Ecological Implications of the Once-Through Cooling Process of Thermal Electric Generation in Canada

by

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NO. 1482

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ABSTRACT

The use of surface waters for once-through cooling of thermal generating stations will increase. The processes in condenser cooling create impingement losses at the intake and pumps, entrainment mortality from temperature and mechanical stresses during passage through condensers, and discharge perturbations caused by temperature and current changes. Unfortunately, the thermal effects observed at discharges have received the most attention although effects - mortality, disrupted movement patterns, loss of viable spawning and nursery areas etc. - are minimal by comparison to mortality caused by impingement and entrainment. Most of the above adverse effects from thermal power generation can be almost eliminated through intelligent siting. Disturbingly, it is now becoming apparent that fossil fuel combustion products are a far greater threat to ecosystems than thermal (or even mechanical) perturbations.

RÉSUMÉ

On s'attend à une utilisation accrue, avec le temps, des eaux de surface pour le refroidissement des centrales thermiques, sans recirculation. Le refroidissement par condensation entraîne une mortalité causée par les heurts, au niveau de l'alimentation et du pompage, une mortalité due à la température et au stress mécanique pendant le passage dans le condenseur et des perturbations dues aux changements de température et de courants au moment du rejet. Malheureusement, les études antérieures ont surtout porté sur les effets thermiques aux exutoires, là où la mortalité, les perturbations motrices et les pertes de frayères et de milieux de croissance sont minimes comparativement à la mortalité due aux heurts et à l'entraînement. La plupart des effets néfastes des centrales thermiques peuvent être pratiquement évités par un choix judicieux de leur emplacement. Malheureusement, il semble de plus en plus évident que l'utilisation des combustibles fossiles pose une menace beaucoup plus sérieuse aux écosystèmes que les perturbations thermiques (ou même mécaniques).

INTRODUCTION

With the increasing demand for electrical energy comes the need to better understand the ecological implications of efforts made to meet demand. Canadian electrical supply originates from hydroelectric and thermal-electric generating stations, the latter coming into prominence about 1950. Although the capacity for hydroelectric power is not fully exploited (Efford 1975), its proportionate contribution to growth of power supply has progressively decreased and is expected to continue decreasing. In provinces like Nova Scotia, Ontario and Saskatchewan, sources for hydroelectric power have largely been exploited and will contribute minimally to future growth in power output.

Annual literature reviews to thermal effects are available (Coutant 1968, 1969, 1970, 1971; Coutant and Goodyear 1972; Coutant and Pfuderer 1973, 1974). However, neither literature reviews nor published symposia (Krenkel and Parker 1969; Parker and Krenkel 1969; Saila 1975) successfully delineate the spectrum of ecological effects let alone relate these to the process of using water for cooling. This article attempts to do so but uses almost exclusive reference to fish. As well, we intend describing type and magnitude of effect, particularly in freshwaters. Measures ensuring environmental integrity will be tendered as amenable to water quality or guideline establishment.

The St. Lawrence Great Lakes currently provides cooling waters for 139 thermal generating stations (IJC 1975) greater than 10 megawatts (Mw). The Canadian portion of this accounts for two-thirds of its current national power production by thermal electric units. Consequently, the Great Lakes shall receive most of our attention.

THE POWER INDUSTRY

Electrical Generation in Canada

"It is sometimes stated that the degree of progress and civilization of a country may be gauged by its electric development; in this respect....Canada stands in the front rank".. Denis (1918).

Water power and wind power have been used industrially for several centuries but it has been only during the last century that the changes in energy sources and consumption rates have been particularly dramatic. As implied by Denis (1918) economic progress is usually associated closely with the available energy. In Canada, generating capacity has increased from a modest production of 133 Mw in 1900 to a total, all types of electrical generation, of 54,271 Mw (Statistics Canada 1974). Thermal electric generation development was slow (Fig. 1) and relatively unimportant until the early 1950's. Thermal electric generation now provides almost 40% of Canada's electrical production.

