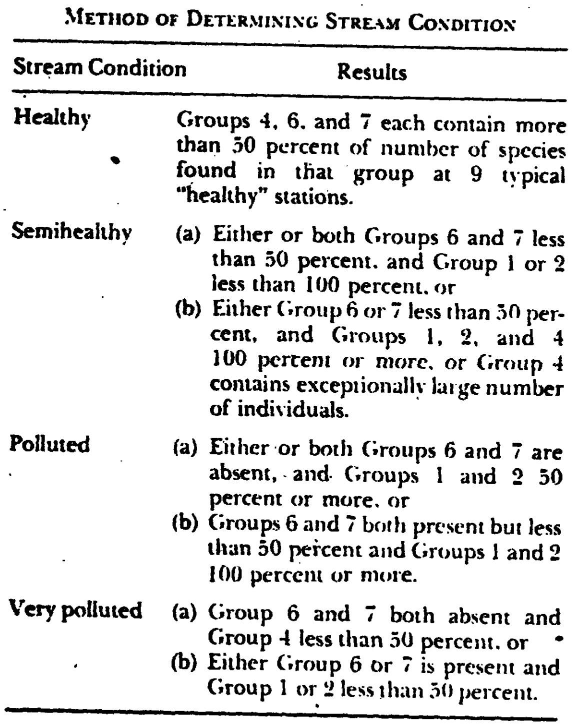
and n is the total number of individuals collected of the s different species, n_i the number of the i^{th} species.[217]

A biological index which does not rely solely on such a species diversity measure is presented in figure 4.2-4.



CLASSIFICATION OF ORGANISMS INTO GROUPS

Group	Organisms
1	The blue-green algae, certain green algae, and certain rotifers
2	Oligochaetes, leeches, and pulmonate snails
3	Protozoa
4	Diatoms, red algae, and most green algae
5	All rotifers not in Group 1, clams, prosobranch snails, and tricladid worms
6	All insects and crustacea
7	All fish



METHOD OF DETERMINING STREAM CONDITION

Stream Condition	Results
Healthy	Groups 4, 6, and 7 each contain more than 50 percent of number of species found in that group at 9 typical "healthy" stations.
Semihealthy	(a) Either or both Groups 6 and 7 less than 50 percent, and Group 1 or 2 less than 100 percent, or (b) Either Group 6 or 7 less than 50 percent, and Groups 1, 2, and 4 100 percent or more, or Group 4 contains exceptionally large number of individuals.
Polluted	(a) Either or both Groups 6 and 7 are absent, and Groups 1 and 2 50 percent or more, or (b) Groups 6 and 7 both present but less than 50 percent and Groups 1 and 2 100 percent or more.
Very polluted	(a) Group 6 and 7 both absent and Group 4 less than 50 percent, or (b) Either Group 6 or 7 is present and Group 1 or 2 less than 50 percent.

Figure 4.2-4 Biological measure of stream conditions[218]

Examples of each of the four possible stream conditions are given on the following page in figure 4.2-5

There are some obvious problems with the criteria developed in this model, e.g. there can be no absolute cutoffs between conditions. Also, a problem which is not immediately apparent, but is still a quite serious drawback, is the duplication of classifications for certain

---

[217] See reference (239), page 478.

[218] From reference (240), originally in reference (241).

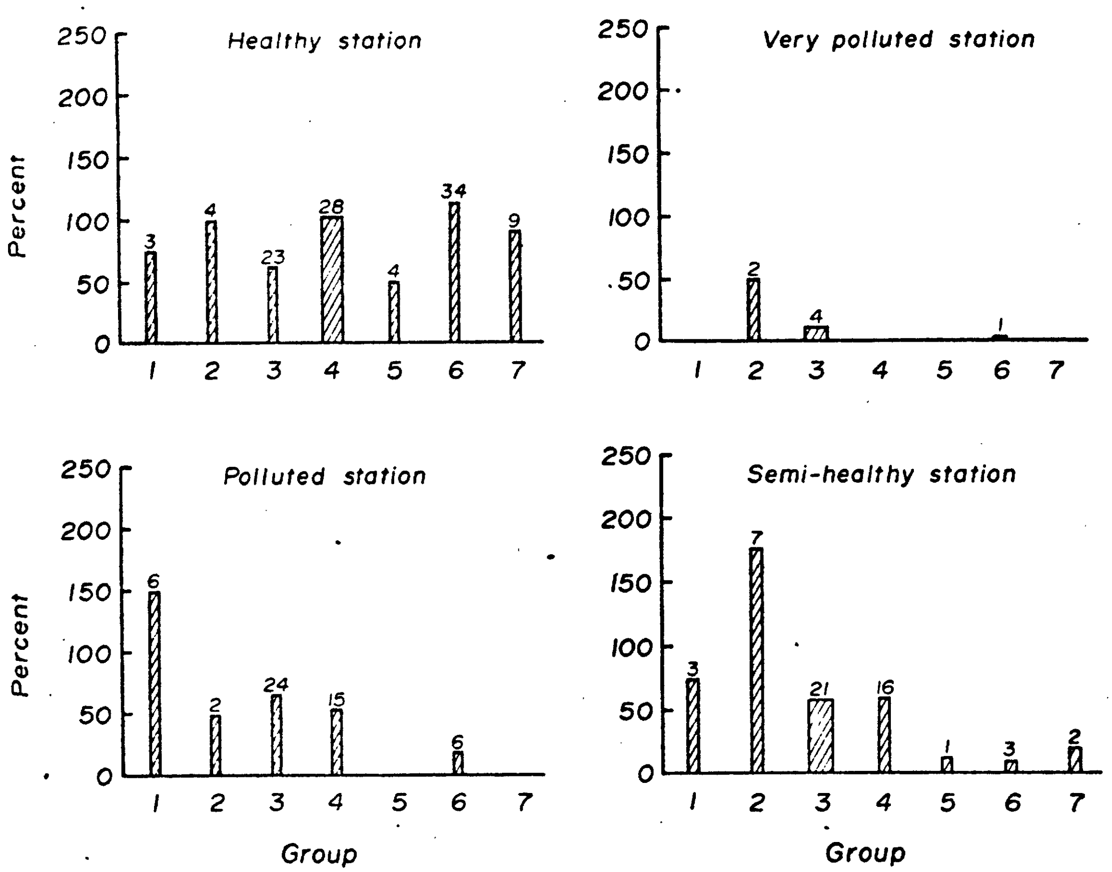


Figure 4.2-5 Examples of different stream conditions and their classifications according to the "biological measure of stream conditions"[218]

situations. Consider, for example, a station with percentages of $x_1 = 40\%$, $x_2 = 40\%$, $x_4 = 60\%$, $x_6 = 60\%$ and $x_7 = 60\%$. This station would be classified as 'healthy,' since x_4, x_6 and x_7 are over 60%, but also 'very polluted' in that at least one of x_6 and x_7 is nonzero and x_1 or x_2 is less than 50%.

To alleviate these problems[219] a plot was made of the four different conditions in the space of the percentages

---

[219] It is also possible rather than a 1.0 rating for a species being found or not, to rate the species say somewhere between -1 and 1 depending on its prevalence and desirability.

present of the different species classifications. After shaping these plots to make them internally consistent, and smoothing the boundaries, an equation for the health, H, of the community was fitted to the plots. With x_4 as the percentage of class 4 present, and with x_1, x_2, x_6 and x_7 representing the percentages of their classes, define

$$A = [3/4 \min(x_1,x_2) + 1/4 \operatorname{ave}(x_1,x_2)] \tag{42-6}$$

$$B = [3/4 \min(x_6,x_7) + 1/4 \operatorname{ave}(x_6,x_7)] \tag{42-7}$$

then the health, H, of the community is

$$\log_{10}^{-1} H = 10^{-6}(A-50)(|A-50|)(x_4+20)^2(B) + 2 \tag{42-8}$$

The scale for converting H into health labels is 0 = very polluted, 1 = polluted, 2 = semi-healthy, and 3 = healthy. The use of this equation on the four examples presented in figure 4.2-5, rates the healthy station as 3.188, semi-healthy as 2.277, polluted as 1.299 and very polluted as 0.159.

Although this equation 42-8 may be useful, its primary purpose is to demonstrate that complex pieces of biological understanding can be transformed into meaningful, highly usable tools.

This perhaps is a good place to include an illustrative example of the quantification procedure. Any resemblance of this example to a real situation is coincidental, and in cases where indicative historical data was not available, best guesses were used (as must be the procedure in any quantification of impacts).

This example deals with a large 1000 megawatt nuclear power plant on a typical[220] northwestern U.S. river. The river width is 600 feet, depth 20 feet, velocity 1 foot per second, and the total flow rate about 11,000 cubic feet per second.

Power plants generally use 0.8 to 1.5 cubic feet of water per second for each megawatt of generating capacity, and since this is a nuclear facility the 1.5 figure is used. Thus, the condenser cooling flow is 1500 cubic feet per second. The temperature differential across the condenser is assumed to be 15°F. Using a suggested[221] formula, the downstream length to a 5°F differential is 5800 feet.

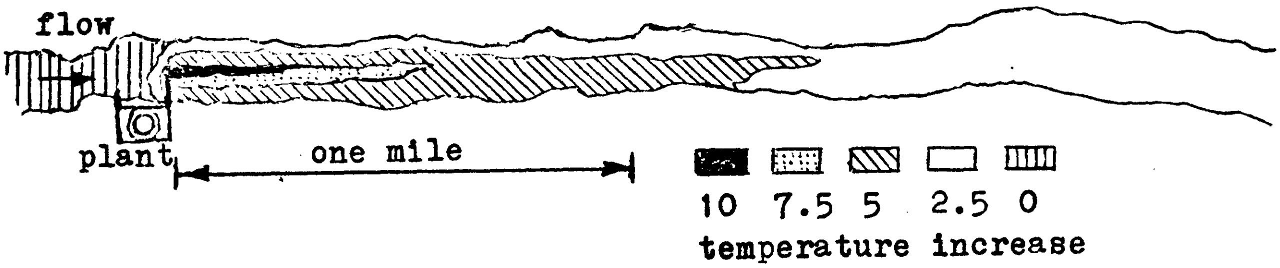


Figure 4.2-6 River isotherms downstream from the power plant (example)

The temperature history of the cooling water, and thus the temperatures experienced by entrained organisms is recorded in figure 4.2-7, where temperature history out of the cooling system is measured down the centerline of the plume.

---

[220] Data for this typical stream is from reference (242).

[221] From reference (243) suggested in reference (242).

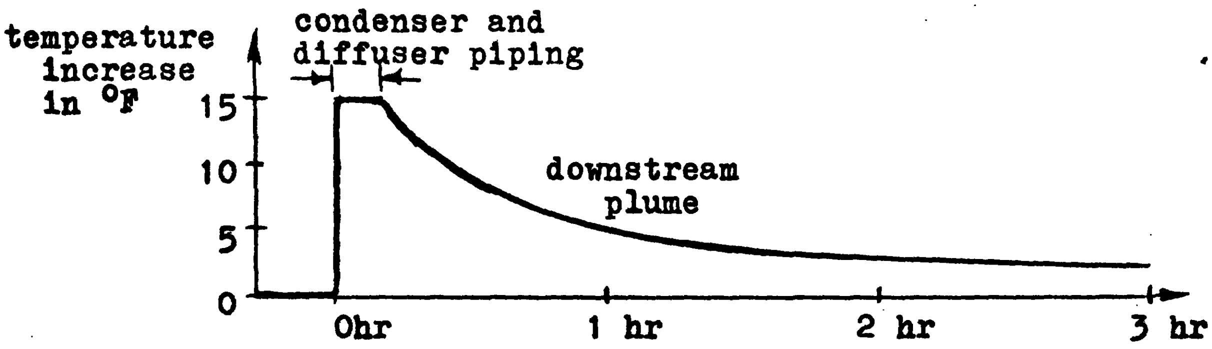


Figure 4.2-7 Time course of temperature changes of cooling water (example)

The discharge mechanism is on the surface of the stream, and thus there is no appreciable change in the bottom temperature (see figure 2.1-7). So, this eliminates the effects on benthic organisms, rooted aquatic plants, incubating fish eggs and reproductive temperature requirements.