Demand and the subsequent growth in the electrical

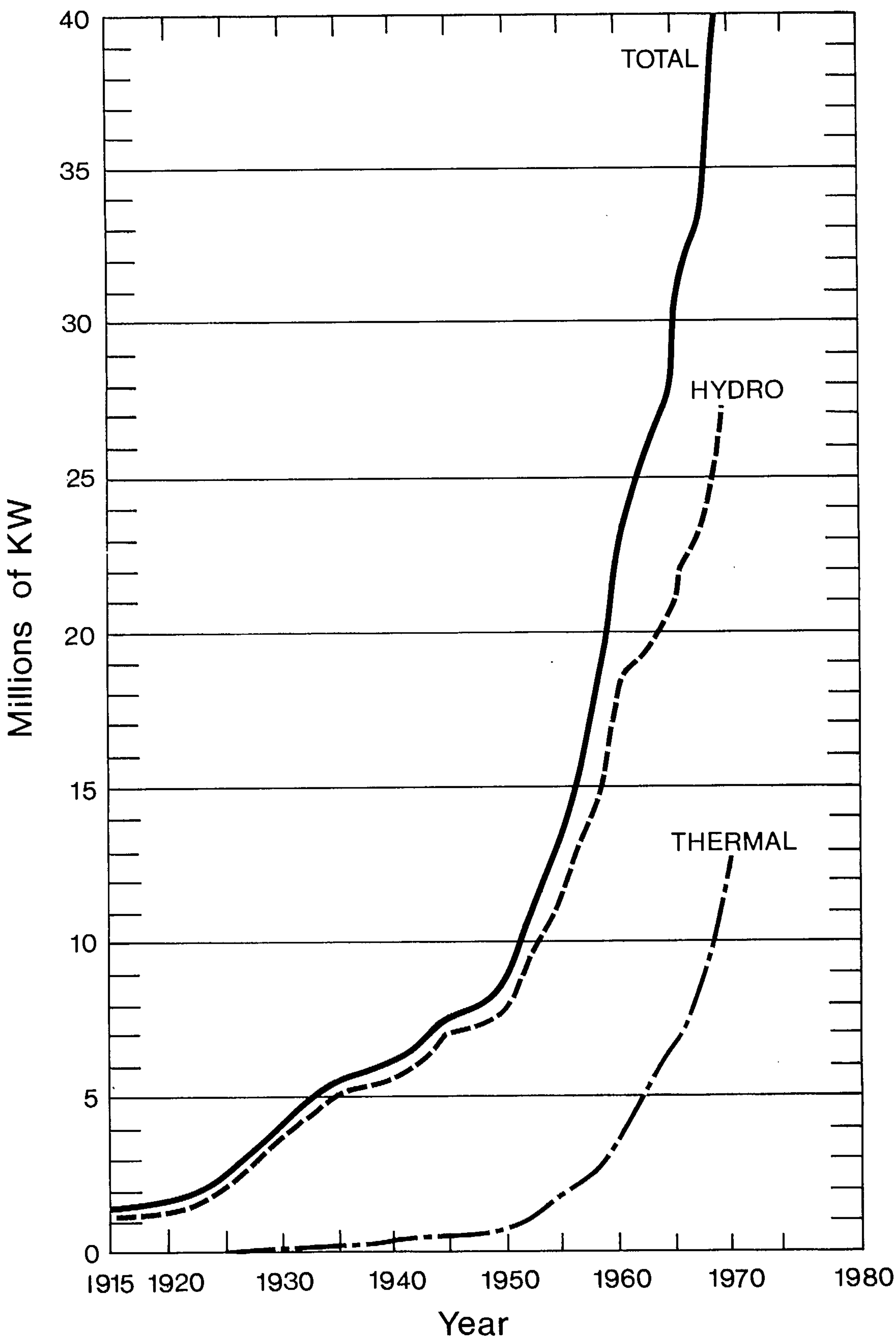

Figure 1. Growth of thermal- and hydro-electric power generating capacity in Canada since 1915. Source: Dept. Energy, Mines & Resources (1969).

generating industry closely paralleled the economy (Fig. 1). During the prosperous 1920's, demand was heavy until depressed conditions in the 1930's curtailed the rate of power plant installation. After World War II, industrial expansion coupled with rapid residential and agricultural development placed heavy demands on electrical generating programs. Although Canada's economically feasible hydroelectric power potential is near 95,000 Mw (Efford 1975), access to transmission systems, environmental effect, and increasing construction cost are curtailing substantial future development. Reflecting this, the contribution of hydroelectric stations to Canada's electrical supply has shrunk from over 90% in 1950 to about 60% in 1973.