The ambient river temperature is given in figure 4.2-8, along with the plot of the maximum temperature

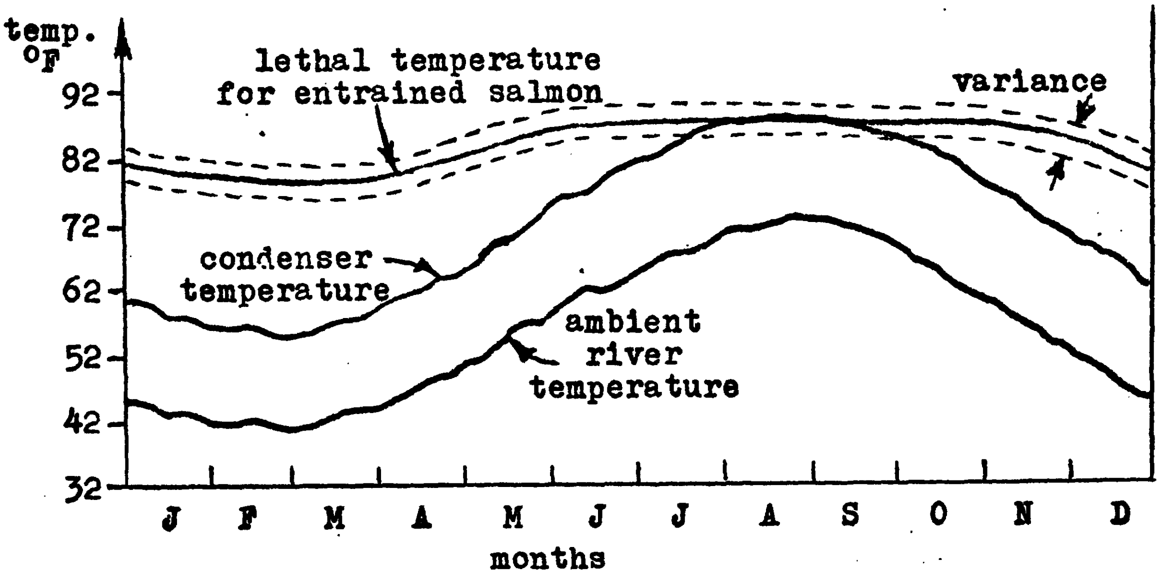


Figure 4.2-8 River temperature, condenser water temperature, and lethal temperature of juvenile salmon (example)[222]

---

[222] For an example of the computation of the variances given here consult the computation in ref. (107) page 19.

of the entrained water, and the lethal temperatures for the most sensitive of the species in the area, with the variances computed.

Now to the computation of the actual thermal deaths. There are assumed to be no other species in the area having lethal temperatures as low as the salmon's, or within 5°F of the salmon, so all other species are assumed to be out of reach of the lethal temperature effects. There will not be any salmon deaths due to swimming through the mixing zone because these temperatures will never reach lethal levels. For those salmon entrained in the intake water, the probability of mortalities can now be computed from the mean and variances of the lethal temperatures in figure 4.2-8. Thus from figure 4.2-8 these probabilities become:

week	percentage	week	percentage
26	2%	34	45%
27	5%	35	40%
28	15%	36	35%
29	34%	37	38%
30	50%	38	30%
31	50%	39	20%
32	52%	40	15%
33	55%	41	2%

Figure 4.2-9 Probability entrained salmon will be killed (example)

The only salmon which will pass through the intake screen are juveniles, and the distribution of these in the area of the power plant is shown in figure 4.2-10 on the following page.

The multiplication of the curves in 4.2-9 and 4.2-10 together week by week, and then multiplying each of these

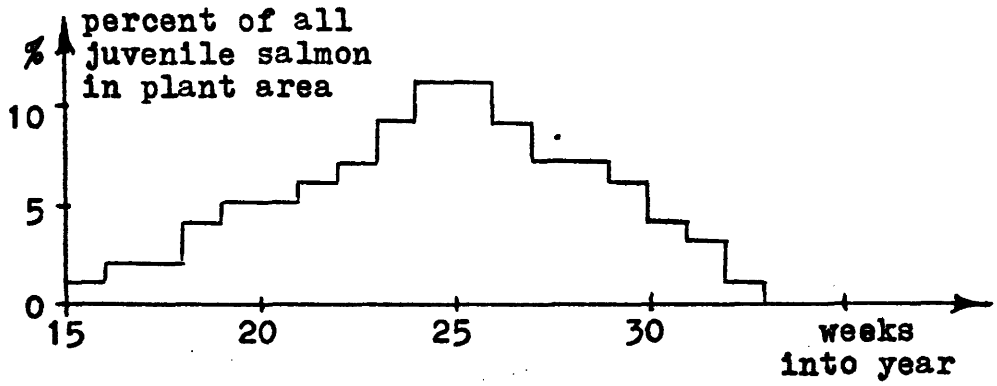


Figure 4.2-10 Percent of total yearly juvenile population in the area of the power plant(example)

figures by 13.6% which is the probability of being in the intake water[223] yields figure 4.2-11.

week	26	27	28	29	30	31	32
percentage	.024%	.048%	.143%	.277%	.272%	.204%	.071%

Figure 4.2-11 Percentage of the generation of juvenile salmon population lost by direct thermal deaths caused by plant operation in given weeks(example)

There are no cold shock deaths, because (see figure 2.3-5) even if the fish were acclimated to the minimum entrainment temperature (55°F) the shock back to the ambient water temperature (40°F) would not kill any.

Assuming salmon will avoid 75°F temperatures in their upstream migration, and since there is always a 2.5°F increased temperature path available (see figure 4.2-6) plus the maximum 72°F ambient river temperature, the salmon migration will not be thermally blocked.

---

[223] This is a straight 1,500/11,000 calculation and excludes effects such as (1) fish, for some reason, spending more time near the intake, or more likely (2) fish avoiding the intake with the same pressure sensors that help fish avoid the suctions of waterfalls.

The indirect effects will now be considered. Again limiting the treatment in this example to salmon — indirectly salmon would be affected by changes in populations of their major food source, zooplankton. Since salmon generally fast going upstream and feed when they are juveniles coming downstream, we are again concerned only with the juvenile salmon. Although figure 2.5-1 shows a loss of a good deal of zooplankton in the vicinity of the thermal outlet, these temperatures are much higher than those contended with in this example. Figure 2.5-3 shows that zooplankton in the temperature range of this example can be expected to more than double in number with a 15°F temperature increase.

This 15°F increase will be realized in full by only the entrained zooplankton, and here it is assumed that 10% of all entrained zooplankton are lost due to mechanical destruction from pressure changes which take place. Using an overall average of 2°F increase over the 15 miles downstream from the outflow this would mean an approximate increase by 20% of the zooplankton concentrations for that 15 miles. This 20% increase is plotted against that of the ambient river concentrations in figure 4.2-12 on the following page.

Using the graph in figure 2.3-16 of the growth rates as a function of food availability and temperatures, and using the seasonal temperature graph of the river

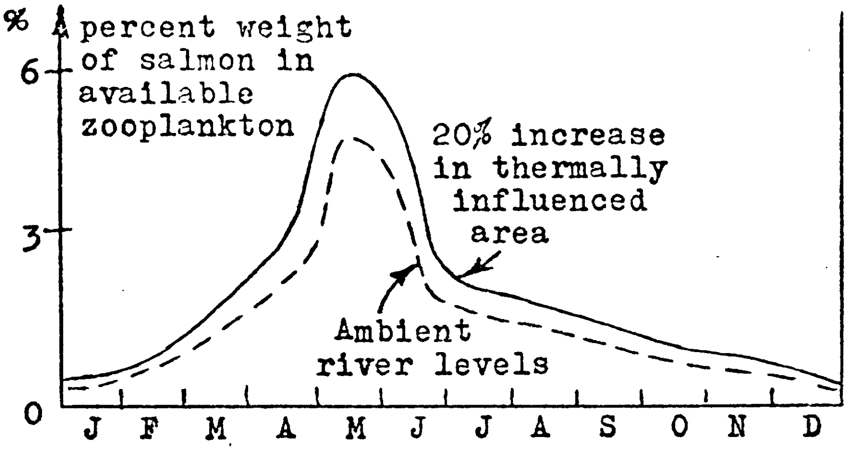


Figure 4.2-12 Seasonal variations in zooplankton availabilties to salmon in the river with and without the influence of the thermal effluent(example)

(plus the 2°F in the influenced area) yields figure 4.2-13 which shows the increase in weight of the influenced salmon at the different times of the year (using a one day travelling time through the 15 mile influenced area).

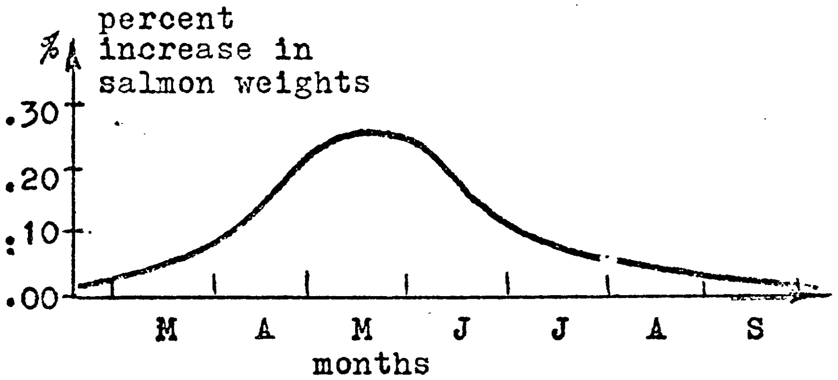


Figure 4.2-13 Percent increase of individual salmon weights due to increased food availability because of plant operation(example)

Multiplying this increase by the percent of the total juvenile salmon population in the area during these weeks yields the total increase in weight of the entire generation of juvenile salmon. This data is thus summarized

Week	Percent of entire salmon population lost by thermal shock if plant operates	Percent gain in weight of entire salmon population if plant operates
15	.000	.001
16	.000	.002
17	.000	.004
18	.000	.005
19	.000	.008
20	.000	.012
21	.000	.014
22	.000	.016
23	.000	.020
24	.000	.021
25	.000	.020
26	.024	.018
27	.048	.011
28	.143	.008
29	.277	.005
30	.272	.003
31	.204	.002
32	.071	.001

Table 4.2-3 Summary of all consequences of plant operation at various weeks in the year(example)

in table 4.2-3 which shows the total exact ecological implication associated with operating the power plant in these weeks. Thus for this example on a purely ecological basis, using the total weight of the salmon population as one possible indicator of desirability, it would be best to perform the five weeks of annual plant nuclear refueling and maintenance, starting in week 28. Of course, total weight may not be a good way of combining these two different consequences, in fact, they may be best kept as separate dimensions in a multi-dimensional environmental impact vector. A discussion of the collection and handling of these changes in the aquasystem so they will reflect proper measures of desirability is discussed next.

4.3 Measure of Desirability

Once the ramifications to the aquasystem have been computed, it is necessary to make an assessment of the relative desirabilities of these possible consequences. For example, if the operation of a proposed power plant would increase fish production, but would also induce foul smelling algal mats every July and August, then it is not clear whether the overall environmental effect would be positive or negative. A study must then be made of the relative importance of the fortunes and burdens that these changes would impose on the users of the water, e.g. municipal and industrial water suppliers, recreational users, commercial fishing, and aesthetic consequences.

Ideally, one would like to be able to set down one single measure of environmental impact, such as an "ecological impact unit."[224] And to enhance the usefulness of this e.i.u. it would be convenient to set its value at approximately that ecological impact that 'man' would be willing to pay $1.00 to avert, so a direct cost-benefits analysis could be made. Unfortunately there is no clear-cut way of obtaining this e.i.u. measure.[225] Even if one were able to put up

---

[224] "Ecological" is used rather than "environmental" because it is precisely the effect upon the living community, in particular man, which is of interest, not the effect on the surroundings, i.e. environs. The term "impact" is used instead of "quality" to emphasize the fact that this is a measure of <u>differences</u> in quality, not a measure of quality itself.

[225] For a verbal discussion see reference (244).

such a proposal for the voters to decide exactly how much they would pay to avert a problem, the results of such an election, it is generally acknowledged, would be relatively worthless, for a number of reasons:

> (1) the average man does not have the proper knowledge to make present, or predict future, quality judgements on such an intricate complex issue as the balance of an ecosystem,
>
> (2) he has no realization of the health or financial implications to himself of the problems which might face minorities such as water suppliers or commercial fishermen,

and there are a multitude of largely <u>unconscious</u> reasons theorized[226] to explain man's apathy toward the environmental crisis, some are:

> (3) the fact that pollution is usually relatively undetectable immediately around, but can clearly be seen over distant cities or in unused waterways, and thus it becomes a force against 'them,' unconsciously including rivals,
>
> (4) the unconscious feeling that we individually can not possibly make changes in a worldwide problem, and thus we will selfishly let others make the sacrifices,
>
> (5) the unconscious desire to ensure that in our eventual dying we will have little or nothing to lose,
>
> and (6) the unconscious defiant refusal to give up those ecologically offensive components making up our high standard of living, e.g. colored (and thus not biodegradable) paper products or our cherished automobile.

---

[226] For those familiar with psychoanalytic terminology these unconscious 'reasons' fall into the catagory of ego defenses against anxieties, at the paranoid, depressive and Oedipal developmental levels. For a more thorough discussion of this topic refer to the source for much of this material reference (245).

So, since the problem of assessing the desirability of ecological changes can apparently not be left safely to a public referendum, where then can the solution be found? The hope for the best possible solution undoubtedly lies in being able to present all of the consequences and ramifications as <u>lucidly</u> as possible to policy makers, planners and concerned citizens, so that they can conduct meaningful discussions among themselves of the tradeoffs available among the alternatives. In the following text are some of the existing tools useful for simplifying and making understandable this complex environmental information for presentation to a panel or forum containing people of diverse interests and fields of knowledge.

Initially it should be made quite clear that there are other problems besides thermal pollution which will contribute to the aquatic impact resulting from power plant operation: Depleted stream levels due to water losses, raising or lowering ground water levels, effects of chemical discharges on people and the recreational usability of the waterbody, chemical and radionuclide contamination of ground water, radionuclide discharge to the water body, and effects on flood and erosion control. These are effects which have been carefully studied and quantified in licensing formalities.[227]

Some methods for sorting, interpreting and quantifying these impacts resulting both from thermal pollution and the

---

[227] See reference (228), pages 9-10.

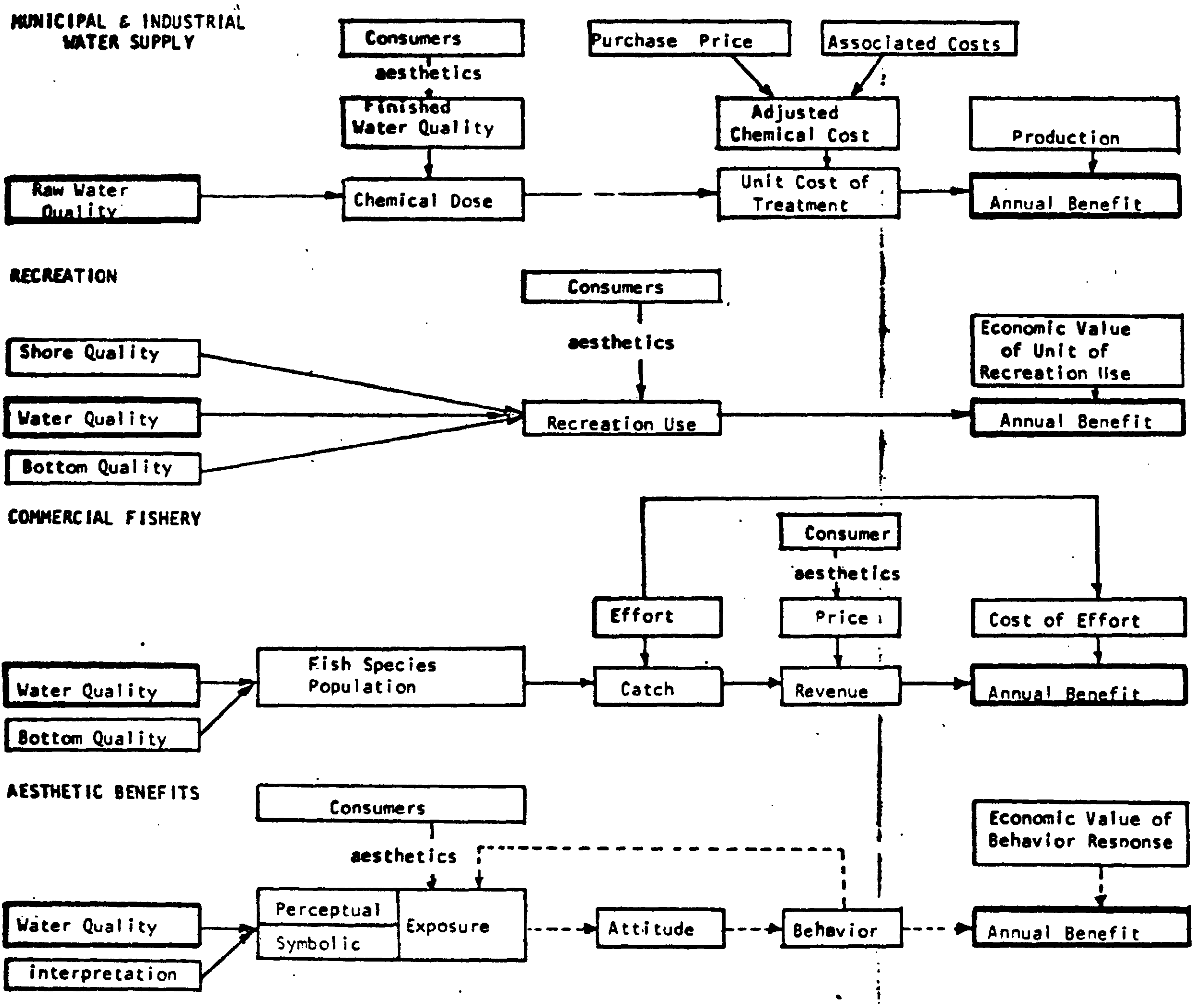


Figure 4.3-1 Diagrams for benefit evaluation of quality (or impacts) of aquatic systems[228]

secondary problems have been formulated, see figure 4.3-1. This is thus a method for quantifying the losses and gains which accrue from changes in numbers and varieties of aquatic organisms and such other hydrologic factors as are deemed environmental, rather than dollar operating cost, factors.

As an example of the calculation of impact consequences consider the ramifications to municipal and industrial water supplies, which must include; water losses induced, water

---

228. See reference (246), page 845.

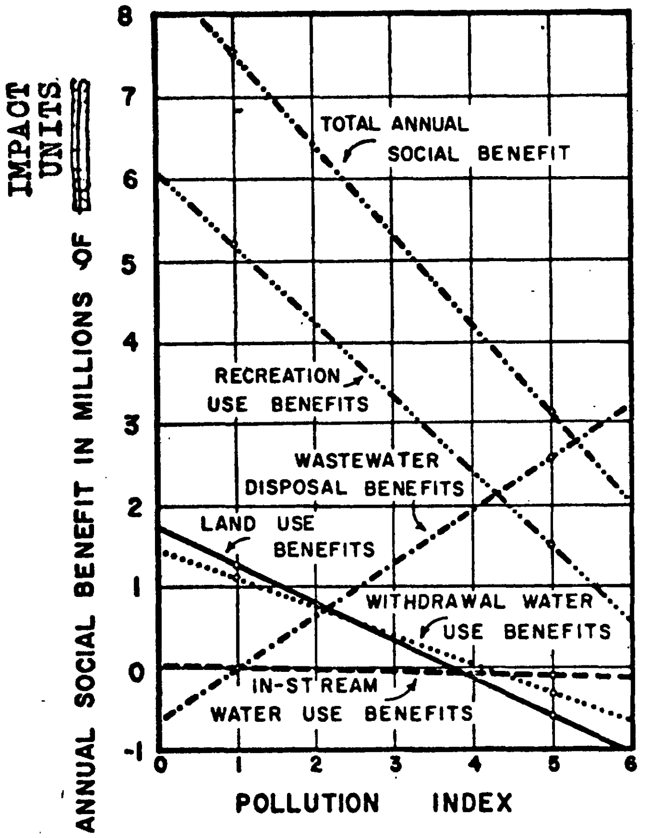


Figure 4.3-2 Graphing the impact benefits versus different pollutant levels, that is, extents of operation[229]

table changes and water made more or less usable by chemical additions, or especially through accelerated eutrophication. Methodologies for the calculations of these and the other impacts diagrammed in figure 4.3-1 are the subject of reference (246).

The collections of all these computations and value judgements can then be made in graphic form as presented in figure 4.3-2. Extent of plant operation would be the parameter that would be associated with the pollution index.

---

229. From reference (247), page 671. There would be no reason why such a display must be restricted to cover an annual time interval, or why it couldn't display nonlinear curves of water quality, salmon lost, algal mats, etc.

This graph should also include the commercial and aesthetic benefits. The concept of such a graph is, however, meaningful although it could hardly be hoped that such curves would be linear.[230]

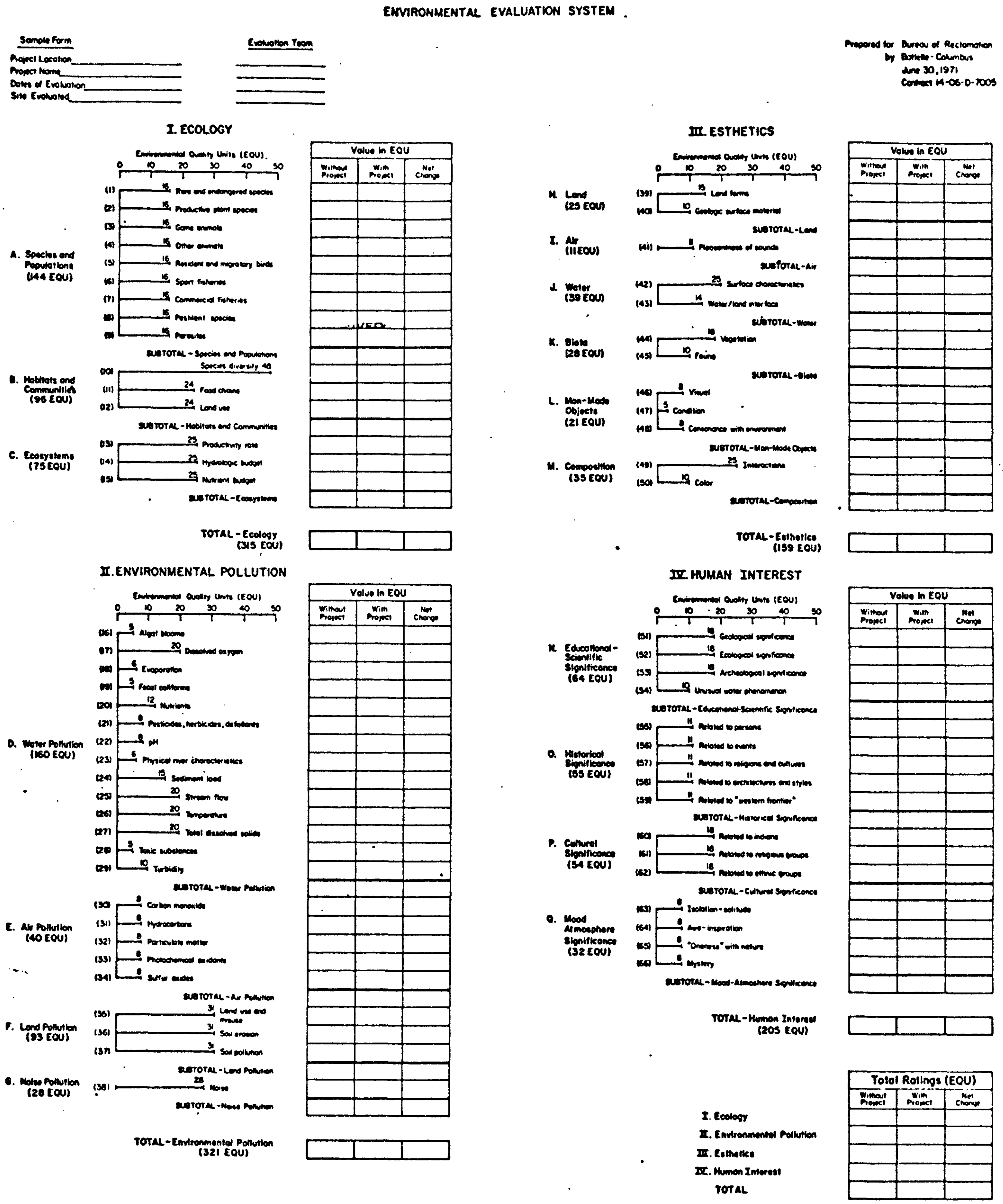
This presented technique appears to be the most appropriate method for use in quantifying desirability of different ecological impacts.[231] Another scheme exists, see figure 4.3-3, and is well known but is not adaptable for the meaningful quantification of operation associated differential impacts. It is, however, a very useful method for "flagging" certain deficiencies while in the planning stage. As an example of this method's inability to measure operating impacts note that it would be considered beneficial to operate a system which covered the lake with algal blooms, -5, and filled the water with toxic substances, -5, but made up for these by filling the lake with productive plant species, +16.

These existing models are relatively naïve in that they perform only additive combinations of various factors. The need for more sophisticated models is great, and thus

---

230. A practical method for evaluating recreational benefits has been developed and is receiving wide usage, reference (248).

231. Other possibilities of some slightly different approaches can be found in references (249) and (250); reference (251) is a review of the use in this field of the latest evaluative tools. Another example of such a 'dollar versus environmental quality' graph can be found in reference (252), and another, more general evaluative effort is described reference (253), but the method can unfortunately only be used for spotting different possible impacts.