Currently, Canada requires annually 97,939 million L^3 day^{-1} of water of which 48% is used for thermal electric generation (Canada Year Book 1972). In Ontario, water use is 52,589 million L^3 day^{-1} of which 67% is required for use in cooling of thermal electric generation. Obviously, water for cooling in thermal electric power plants comprises the major use of water in Canada.

Predictions of future energy needs in Canada (National Energy Board 1969; Dennison and Elder 1970; Montreal Engineering Co. Ltd. 1971; Ontario Hydro 1974) differ only marginally in their interpretations of events to come. In general, use of electricity will apparently double each 10 years or possibly less and the percentage of generation from thermal means is

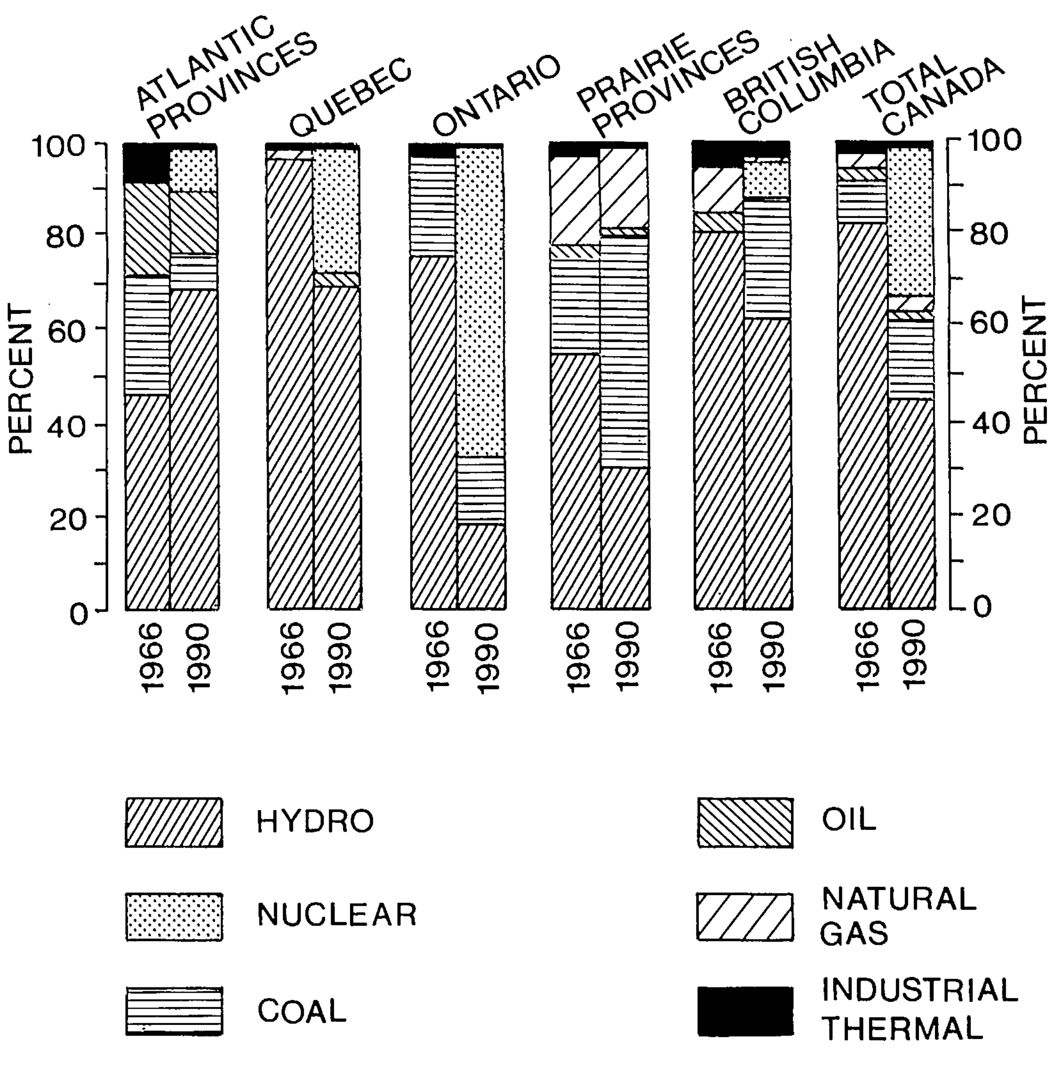

Figure 2. Energy source by region in Canada for electrical power generation, 1966-1990.
Source: National Energy Board (1969).

expected to increase from 37% in 1973 to 85% in the year 2000 (Montreal Engineering Co. Ltd. 1971). Although regional differences (Fig. 2) have existed in method of power production and will continue to exist, the general Canadian trend toward thermal generation of electricity will persist.

Population and industrial production in the Great Lakes basin has more than tripled in the last 50 years and the press of development has created a substantial demand for water. As in other parts of Canada, electrical utilities have adopted direct condenser cooling systems. In 1974, 139 thermal power plants greater than 10 Mw ringed the shores of the Great Lakes, but of these, only 10 are located in Canada (IJC 1975). These Canadian power plants averaged 1580 Mw with none smaller than 100 Mw. A few power plants (Environmental Protection Service 1975) were not included in the IJC (1975) survey; however, total generating capacity of these 8 stations is only 104.5 Mw. Average size of power plants will undoubtedly increase (Ontario Hydro 1974) as consumer demand is met, in many cases, by increasing the capacity of existing stations.

Dennison and Elder (1970) have estimated that in Lake Ontario, by 2000 AD, all man-made thermal inputs to the Great Lakes will be equivalent to 6% of the existing annual natural heat content variation within the lake. Although calculations like these are impressive, they make no ecological sense since the very important local effects are masked by translating the