ENVIRONMENTAL EVALUATION SYSTEM

Sample Form
Project Location________
Project Name________
Dates of Evaluation________
Site Evaluated________

Evaluation Team
____
____
____
____

Prepared for Bureau of Reclamation
by Battelle - Columbus
June 30, 1971
Contract 14-06-0-7005

I. ECOLOGY

Environmental Quality Units (EQU) 0 10 20 30 40 50

				Value in EQU		
				Without Project	With Project	Net Change
A. Species and Populations (144 EQU)	(1)	16	Rare and endangered species			
	(2)	16	Productive plant species			
	(3)	16	Game animals			
	(4)	16	Other animals			
	(5)	16	Resident and migratory birds			
	(6)	16	Sport fisheries			
	(7)	16	Commercial fisheries			
	(8)	16	Pestilent species			
	(9)	16	Parasites			
			SUBTOTAL - Species and Populations			
B. Habitats and Communities (96 EQU)	(10)	48	Species diversity			
	(11)	24	Food chains			
	(12)	24	Land use			
			SUBTOTAL - Habitats and Communities			
C. Ecosystems (75 EQU)	(13)	25	Productivity rate			
	(14)	25	Hydrologic budget			
	(15)	25	Nutrient budget			
			SUBTOTAL - Ecosystems			
			TOTAL - Ecology (315 EQU)			

II. ENVIRONMENTAL POLLUTION

Environmental Quality Units (EQU) 0 10 20 30 40 50

				Value in EQU		
				Without Project	With Project	Net Change
D. Water Pollution (160 EQU)	(16)	5	Algal blooms			
	(17)	20	Dissolved oxygen			
	(18)	6	Evaporation			
	(19)	5	Fecal coliforms			
	(20)	12	Nutrients			
	(21)	8	Pesticides, herbicides, defoliants			
	(22)	8	pH			
	(23)	6	Physical river characteristics			
	(24)	15	Sediment load			
	(25)	20	Stream flow			
	(26)	20	Temperature			
	(27)	20	Total dissolved solids			
	(28)	5	Toxic substances			
	(29)	10	Turbidity			
			SUBTOTAL - Water Pollution			
E. Air Pollution (40 EQU)	(30)	8	Carbon monoxide			
	(31)	8	Hydrocarbons			
	(32)	8	Particulate matter			
	(33)	8	Photochemical oxidants			
	(34)	8	Sulfur oxides			
			SUBTOTAL - Air Pollution			
F. Land Pollution (93 EQU)	(36)	31	Land use and misuse			
	(36)	31	Soil erosion			
	(37)	31	Soil pollution			
			SUBTOTAL - Land Pollution			
G. Noise Pollution (28 EQU)	(38)	28	Noise			
			SUBTOTAL - Noise Pollution			
			TOTAL - Environmental Pollution (321 EQU)			

III. ESTHETICS

Environmental Quality Units (EQU) 0 10 20 30 40 50

				Value in EQU		
				Without Project	With Project	Net Change
H. Land (25 EQU)	(39)	15	Land forms			
	(40)	10	Geologic surface material			
			SUBTOTAL - Land			
I. Air (11 EQU)	(41)	11	Pleasantness of sounds			
			SUBTOTAL - Air			
J. Water (39 EQU)	(42)	25	Surface characteristics			
	(43)	14	Water/land interface			
			SUBTOTAL - Water			
K. Biota (28 EQU)	(44)	18	Vegetation			
	(45)	10	Fauna			
			SUBTOTAL - Biota			
L. Man-Made Objects (21 EQU)	(46)	8	Visual			
	(47)	5	Condition			
	(48)	8	Consonance with environment			
			SUBTOTAL - Man-Made Objects			
M. Composition (35 EQU)	(49)	25	Interactions			
	(50)	10	Color			
			SUBTOTAL - Composition			
			TOTAL - Esthetics (159 EQU)			

IV. HUMAN INTEREST

Environmental Quality Units (EQU) 0 10 20 30 40 50

				Value in EQU		
				Without Project	With Project	Net Change
N. Educational - Scientific Significance (64 EQU)	(51)	18	Geological significance			
	(52)	18	Ecological significance			
	(53)	18	Archeological significance			
	(54)	10	Unusual water phenomenon			
			SUBTOTAL - Educational-Scientific Significance			
O. Historical Significance (55 EQU)	(55)	11	Related to persons			
	(56)	11	Related to events			
	(57)	11	Related to religions and cultures			
	(58)	11	Related to architectures and styles			
	(59)	11	Related to "western frontier"			
			SUBTOTAL - Historical Significance			
P. Cultural Significance (54 EQU)	(60)	18	Related to indians			
	(61)	18	Related to religious groups			
	(62)	18	Related to ethnic groups			
			SUBTOTAL - Cultural Significance			
Q. Mood Atmosphere Significance (32 EQU)	(63)	8	Isolation - solitude			
	(64)	8	Awe - inspiration			
	(65)	8	"Oneness" with nature			
	(66)	8	Mystery			
			SUBTOTAL - Mood-Atmoshere Significance			
			TOTAL - Human Interest (205 EQU)			

	Total Ratings (EQU)		
	Without Project	With Project	Net Change
I. Ecology			
II. Environmental Pollution			
III. Esthetics			
IV. Human Interest			
TOTAL			

Figure 4.3-3 Environmental evaluation system for use in siting power plants[232]

---

232. See reference (254).

in time, the extensive ongoing research efforts will certainly bring about refinements including synergistic and antagonistic combinations, and single models flexible enough for considering the particular areas of stress associated with specific water systems and the particular uses required for that water.

On the broader level there is some research directed at the assignment of weightings of the importance of various air pollution problems relative to the various water pollution problems. Some of this highly speculative work has focused attention on various environmental stresses based on their persistence, range of territory affected, and the complexity of their complications.[233] For example, table 4.3-1 lists some relative weightings of water pollution and air pollution problems for the present time and for a projected (unspecified) future time.

Although there will obviously be disagreements about the relative weightings given certain of these problems, this actual effort of collecting speculations from a group of individuals with broad and comprehensive understandings and interests is a praiseworthy first step in building some perspective on the inevitable problem of assigning relative weightings to air and water impact problems. For in the power system scheduling or simulating procedure even if these impacts are kept as separate dimensions,

---

[233] This research is reviewed in reference (255).

Water Pollution	**Present**	**Future**
pesticides	140	30
waterborne industrial wastes	48	84
organic sewage	24	48
radioactive waste storage	20	40
tritium and ^{85}krypton	16	120
waste heat	5	72
Air Pollution		
carbon dioxide	75	75
sulfur dioxide	72	72
suspended particulate matter	72	90
oxides of nitrogen	24	42
photochemical oxidants	12	18
hydrocarbons in air	10	18
carbon monoxide	9	12

Table 4.3-1 Relative weightings of present and future air and water pollution problems[234]

and indeed even if these themselves are divided into dimensions representing various specific impact problems, there will undoubtedly have to be some time when a decision has to be made and one particular operating point chosen. This choice then implies a whole set of criteria, tradeoffs and combinations between the various environmental consequence commodities. And even if this decision is made by a panel with constituents from the various interest groups, expert recommendations such as are given in table 4.3-1 of the possible relative weightings between different environmental problems can still be of great help.

---

[234] See reference (255) from which this material was obtained.

5. Coordination with Atmospheric Model

The usefulness of an environmental impact model for water systems will depend to a great extent upon the existence of a compatible air systems model. Work is underway on a model to develop pollutant concentrations downwind from power plants[235] and it is instructive to see how this effort will be useful in the total atmospheric model.

Ideally, the atmospheric model should be symmetric to the aquaspheric model, so the results and tradeoffs can be mixed meaningfully.

To use the same systems approach diagrammed in figure 4.1-1 the appropriate atmospheric model becomes that of figure 5.-1

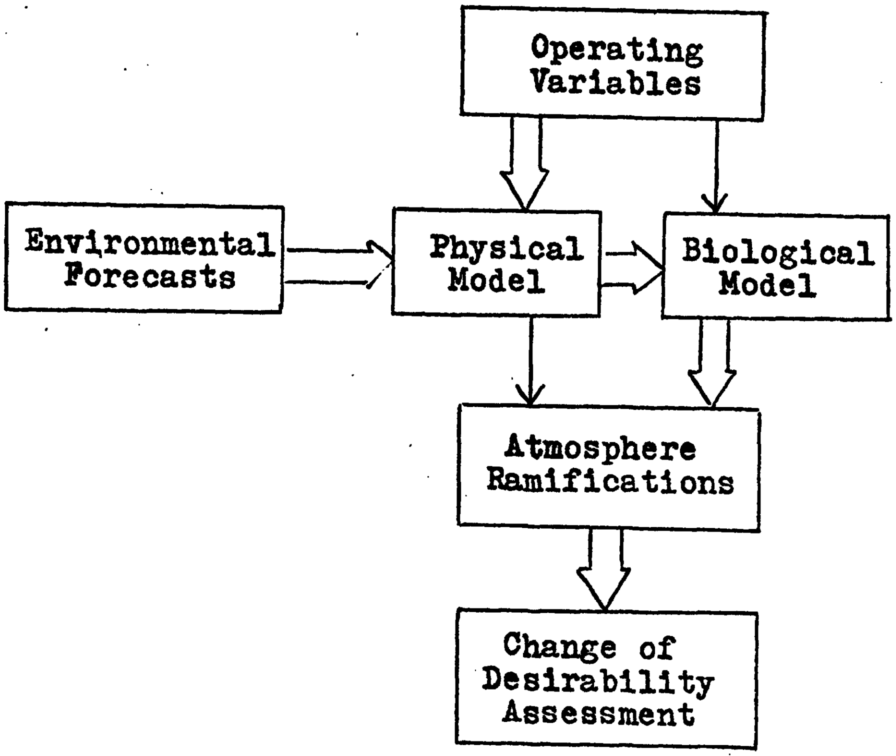


Figure 5.-1 General systematic representation of atmospheric impact

---

[235] This work is being further refined at MIT and at Environmental Research and Technology, Lexington, Mass.

The careful definition of the functions of each of these modules has been developed, see reference (212), so here only a cursory overview will be given to demonstrate the viability of this scheme, and thus no attempt will be made here to document the arguments.

The operating variables will include the time intervals selected, operation modes such as base loaded or cycling, and air pollutant outputs including SO_2, NO_x, particulates, radionuclides, heat and moisture. These quantities are input to the physical model. The time interval (to key the seasonal variations, i.e. indoor and outdoor activities, agriculture and livestock seasonal variations) will go directly to the biological model.

Forecasts of environmental factors include air temperatures, wind speeds, mixing heights (i.e. turbulance or stratification) and ambient air quality measures for the assessment of <u>differences</u> due to plant operation.

The physical model then predicts as best it can the probabilistic space-time distributions which might be expected for the different pollutants during the interval of concern (an hour or a week) for the different modes of operation, as compared with non-operation. Some of these results feed directly into the atmospheric ramifications, e.g. effects of air quality changes on structures (estimated as $100 million per year on steel alone[236]), fabrics ($800 million/year[236]),

---

[236] See reference (256).

etc; and the purely physical aesthetic considerations such as odor and looks of air, etc.[237]

The biological model must include plants and animals, particularly agriculture and livestock ($500 million per year loss due to air pollution[236]) as well as a model of man. The mechanism for determining impact is the same as that in the water model: probability a population is affected convolved with the probability of impact. In the case of man the model for impact can be represented as in figure 5.-2.

Pollutant concentration
at a given distance in
a certain direction

↓ translated to

Impact potential at a
given distance in a
certain direction

↓ convolved with

Population density and
probabilistic 'health'
measure at given distance
in a certain direction

Figure 5.-2 Assessing atmospheric impact to man

The probabilistic loss curves will show populations at various stages of disability and the impact caused by the operation of the plant, see figure 5.-3.

---

237. This, however, may not be a significantly large problem considering the results of a May 1969 Gallup poll for the National Wildlife Federation which showed only 14% of the people would agree to a $2.00 increase in monthly utility bills earmarked to stop pollution by electric power plants. This is apparently more an indication of aesthetic value insofar as most people are probably not aware of the health, particularly respiratory, complications inherent in air pollution.

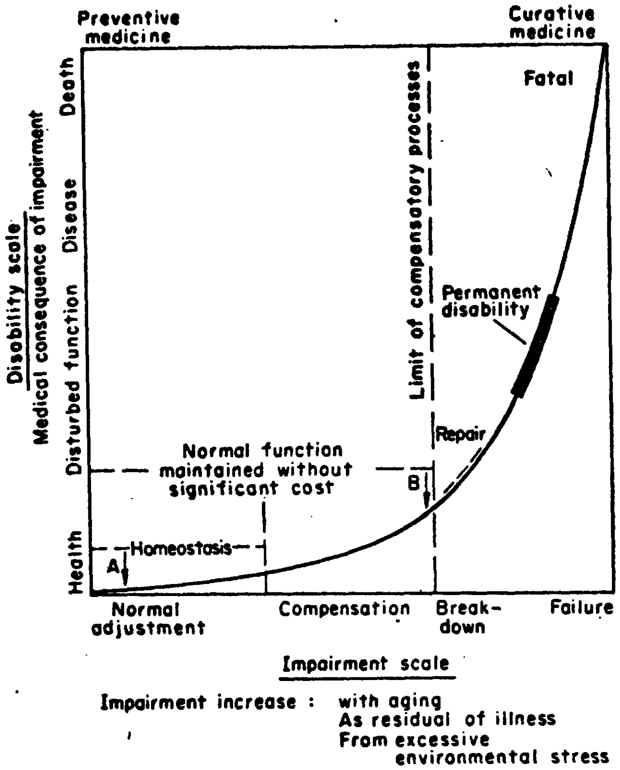


Figure 5.-3 Various stages of disability in man due to atmospheric pollution increases[238]

Attempts have already been made at defining the different stages of disability due to air pollution, see table 5.-1.

Stage 0	No measurable effect
Stage 1	Awareness of pollution at a level sufficient to lead individuals to change residence or place of employment
Stage 2	Reversible alteration in physiological functions
Stage 3	Untoward symptoms of bodily dysfunction
Stage 4	Irreversible alteration in vital physiological functions
Stage 5	Chronic disease
Stage 6	Acute sickness or death in debilitated persons
Stage 7	Acute sickness or death in healthy persons

Table 5.-1 Different discrete stages of human health with respect to air pollution exposures[239]

---

[238] Excerpt from reference (257) page 160.

[239] Adapted from reference (258).

Assessing atmospheric ramifications amounts to a quantification of future effects inherent in current operation procedures. A common speculation is that man may be transformed via mutagenetics, however, there are more tangible assessments required of this module. Basically, a measure of any resulting changes to the health of the members of the community must be assessed, specifically the buildup of doses within man that may have long term effects on his decreased immunity to respiratory diseases.

Calculation of social benefits, or relative desirability, associated with different operating modes is a field fraught with difficulties. The problem is, however, being vigorously tackled from a number of angles, and it is a problem which man has apparently become determined to resolve.

Glossary

acclimation	an adaptation to a specific temperature or stress, perhaps experimentally induced, a relatively rapid process with respect to nature's changes
acclimatization	the very slow naturally occurring adaptation to a specific temperature
adventive	organisms that have been artificially introduced into an environment
aestivation	inactivity or dormancy during relatively hot periods
anadromous	going up river to spawn
benthic	refering to plants or animals which are primarily restricted to the bottom of a water body
biocoenosis	plants and animals of an ecosystem
canalization	where genetically identical adults in the same environment differ because of different early experiences
colonialism	gregarious tendencies of a species
cyclomorphosis	the cyclic series of gradual changes in characteristics of a species occurring during successive generations
diapause	period of suspended development due to decreased metabolism or inactivity
entrainment	inclusion in the water which goes through the condenser cooling system
epilimnion	the upper stratified layer of a water body, usually at a nearly even temperature through its depth
eurythermal	organisms which can live over a broad range of temperatures
eutrophic	an environment flourishing with nutrients
extirpation	a complete abolishment of a community, generally effected by the existence of an intolerable situation

homeostatic	the tendency of a system to return to its former stable or static condition
hypolimnion	the lower stratified layer of a water body usually of a nearly constant temperature all year long
incipient	first stage of observability
littoral	shallow portions of a waterbody, usually from shoreline to a point 200 meters depth
motile	capable of moving, generally restricted to use for organisms which can propel themselves away from stressing situations
mutagenetics	mutation of the genetic composition
oligotrophic	an environment with a deficiency of nutrients
planktonic	any organism at the mercy of winds and currents
poikilotherms	any animal whose body temperature remains close to that of its environment
sessile	not moveable, fixed, sedentary
speciation	process of the formation of a new species through the mechanisms of evolution
stenothermal	organisms which are narrowly restrictive in their tolerance to temperature changes
synergism	situation where a joint action is greater than the sum of individual actions
thermocline	the middle stratified layer of a water body containing the main portion of the temperature change from the floor to the surface
thermotoxic	combining of thermal stress and concentrations of harmful chemicals and/or microorganisms
zooplankton	planktonic animals

References

(1) Sporn, P., "Our environment - options on the way into the future," IEEE Spectrum, volume 8, number 5, pages 49-58, May 1971.

(2) White, D. C. (principle investigator), "Dynamics of energy systems, supplement - working papers," program of research by MIT School of Engineering, et al, December 1971.

(3) National Academy of Engineering, Committee on Power Plant Siting, "Engineering for the resolution of the energy-environment dilemma, " NAE, Washington, D. C., 1972.

(4) Gruhl, J., "Minimizing cost and environmental impact of electric power system operation," (unpublished), Ph.D. thesis preliminary working paper, MIT Department of Electrical Engineering, 45 pages, March 1972.

(5) Gruhl, J., "Electric generation production scheduling using a quasi-optimal sequential technique," report number 3, Energy Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts, 145 pages, April 1972.

(6) Gruhl, J., "Electric power unit commitment scheduling using a dynamically evolving mixed integer program," Report number 7, Energy Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts, January 1973.

(7) Gruhl, J., "Economic-environmental-security transform curves of electric power system production schedules and simulations," Report number 6, Energy Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts, 90 pages, November 1972.

(8) Jensen, L. D., Davies, R. M., Brooks, A. S., Meyers, C. D., "The effects of elevated temperatures upon aquatic invertebrates," Cooling Water Studies for Edison Electric Institute, Research Project RP-49, Johns Hopkins University, September 1969.

(9) Templeton, W. L. and Coutant, C. C., "Studies on the biological effects of thermal discharges from nuclear reactors to the Columbia River at Hanford," Environmental Aspects of Nuclear Power Stations, International Atomic Energy Agency, Vienna, page 591, 1971.

(10) Federal Power Commission, "Steam electric plant construction cost and annual production expenses," 1966.

(11) Resources for the Future, Inc. and Massachusetts Institute of Technology Environmental Laboratory, "Energy research needs," Report to the National Science Foundation under the contract number NSF-C644, October 1971.

(12) Kinsman, G., "Power plant cooling systems," Journal of the Power Division from the Proceedings of the American Society of Civil Engineers, volume 98, number PO2, pages 247-252, October 1972.

(13) Heronemus, W. E., "A national network of pollution-free energy sources," proposal to the National Science Foundation by the Multidisciplinary Group at the University of Massachusetts, Amherst, Massachusetts, April 1971.

(14) Shaw, T. L., "Tidal energy and national needs," Water Power, volume 24, number 10, pages 382-384, October 1972.

(15) Balzhiser, R. E., "The energy horizon-technology's contribution," American Power Conference Proceedings, volume 34, pages 19-27, 1972.

(16) Altman, M., Telkes, M., and Wolf, M., "The energy resources and electric power situation in the United States," Energy Conversion, volume 12, number 2, pages 53-64, June 1972.

(17) Drummond, W. E., "The promise of controlled thermonuclear power," American Society of Heating, Refrigeration, and Air Conditioning Engineering Journal, pages 34-36, February 1973.

(18) Friedlander, G. D., "Floating reactor : 'crisis' solution?" IEEE Spectrum, volume 10, number 2, pages 44-51, February 1973.

(19) Collier, A. R., and Nichols, R. C., "Floating nuclear power plants for offshore siting," Westinghouse Engineering, volume 32, pages 162-169, November 1972

(20) Coutant, C. C. "Biological aspects of thermal pollution I. Entrainment and discharge canal effects," CRC Critical Reviews in Environmental Control, volume 1, issue 3, pages 341-381, November 1970.

(21) Parker, F. L., and Krenkel, P. A., Engineering Aspects of Thermal Pollution, Vanderbilt University Press, Nashville, Tennessee, 1969.

(22) Nahavandi, A., and Campisi, J., "Parametric study of power plant thermal pollution," Journal Water Pollution Control Federation, volume 43, number 3 part 1, pages 506-514, March 1971.

(23) U. S. Atomic Energy Commission, Thermal Effects Studies by Nuclear Power Plant Licenses and Applicants, U. S. Government Printing Office, 1969.

(24) Coutant, C. C., "Effects on organisms of entrainment in cooling water : steps toward predictability," Nuclear Safety, volume 12, number 6, pages 600-607, December 1971.

(25) Marks, D. H. and Adams, E. E., "Spatial and temporal temperature distribution resulting from heated discharges into natural waterbodies," preliminary draft, MIT Department of Civil Engineering, November, 1971.

(26) Harleman, D. R. F., "Chapter 7, Temperature distribution in near field region : case studies and design problems," Engineering Aspects of Heat Disposal from Power Generation, R. M. Parsons Laboratory for Water Resources and Hydrodynamics, Department of Civil Engineering, MIT, 1971.

(27) Parker, F. L. and Krenkel, P. A., "Physical and engineering aspects of thermal pollution," CRC Critical Reviews in Environmental Control, volume 1, number 1, pages 101-192, February 1970.

(28) Coxe, E. F., and Elrod, A. C., "The prediction of temperature profiles in arbitrarily shaped cooling lakes by finite differences technique," presented at the 1971 Intersociety Energy Conversion Engineering Conference, Boston, Massachusetts, pages 695-699, August 1971.

(29) Yotsukura, N., Jackman, A. P., and Faust, C. R., "Approximation of heat exchange at the air-water interface," Water Resources Research, volume 9, pages 118-128.

(30) Brown, G. W., "Temperature prediction using energy budget techniques on small mountain streams," Thesis, University of Oregon State, 129 pages, 1967.

(31) McMichael, F. C. and Hunter, J. S., "Stochastic modelling of temperature and flow in rivers," Water Resources Research, volume 8, number 1, pages 87-98, February 1972.

(32) Morse, W. C., "Stream temperature prediction model," Water Resources Research, volume 6, number 1, 1970.

(33) Novotny, V. and Krenkel, P. A., "Simplified mathematical model of temperature changes in rivers," Journal Water Pollution Control Federation, volume 45, number 2, pages 240-248, February 1973.

(34) Jirka, G. H., "Location of thermal power plants under environmental considerations," Master of Science Thesis, Department of Civil Engineering, Massachusetts, Institute of Technology, Cambridge, Massachusetts, January 1971.

(35) Argonne National Laboratory, "Heated-effluent dispersion in large lakes," Argonne National Laboratory Environmental Sciences Report number ES-11, Argonne, Illinois, 391 pages, January 1972.

(36) Esprey, W. H., and Ward, G. H., "Estuarine water quality models," Water Research, volume 6, number 10, pages 1117-1131, October 1972.

(37) Water Resources Engineers, Inc., Mathematical Models for the Prediction of Thermal Energy Changes in Impoundments, Environmental Protection Agency, Water Quality Office, Water Pollution Control Research Series 16130 EXT, December 1969.

(38) Cordaro, M. C. , and Matchett, D. L., "The design of a once-through cooling system to meet the challenge of strict thermal criteria," Journal of Environmental Science, volume 2, number 3, pages 207-224, September 1972.

(39) Golze, A. R., "The environmental impact of a multipurpose pumped storage project," Water Power, volume 24, number 12, pages 459-463, December 1972.

(40) Enviro Control, Incorporated, "Systems analysis for water quality management," by Enviro Control, Inc, Survey and Abstracts, Document numbers PB-209 894, W72 09229, FWQA 68 01 0096, Washington, D. C., 200 pages, September 1971.

(41) Shiers, P. F. and Marks, D. H., "Thermal pollution abatement evaluation model for power plant siting," Energy Laboratory Report number 13, Massachusetts Institute of Technology, February 1973.

(42) Benedict, B. A., Motz, L. H. and Yandell, E. L. Jr., "Use of heated surface jet model for Lake Michigan analysis," Journal Water Pollution Control Federation, volume 45, number 2, pages 353-364, February 1973.

(43) Stolzenbach, K. D., and Harleman, D. R. F., "Three-dimensional heated surface jets," Water Resources Research, volume 9, number 1, pages 129-137, February 1973.

(44) Stolzenbach, K. D. and Harleman, D. R. F., "An analytic and experimental investigation of surface discharges of heated water," Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, February 1971.

(45) Harleman, D. R. F., et al, "Engineering aspects of heat disposal from power generation," Department of Civil Engineering, Massachusetts Institute of Technology, Summer Session Course Notes, Volumes I and II, June 1971.

(46) Von Ammon, F. K., "Thermal pollution control in Baveria," Proceedings 24th Industrial Water Conference, Purdue University, Extension Series 135, page 1357, 1970.

(47) Christianson, A. G. and Tichenor, B. A., "Industrial waste guide on thermal pollution," Federal Water Pollution Control Administration, Northwest Region, Pacific Northwest Laboratory, Corvallis, Oregon, September 1968.

(48) Federal Water Pollution Control Administration, "Report of the committee on water quality criteria," U. S. Government Printing Office, Washington, D. C., 1968.

(49) Mount, D. I., "Thermal standards in the United States of America," Symposium on Environmental Aspects of Nuclear Power Stations, Preprint number 15, New York, N. Y., August 1970.

(50) Eisenbud, M., Gleason, G. (editors), Electric Power and Thermal Discharges, Gordon and Breach Science Publisher, New York, 1969.

(51) Stein, M., "Enforcement limitations in water quality control," Water Resources Bulletin, volume 6, number 4, page 473, July 1970.

(52) Federal Water Quality Administration, "Clean water for the 1970's - a status report," F.W.Q.A., U. S. Department of the Interior, Washington, D. C., June 1970.

(53) Chemical Engineering News, "The environment : scrutining by lawyers," C.E.N. Columbia University Conference on International and Interstate Regulation of Water Pollution, volume 48, number 12, page 16, 1970.

(54) Fifth Circuit Court of Appeals, "Thermal Discharges and the Refuse Act of 1899," Air and Water News, volume 4, number 5, page 1, 1970.

(55) Tarzwell, C. M., "Thermal requirements to protect aquatic life," Journal Water Pollution Control Federation, volume 42, page 824, 1970.

(56) Federal Water Quality Administration, Department of the Interior, "Pollution policy, new Lake Michigan thermal decree allows dischargers only one degree," Engineering News - Record, volume 184, number 20, page 11, 1970.

(57) Lake Michigan Enforcement Conference, "Utilities refute Lake Michigan White paper," Air and Water News, volume 4, number 40, page 1, 1970.

(58) Federal Water Quality Administration, Department of the Interior, "Lake Michigan thermal ban," Air and Water News, volume 4, number 39, page 3, 1970.

(59) Environmental Protection Agency, "Early clue to anti-pollution stance," Air and Water Pollution report, volume 8, page 487, 1970.

(60) Federal Water Quality Administration, "Lake Michigan thermal standards," Air and Water News, volume 4, number 44, page 1, 1970.

(61) Teal, J. M., article in Ecological Monographs, volume 27, page 283, 1957.

(62) Mihursky, J. A., McErlean, A. J. and Kennedy, V. S., "Thermal pollution, aquaculture and pathobiology in aquatic systems," Journal of Wildlife Diseases, volume 6, pages 347-355, October 1970.

(63) Wurtz, C. B., Penny, J. S., "Measuring the biological effects of heated discharges," American Power Conference, April 1969.

(64) Brookhaven National Laboratory, "Diversity and stability in ecological systems," Brookhaven Symposia in Biology, Number 22, Publication number BNL 50175 (c-56), Upton, New York, 1969.

(65) Hulbert, S. H., "The nonconcept of species diversity : a critique and alternative parameters," Ecology, volume 52, number 4, pages 577-586, 1971.

(66) Vandermeer, J. H., "On the covariance of the community matrix," Ecology, volume 53, number 1, pages 187-189, 1972.

(67) Koss, R. W. (editor), "Environmental responses to thermal discharges from Marshall Stream Station, Lake Norman, North Carolina," Interim Report, Johns Hopkins University, Department of Geography and Environmental Engineering, Baltimore, Maryland, 67 pages, August 1971.

(68) Copeland, B. J., and Davis, H. L., "Estuarine ecosystems and high temperatures," North Carolina University, State College of Agriculture and Engineering, Raleigh Water Resources Research Institute Report number 68, 101 pages, June 1972.

(69) Batelle Memorial Institute, "Ecological problems and the marine environment," National Biological Congress, Batelle Memorial Institute, Columbus, Ohio, 49 pages, 1970.

(70) Mihursky, J. A., et al, "Effects of thermal pollution on productivity and stability of estuarine communities," University of Maryland, National Resources Institute Report number A-002-Md, 65 pages, July 1971.

(71) Kennedy, V. S., and Mihursky, J. A., "Bibliography on the effects of temperature in the aquatic environment," University of Maryland, National Resources Institute, Contribution #326.

(72) Coutant, C. C., "Thermal pollution - biological effects," Journal Water Pollution Control Federation, pages 1292-1334, June 1971.

(73) Coutant, C. C., and Goodyear, C. P., "Thermal effects," Journal Water Pollution Control Federation, volume 44, number 6, pages 1250-1294, June 1972.

(74) Nikolsky, G. V., The Ecology of Fishes, Academic Press, New York, 352 pages, 1963.

(75) Sprague, J. B., "Resistance of four freshwater crustaceans to lethal high temperatures and low oxygen," Journal Fish Resource Board Canada, volume 20, page 387, 1963.

(76) Vernberg, F. J., "Studies on the physiological variation between tropical and temperate zones. Fiddler crabs of the genus Uca," Biological Bulletin, volume 115, pages 163-184, 1959.

(77) Baker, C. D., Niell, W. H., and Strawn, K., article in Transactions American Fisheries Society, volume 99, page 588, 1970.

(78) Hoar, W. S. and Robertson, G. B., "Temperature resistance of Goldfish maintained under controlled photoperiods," Canadian Journal of Zoology, volume 37, pages 419-428, 1959.

(79) Hoar, W. S., "Seasonal variation in the resistance of Goldfish to temperature stress," Transactions Royal Society of Canada, section III, series V, volume 49, pages 25-34, 1955.

(80) Hoar, W. S., Symposium on Comparitive Endocrinology, John Wiley & Sons, New York, part 1, 1959.

(81) Smirnova, G. P., "Report Summary of all-Union conference on ecology and physiology of fishes," Moscow, page 114, 1966, in Biological Abstracts, volume 48, Abstract number 46325, 1967.

(82) Fisher, K. C. and Prosser, C. L. (editor), Physiological Adaptation of temperature in fish and small mammals, American Physiological Society, Washington D.C., part B, 1958.

(83) Halsband, E., "Studies of the behavior of trout and chub under the influence of various external factors," Zeitschreibung Fischerei, volume 2, page 227, 1953.

(84) Craigie, D. E., "An effect of water hardness on thermal resistance of the rainbow trout," Canadian Journal of Zoology, volume 41, pages 825-830, 1963.

(85) McCauley, R. W., "Thermal relations of geographic races of Salveleniu," Canadian Journal of Zoology, volume 36, pages 655-662, 1958.

(86) Wurtz, C. B., "The realities of thermal pollution - environmental limitations and ecological adaptations," 17th Southern Water Resources and Pollution Control Conference, University of North Carolina, April 1968.

(87) Hart, J. S., "Geographic variation of some physiologic and morphologic characteristics in certain freshwater fish," Publication of the Ontario Fish. Resources Laboratory, volume 72, page 179, 1952.

(88) Federal Water Pollution Control Administration, "Water Quality Criteria," Report of the National Technical Advisory Commission to the Secretary of the Interior, Washington, D. C., April 1968.

(89) Merriman, D. et al, "The Connecticut River investigation, 1965-72," Semiannual progress reports to Connecticut Yankee Atomic Power Company, Haddam, Connecticut, 1965.

(90) Meldim, J. W., and Gift, J. J., "Temperature preference, avoidance, and shock experiments with estuarine fishes," Bulletin Number 7, Ichthyological Association, Middletown, Delaware, 1971.

(91) Cocking, A. W., "Relationship between the ultimate upper lethal temperature and the temperature range for good health in the roach," Nature, volume 180, pages 661-663, London, 1957.

(92) Ferguson, R. G., "The preferred temperature of fish and their midsummer distribution in temperate lakes and streams," Journal of the Fisheries Research Board of Canada, volume 15, pages 607-624, 1958.

(93) Technical Advisory and Investigations Branch, Federal Water Pollution Control Administration, "Temperature and aquatic life - laboratory investigations number 6," Cincinnati, Ohio, 151 pages, 1967.

(94) Fry, F. E. J., Hart, J. S. and Walker, K. F., "Lethal temperature relationship for a sample of young speckled trout (Salvelinus fontinalis)," University of Toronto Studies in Biology Series 54, Publication of Ontario Fishery Research Laboratory, volume 66, page 5, 1946.

(95) Brett, J. R., "Temperature tolerance in young Pacific salmon, genus Oncorhynchus," Journal Fish Resources Board of Canada, volume 9, number 6, pages 265-323, 1952.

(96) Brett, J. R., "Thermal requirements of fish - three decades of study, 1940-1970," in Biological Problems in Water Pollution, Robert A. Taft Sanitary Engineering Center Technical Report W60-3, pages 110-117, 1960.

(97) Brett, J. R., "Temperature : animals : fishes," in <u>Marine Ecology</u>, Kinne, O. (editor), volume 1, part 1, pages 515-560, Wiley Interscience, New York, N.Y. 1972

(98) Hoff, J. H., and Westman, J. R., "The temperature tolerances of three species of marine fishes," <u>Journal Marine Research</u>, volume 24, pages 131-140, 1966.

(99) Somero, G. N., and DeVries, A. L., "Temperature tolerance of some Antarctic fishes," <u>Science</u>, volume 156, New York, pages 257-258, 1967.

(100) Speakman, J. N., and Krenkel, P. A., "Quantification of the effects of rate of temperature change on aquatic biota," <u>Water Research</u>, volume 6, number 11, pages 1283-1290, November 1972.

(101) Cairns, J. Jr., "Thermal pollution - a cause for concern," <u>Journal Water Pollution Control Federation</u>, volume 43, number 1, pages 55-66, January 1971.

(102) Batelle-Northwest, "Nuclear power plant siting in the Pacific Northwest," Research Report for Bonneville Power Administration, 547 pages plus appendices, 1967.

(103) Coutant, C. C., "Temperature, reproduction and behavior," <u>Chesapeake Science</u>, volume 10, pages 261-274, 1969.

(104) Fry, F. E., Brett, J. R., and Clawson, G. H., "Lethal limits of temperature for young Goldfish," <u>Review Canadian Biology</u>, volume 1, page 50, 1941.

(105) Block, E. C., "Upper lethal temperature of some British Columbian freshwater fishes," <u>Journal Fisheries Research Board of Canada</u>, volume 10, number 196, 1953.

(106) Coutant, C. C., "Effect of thermal shock on vulnerability to predation in juvenile salmonides," United States Atomic Energy Commission Report number BNWL-1519, Battelle Northwest, 1970.

(107) Coutant, C. C., "Biological aspects of thermal pollution II. Scientific basis for water temperature standards at power plants," <u>C R C Critical Reviews in Environmental Control</u>, volume 3, issue 1, Chemical Rubber Company, pages 1-24.

(108) Kinne, O., "Temperature : animals : invertebrates," in Marine Ecology, Kinne, O. (editor), volume 1, part 1, Wiley Interscience, New York, N.Y., pages 407-514, 1972.

(109) Sylvester, J. R., "Effect of thermal stress on predator avoidance in sockeye salmon," Canadian Fisheries Research Board Journal, volume 29, number 5, pages 601-603, May 1972.

(110) Pennsylvania Department of Health, "Heated discharges-their effect on streams," Pennsylvania Department of Health Publication number 3, Harrisburg, Pennsylvania, 108 pages, 1962.

(111) Sylvester, J. R., "Possible effects of thermal effluents on fish : a review," Environmental Pollution, volume 3, number 3, pages 205-216, July 1972.

(112) Brett, J. R., "Energetic responses of salmon to temperature," American Zoology, volume 11, page 99, 1971.

(113) Brett, J. R., Shelbourn, J., and Shoop, C. T., "Growth rate and body consumption of fingerling sockeye salmon in relation to temperature and rationing," Journal Fish Resources Board of Canada, volume 26, page 2363, 1969

(114) Brett, J. R., and Sutherland, D. B., "Improvement in the artificial rearing of sockeye salmon by environmental control," Fish Resources Board of Canada, Biological Station, Nanaimo, British Columbia, Circulation no. 89, 1970.

(115) Major, R. L., and Mighell, J. L., "Influence of Rocky Reach Dam and the temperature of the Okanogan River on the upstream migration of sockeye salmon," Fisheries Bulletin, U. S. Fish and Wildlife Service, volume 66, number 1, page 131-147, 1966.

(116) Fisheries Board of Canada, Annual Report 1961-1962, from the Fisheries Board of Canada, 206 pages, 1962.

(117) Collier, A. W., "Oceans and coastal waters as life-supporting environments," in Marine Ecology, Kinne, O. (editor), volume 1, part 1, Wiley Interscience, New York, N.Y., pages 1-93, 1972.

(118) Kalle, K., "Salinity - general introduction" in Marine Ecology, Kinne, O. (editor), volume 1, part 2, Wiley Interscience, New York, N.Y., pages 683-688, 1972.

(119) Kinne, O., "Salinity ; animals : invertebrates," in Marine Ecology, Kinne, O. (editor), volume 1, part 2, Wiley Interscience, New York, N.Y., pages 821-995, 1972.

(120) Alderdice, D. F., "Factor combinations - responses of marine poikilotherms to environmental factors acting in concert," in Marine Ecology, Kinne, O. (editor), volume 1, part 3, Wiley Interscience, New York, N.Y., pages 1659-1722, 1972.

(121) Lindsey, J. K., Alderdice, D. F. and Pienaar, L. V., "Analysis of nonlinear models - the nonlinear response surface," Journal Fisheries Research Board Canada, volume 27, page 765-791, 1970.

(122) Ansell, A. D., "The rate of growth of the hard clam," J. Cons. Int. Explor. Mer., volume 31, page 364, 1968.

(123) Strawn, K., and Galloway, B. J., "Final report on the seasonal abundance, distribution and growth of commercially important crustaceans at a hot water discharge in Galveston Bay, Texas," Texas A & M Research Foundation Report to Electric Utility Commission on Water Quality, 1970.

(124) Ansell, A. D., "Thermal releases and shellfish culture : possibilities and limitations," Chesapeake Science, volume 10, page 256, 1969.

(125) Silverman, M. J., "Tragedy at Northport," Underwater Naturalist, volume 7, number 2, pages 15-18, 1971.

(126) Marine Pollution Bulletin, "Oyster Creek Fish Kill," volume 3, number 4, pages 52-53, April 1972.

(127) Doudoroff, P., "The resistance and acclimation of marine fishes to temperature changes : I. Experiments with Girella nigricans (Ayres)," Biological Bulletin, volume 83, pages 219-244, 1942.

(128) Allen, J. A., "Ecology and functional morphology of molluscs," Oceans - Marine Biology Annual Review, Barnes, H. (editor), volume 1, pages 253-288, 1963.

(129) Galtstoff, P. S., "The American oyster Crassostrea virginica Gmelin," U. S. Fish and Wildlife Service, Special Science Reports - Fish, number 64, 480 pages, 1964.

(130) Naylor, E., "Effects of heated effluents on marine and estuarine organisms," in Advances in Marine Biology, Russell, Sir F. S. (editor), Academic Press, pages 63-103, 1965.

(131) Costlow, J. D., "The effect of salinity and temperature on survival and metamorphosis of megalops of the blue crab," Helgoländer wissenschafter Meeresunterstandung, volume 15, pages 84-97.

(132) McLeese, D. W., "Effects of temperature, salinity, and oxygen on the survival of the American lobster," Journal Fisheries Research Board Canada, volume 13, pages 247-272, 1956.

(133) McLeese, D. W., and Wilder, D. G., "The activity and catchability of the lobster in relation to temperature," Journal Fisheries Research Board Canada, volume 15, pages 1345-1354, 1958.

(134) Cheney, P. B. and Smith, F. A., "A systems analysis of aquatic thermal pollution and its implications, volume 1 summary report," Travelers Research Corporation, Hartford, Connecticut, January 1969.

(135) Hemens, J., "Waste heat and the water environment," Symposium on Water Conservation and Pollution Control, American Institute of Chemical Engineers, March 1969.

(136) Churchill, M. A. and Mojtalik, T. A., "Effects of heated discharge on the aquatic environment : the TVA experience," Nuclear News, page 80, September 1969.

(137) Quinlan, A. V., "Factors affecting the growth and productivity of marine phytoplankton," Engineering 376, Course in Environmental Biology, January 1972.

(138) Kullberg, R. G., article in Ecology magazine, volume 49, page 751, 1968.

(139) Gunkel, W., "Light : bacteria, fungi and blue-green algae," in Marine Ecology, Kinne, O. (editor), volume 1, part 1, Wiley Interscience, New York, N.Y., pages 103-124, 1972.

(140) Gessner, F., "Temperature : plants," in Marine Ecology, Kinne, O. (editor), volume 1, part 1, Wiley Interscience, New York, N.Y., pages 363-406, 1972.

(141) Braarud, T., "Cultivation of marine organisms as a means of understanding environmental influences on population," in Oceanography, Sears, M. (editor) A.A.A.S., Washington, D.C., pages 271-298, 1961.

(142) Matsuura, M., "Observation on annual growth cycle of marine algae on a reef at Manadzuru on the Pacific coast of Japan," Botanical Magazine, Tokyo, volume 71, pages 93-109, 1958.

(143) North, W. J., article in the Proceedings of the International Seaweed Symposium, volume 6, page 275, 1969.

(144) Cairns, J. Jr., "Effects of increased temperatures on aquatic organisms," Industrial Wastes, volume 1, page 150, 1956.

(145) Prowse, G. A., "Digestion of freshwater algae by Tilapia mossambica," Report 1960-61 : Tropical Fish Culture Institute, Melacca, 1960.

(146) Gorham, P. R., (Jackson, D. R. editor) Algae and Man, Plenum Press, New York, page 307, 1964.

(147) Fogg, G. E., (Lewin, R. A., editor), Physiology and Biochemistry of Algae, Academic Press, New York, page 161, 1962.

(148) Stewart, W. D. P., Nitrogen Fixation in Plants, Althlone Press, University of London, 1966.

(149) Golovacheva, R. S. and Kalininskaya, T. A., "Pseudomonas ambigua - a nitrogen fixing bacterium from thermal springs," Mikrobiologiya (USSR), volume 37, page 941, 1969.

(150) Stewart, W. D. P., article in Science, volume 158, page 1426, 1967.

(151) Marine Pollution Bulletin, "Post-mortem on fish kills," volume 3, number 7, pages 100-101, July 1972.

(152) Jaske, R. T., Templeton, W. L. and Coutant, C. C., "Thermal death models," Industrial Waste Engineering, volume 6, number 10, pages 25-27, October 1969.

(153) Morita, R. Y., "Pressure : bacteria, fungi, and blue-green algae," in Marine Ecology, Kinne, O. (editor), volume 1, part 3, Wiley Interscience, New York, N.Y., pages 1361-1388, 1972.

(154) Flugel, H., "Pressure : animals," in Marine Ecology, Kinne, O. (editor), volume 1, part 3, Wiley Interscience Series, Wiley Publishing Co., pages 1407-1450, 1972

(155) Bates, D. W., "The horizontal travelling screen," in <u>Engineering Aspects of Thermal Pollution</u>, Vanderbilt University Press, 1969.

(156) Trembly, F. J., "Research project on effects of condenser discharge water on aquatic life," Progress Report 1956-59, Institute of Research, Lehigh University, Bethlehem, Pennsylvania, 1960.

(157) Clark, J. R., "Thermal pollution and aquatic life," <u>Scientific American</u>, volume 220, number 3, pages 19-27, March 1969.

(158) Alabaster, J. S. and Downing, A. L., "A field and laboratory investigation of the effect of heated effluent on fish," Investigations Series I, Ministry of Agriculture, Fisheries and Food, United Kingdom, volume 6, number 4, 1966.

(159) LaBerge, R. H., "Thermal discharges," <u>Water and Sewage Works</u>, pages 536-540, 1959.

(160) Oppenheimer, C. H., "Temperature : bacteria, fungi and blue-green algae," in <u>Marine Ecology</u>, Kinne, O. (editor), volume 1, part 1, Wiley Interscience, New York, N.Y., pages 347-361, 1972.

(161) Morita, R. Y., Burton, S. D., "Influence of moderate temperature on growth and malic dehydrogenase activity of a marine psychrophile," <u>Journal Bacteriology</u>, volume 5, pages 1025-1029, 1963.

(162) Howath, R. S., and Brent, M. M., "Thermal pollution and the aquatic microbial community : possible consequences," <u>Environmental Pollution</u>, volume 3, number 2, pages 143-146, April 1972.

(163) Umminger, B. L., "Effects of temperature on serum protein components in the killfish, Fundulus heteroclitus," <u>Journal Fish Resources Board of Canada</u>, volume 27, page 404, 1970.

(164) Marnell, L. F. and Hunsaker, D., II, "Hooking mortality of lure-caught cutthroat trout (Salmo clarki) in relation to water temperature, fatigue and reproductive maturity of released fish," <u>Transactions American Fisheries Society</u>, volume 99, page 684, 1970.

(165) Hunsaker, D., II, et al, "Hooking mortality of Yellowstone cutthroat trout," <u>Progressive Fish Culturist</u>, volume 32, page 231, 1970.

(166) Amend, D. F., "Control of infectious hematopoietic necrosis virus disease by elevating the water temperature," Journal of Fish Resources Board of Canada, volume 27, page 265, 1970.

(167) McDaniel, S. J., "Littorina littorea : lowered heat tolerance due to Cryptocotyle lingua," Experimental Parasitology, volume 25, page 13, 1969.

(168) Dubos, R., "Second thoughts on germ theory," Scientific American, volume 192, pages 31-35, 1955.

(169) Sinderman, C. J., "Diseases of marine fishes," Advancements in Marine Biology, volume 4, pages 1-89, 1966.

(170) Stanier, R. Y., Doudoroff, M., Adelburg, E. A., The Microbial World, Prentice Hall, Englewood Cliffs, New Jersey, 753 pages, 1963.

(171) Allen, N., and Pelczar, M. J. Jr., "Bacterial studies on white perch," Chesapeake Science, volume 8, number 3, pages 135-154, 1967.

(172) deSylva, D., "Theoretical considerations of the effects of heated effluents on marine fishes," in Biological Aspects of Thermal Pollution, (Krenkel, P. A. and Parker, F. L. editors), Vanderbilt University Press, 1969.

(173) Brett, J. R., "Some principles in the thermal requirements of fishes," Quarterly Review of Biology, volume 31, number 2, pages 75-87, 1956.

(174) Ordal, E. J. and Pacha, R. E., "The effects of temperature on diseases in fish," in Water Temperature ; Influence, Effects and Control, Proceedings 12th Pacific Northwest Symposium on Water Pollution Research; Portland, Oregon, Federal Water Pollution Control Administration, 1967.

(175) Snieszko, S. F., Bullock, G. L., Hollis, E. and Boone, J. G., "Pasteulla sp. from an epizootic of white perch in Chesapeake Bay - tidewater areas," Journal Bacteriology, volume 88, pages 1814-1815, 1964.

(176) Janssen, W. A. and Surgalla, M. J., "Morphology, physiologoy and serology of a Pasteurella species pathogenic for white perch," Journal Bacteriology, volume 96, pages 1606-1610, 1968.

(177) Fujihara, M. P., Olson, P. A., Nakatani, R. E., "Antibody production and immune response of fish to C. Columnaris," Pacific Northwest Laboratory Annual Report, 1964, to U. S. Atomic Energy Commission Division of Biology and Medicine, (Thompson, R. C., Teal, P., Swezea, E. G. editors) Richland, Washington, Biological Science BNWL-714, pages 194-196, 1965.

(178) Burrows, W., <u>Textbook on Microbiology</u>, W. B. Saunders Company, Philadelphia, Pennsylvania, 1959.

(179) Peterson, J., "Connecticut nuclear plant, fish kill linked," <u>Boston Sunday Globe</u>, page 84, May 7, 1972.

(180) Nakatani, R. E., "Effects of heated discharges on anadromous fishes," Chapter 10, <u>Biological Aspects of Thermal Pollution</u>, (Krenkel, P. A, and Parker, F. L. editors), Vanderbilt University Press, pages 294-317, 1969.

(181) Höhne, E., "Assessment of degree of eutrophication by measurement of light dispersion," Fortschreibungen Wasschemie Grenzgeb,, volume 8, pages 82-98, 1968.

(182) MacKenthun, K. M. and Kemp, L. E., "Assessing temperature effects with biology," <u>Proceedings American Power Conference</u>, volume 31, 1969.

(183) Armstrong, N. E., Gloyna, E. F. and Copeland, B. J., "Ecological aspects of stream pollution," University of Texas Water Resources Symposium, number 1, pages 83-95, 1968.

(184) Kowo, A. J. and Philips, G. R., "Identification pf mathematical models for DO and BOD concentration in polluted streams from noise corrupted measurements," <u>Water Resources Research</u>, volume 7, number 4, pages 853-862, August 1971.

(185) Davidson, B. and Bradshaw, R. W., "Thermal pollution of water systems," <u>Environmental Science and Technology</u>, volume 1, page 618, 1967.

(186) Koivo, A. J. and Phillips, G. R., "On determination of BOD and parameters in polluted stream models from DO measurements only," <u>Water Resources Research</u>, volume 8, number 2, pages 478-486. April 1972.

(187) Lee, E. S. and Hwang, I. K., "Dynamic modelling of stream quality by invariant imbedding," Water Resources Bulletin, volume 7, number 1, pages 102-114, February 1971.

(188) Hoover, T. E. and Arnoldi, R. A., "Computer model of Connecticut River pollution," Journal Water Pollution Control Federation, volume 42, page 67, 1970.

(189) Dysart, B. C., III, "Water quality planning in presence of interacting pollutants," Journal Water Pollution Control Federation, volume 42, page 1515, 1970.

(190) Fan, L. T. et al, "Optimization of power plant cooling water discharge in streams", Proceedings American Society of Civil Engineering, volume PO4, pages 841-860, Dec. 1971.

(191) Itazawa, Y., "An estimation of the minimum level of DO in water required for normal life of fish," Bull. Japan Soc. Sci. Fisheries, volume 37, number 4, pages 273-276, 1971.

(192) Vernberg, F. J. and Vernberg, W. B., "Metabolic diversity in oceanic animals," Marine Biology(W. Ger.), volume 6, page 33, 1970.

(193) Eipper, A. W., "Nuclear power on Cayuga Lake," in Patient Earth, Hart, J. and Socolow, R. H. (editors), Holt, Rinehart, and Winston Publishers, New York, N.Y., 1971.

(194) Roosenburg, W. H., "Greening and copper accumulation in the American oyster in the vicinity of a steam electric gen. station," Proceedings 2nd Thermal Workshop, Chesapeake Science, volume 10 (3-4), pages 241-252, 1969.

(195) Columbia Basin Interagency Committee, "Columbia River water temperature conditions and research requirements," edited by Federal Water Pollution Control Administration, Portland, Oregon, 1966.

(196) Bella, D. A., "Environmental considerations for estuarine benthal systems," Water Research, volume 6, number 11, pages 1409-1418, November 1972.

(197) Soltero, R. A., Wright, J. C., and Horpestad, A. A., "Effects of impoundment on the water quality of the Bighorn River," Water Research, volume 7, number 3, pages 343-354, March 1973.

(198) Dailey, J. E., and Harleman, D. R. F., "Numerical model for the prediction of transient water quality in estuary networks," Ralph M. Parsons Laboratory Report number 158, Department of Civil Engineering, M.I.T., 226 pages, October 1972.

(199) Wilbur, C. G. (editor), The Biological Aspects of Water Pollution, C. C. Thomas, Publisher, Springfield, Illinois, 1971.

(200) Koolen, J. L., "Biological effects of cooling water discharge," Government Institute of Sewage Purification and Industrial Waste Treatment, Report number 7, Department of Surface Water, Voorburg, Netherlands, pages 39-49, April 1971.

(201) Gloyna, E. F., "Unsolved engineering problems in water quality management," in Man and his Environment, volume 1, Pergamon Press, New York, pages 29-42, 1970.

(202) Sladen, B. K., "Ecology of animal communities" in Biology of Populations, American Elsevier Publishing Company, New York, Nuclear Science Abstracts, volume 25, 11006, 1971.

(203) Tyler, G., "Heavy metals pollute nature, may reduce productivity," Ambio, volume 1, number 2, pages 52-59, April 1972.

(204) Marine Pollution Bulletin, "Heavy metals in Somerset marine organisms," Marine Pollution Bulletin, volume 4, number 1, (author Peden, J. D., et al), pages 7-9, January 1973.

(205) Freke, A. M., "A model for the approximate calculation of safe rates of discharge of radioactive wastes into marine environments," Health Phys., volume 13, pages 743-758, July 1967.

(206) Chipman, W. A., "Ionizing radiation," in Marine Ecology, volume 1, part 3, Kinne, O. (editor), Wiley Interscience, New York, pages 1579-1658, 1972.

(207) Donaldson, L. R., "Evaluation of radioactivity in the marine environment of the Pacific Proving Ground," in Nuclear Detonations and Marine Radioactivity, Small, S. H. (editor), Norwegian Defense Research Establishment, Kjiller, Norway, pages 73-83, 1964.

(208) Auerbach, S. I., "Ecological considerations in siting nuclear power plants : The long-term biotic effects problem," Nuclear Safety, volume 12, number 25, 1971.

(209) Staub, C. P., "Radioactive wastes," Literature review in Journal Water Pollution Control Federation, annual feature, volume 44, number 6, pages 1115-1123, June 1972.

(210) Garner, R. J., "Transfer of radioactive materials from the terrestrial environment to animals and man," C.R.C. Critical Reviews in Environmental Control, Chemical Rubber Company, volume 2, number 3, pages 337-385, 1971.

(211) Berkowitz, D. A., and Squires, A. M., "Power generation and environmental change," Massachusetts Institute of Technology Press, Cambridge, Mass., 1971.

(212) Gruhl, J., "Quantification of atmospheric environmental impact of electric power generation," Report number 5, Energy Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts, March 1973.

(213) Krenkel, P. A. and Parker, F. L., "Engineering aspects, sources and magnitudes of thermal pollution," in Biological Aspects of Th. Poll., Vanderbilt U. Press, pages 10-52, 1969.

(214) Hill, C. T., "Thermal pollution and its control," in Environmental Affairs, volume 2, number 2, pages 406-420, Fall 1972.

(215) Singer, F. S., "Environmental quality and the economics of cooling," in Power Generation and Environmental Change, Berkowitz, D. A. and Squires, A. M. (editors), Massachusetts Institute of Technology Press, Cambridge, Massachusetts, pages 343-350, 1971.

(216) Belter, W. G., "Thermal effects - a potential problem in perspective," in Power Generation and Environmental Change, Berkowitz, D. A. and Squires, A. M (editors), Massachusetts Institute of Technology Press, Cambridge, Massachusetts, pages 365-386, 1971.

(217) Woodson, R. D., "Cooling towers," Scientific American, volume 224, number 5, pages 70-79, May 1971.

(218) Power magazine special report, "Cooling towers," Power, volume 117, number 3, pages 17-40, March 1973.

(219) Environmental Science and Technology article, "Canals cool hot water for reuse," Environmental Science and Technology, volume 7, number 1, pages 20-21, January 1973.

(220) Davies, I., "Chemical changes in cooling water towers," Air and Water Pollution, volume 10, page 853, 1966.

(221) Czapski, U. H., "Possible effects of thermal discharges to the atmosphere," Proceedings 5th Annual Environmental Health Research Symposium - Thermal Discharges, New York State Department of Health, 1968.

(222) Stephen, D. W., Moroz, W. J., "Plume rise from wet cooling towers in strong winds," Pennsylvania State University, Engineering Research Bulletin B-107, University Park, Pennsylvania, 44 pages, September 1972.

(223) Buss, J. R., "Control of fog from cooling towers," Cooling Tower Institute Meeting, June 26-28, 1967.

(224) Richards, R. T., "Environmental aspects of thermal station design," Civil Engineering, volume 38, number 5, pages 45-47, 1968.

(225) Jensen, L. D., "Nuclear power in the South," Report of the Southern Governor's Task Force for Nuclear Power Policy, 1970 Southern Governor's Conference, pages 89-99, September 22, 1970.

(226) Miller, L. and Long, F. M., "A practical approach to cooling tower noise," Heating, Piping and Air Conditioning, volume 34, pages 141-142, 1962.

(227) Davies, I., "Chemical changes in cooling water towers," Air and Water Pollution International Journal, volume 10, pages 853-863, 1966.

(228) Atomic Energy Commission,"Cost description of alternative plant designs," from form for licensing of new facilities, Form AEC - 1/7/72, pages 9-10.

(229) Van der Horst, J. M. A., "Waste heat in greenhouses," Journal Water Pollution Control Federation, volume 44, number 3, pages 494-496, March 1972.

(230) Mathur, S. P., and Stewart, R. (editors), "Proceedings of the Conference on the Beneficial Uses of Thermal Discharge," New York State Department of Environmental Conservation, Albany, New York, 1970.

(231) Kligfield, G., "Thermal water multi-use demonstration," presented at 1971 Intersociety Energy Conversion Engineering Conference, Boston, Massachusetts, pages 700-710, August 1971.

(232) Kligfield, G., "Utilization of thermal water from nuclear power plants," in Developments in Water Quality Research, Shival, H. I. (editor), Science Publishers, London, Ann Arbor-Humphrey, pages 173-188, 1970

(233) Ludlam, S. D., and McGowan, J. G., "An ecological-engineering study of an agricultural or silvacultural system utilizing heated water from powerplants," presented at 1971 Intersociety Energy Conversion Engineering Conference, Boston, Massachusetts, pages 711-721, August 1971.

(234) Keeney, R. L. and Raiffa, H., "A critique of formal analysis in public decision making," draft copy of a chapter in a book to be published.

(235) Russell, C. S. and Spofford, W. O., "A quantitative framework for residuals - environmental quality management," Proceedings of 1969 Water Resources Seminar, Water Research Center, Purdue University, Lafayette Indianna, page 66, 1969.

(236) Mount, D. I., "Thermal requirements for Lake Michigan," National Water Quality Laboratory, Environmental Protection Agency Report, 1971.

(237) Butler, J. N., "Water quality and chemical models," in Environmental Affairs, volume 2, number 2, pages 382-398, Fall 1972.

(238) Brown, R. M., et al, "A water quality index - crashing the psychological barrier" a paper in Indicators of Environmental Quality, 1972.

(239) Wilhm, J. L. and Dorris, T. C., "Biological parameters for water quality criteria," Bioscience, volume 18, pages 477-481, 1968.

(240) Warren, C. E., Biology and Water Pollution Control, W. B. Saunders Company, London, 1971.

(241) Patrick, R., "Biological measures of stream conditions," Sewage and Industrial Wastes, volume 22, pages 926-938, 1950.

(242) Parker, F. L., Benedict, B. A., and Polk, E. M., "Mixing zones below thermal power plants," a paper presented at the 1971 Intersociety Energy Conversion Conference, Proceedings 1971 Intersociety Energy Conversion Conference, Boston, Massachusetts, pages 722-727, August '971.

(243) Rimmar, G. M., "Use of electrical conductivity for measuring discharges by the dilution method," translated from the original Russian "Trudy GGI," volume 36, number 90, pages 18-48, East Kilbride National Engineering Laboratory, Translation number 749, 1960.

(244) Jones, H. B., "Economics of environmental quality : an ecological perspective," Journal of Environmental Systems, volume 2, number 3, pages 243-254, September 1972.

(245) Searles, H. F., "Unconscious processes in relation to the environmental crisis," The Psychoanalytic Review, volume 59, number 3, pages 361-374, Fall 1972.

(246) Meredith, P. D. and Ewing, B. B., "Systems approach to the evaluation of benefits from improved Great Lakes water quality," Proceedings 12th Conference Great Lakes Resources, pages 843-870, 1969.

(247) Nemerow, N. L. and Faro, R. C., "Total dollar benefit of water pollution control," Proceedings American Society of Civil Engineers, volume SA3, pages 665-674, June 1970.

(248) Smith, R. J., "The evaluation of recreational benefits : the Clawson Method in practice," Urban Studies, volume 8, number 2, pages 89-102, 1971.

(249) Parker, D. S. and Crutchfield, J. A., "Water quality management and a time profile of benefits and costs," Water Resources Research, volume 4, pages 233-246, 1968.

(250) Cooper, C. F., "Systems analysis of water management," Chapter IX in The Ecosystems Concept in Natural Resource Management, (Dyne, G. M. V. editor) Academic Press, Inc, New York, 1969.

(251) Whipple, W., Jr., "Economics," Journal Water Pollution Control Federation, Annual Literature Review, pages 1370-1376, June 1971.

(252) Miller, W. L., and Byers, D. M., "Development and display of multiple - objective project impacts," Water Resources Research Journal, volume 9, number 1, pages 11-20, February 1973.

(253) Morrison, D. L., et al, "Environmental benefit-cost analysis for power generation," American Power Conference Proceedings, volume 34, pages 238-254, 1972.

(254) Whitman, I. L., et al, "Design of an environmental evaluation system," prepared for the Bureau of Reclamation, Battelle, Columbus, Ohio, June 1971.

(255) Reiquam, H., "Establishing priorities among environmental stresses," in Indicators of Environmental Quality, page 71, 1972.

(256) Presidential Committee on Environmental Quality, "First annual report of the Presidential Committee on Environmental Quality," 1970.

(257) de Villiers, A. J., "Effects of air pollution on health," in Man and his Environment, volume 1, (M. A. Ward, editor), Pergamon Press, New York, N. Y., pages 159-176, 1970.

(258) Anderson, D. O., "The effects of air contamination on health : part III," Canadian Medical Association Journal, volume 97, page 802, September 23, 1967.

(259) Kolde, H. E., and Kahn, B., "Radiological surveillance studies at a boiling water reactor nuclear power station - estimated dose studies," paper presented at Health Physics Symposium on Aspects of Nuclear Facility Siting, Idaho Falls, Idaho, November 3-6, 1970.

(260) List, E. J., "Energy use in California : Implications for the environment," California Institute of Technology, Environmental Quality Laboratory Report number 3, Pasadena, California, December 1971.