Table 1. Heat rejection to cooling water - Canada.
From Montreal Engineering Co. Ltd. (1971)

Year	Heat Rejection	Great Lakes	Remainder of Canada			Canada		
		Fresh Water	Fresh Water	Tidal Waters[a]	Total	Fresh	Tidal	Total
1970	BTU/Hr. x 10^{10}	3.165[b]	1.65	1.21	2.86	4.815	1.21	6.025
	Water Loss by Evaporation USgpd x 10^{6}	69	36	28	64	105	28	133
2000	BTU/Hr. x 10^{10}	60	38.6	38.1	76.7	98.6	38.1	136.7
	Water Loss by Evaporation USgpd x 10^{6}	1308	846	838	1684	2154	838	2992

(a) 100% of future thermal plant assumed to be Salt Water Cooled in Newfoundland, Prince Edward Island, Nova Scotia, New Brunswick, British Columbia and 50% in Quebec.

(b) 1968 total x 1.3225, assuming 15% annual growth rate for region.

(c) Using ratio $\frac{\text{BTU/Hr.}}{\text{USgpd}}$ = 21.8 derived from figures for Remainder of Canada.

problem into lakewide terms. Nevertheless, the Great Lakes today carry 66% of Canadian thermal generation (Table 1) and although this is predicted to decrease slightly to 61% by 2000 AD (Montreal Engineering Co. Ltd. 1971) the brunt of the requirement for cooling water will still be borne by the Great Lakes.

A nation's economic progress is usually allied with its available energy as demonstrated by the relation between *per capita* energy consumption and its gross national product (Fig. 3). It should be noted, however, that Canada uses twice the amount of electricity per capita than that consumed by Sweden, a country with comparable climate, GNP and standard of living (International Atomic Energy Agency 1973). With the observed changes in electrical production and predicted future trends, the need to grapple with sources for generation of thermal electrical power, and ensuing environmental influences, becomes more pressing.

Power Production Process and Once-Through Cooling

Thermal electric (steam electric) generating stations convert water to the high pressure steam which powers turbines and electric generators. The difference between systems arises from the use of fossil fuels -- oil, natural gas or coal -- as opposed to nuclear energy to create high pressure steam. In nuclear power generation, the reactor corresponds to the

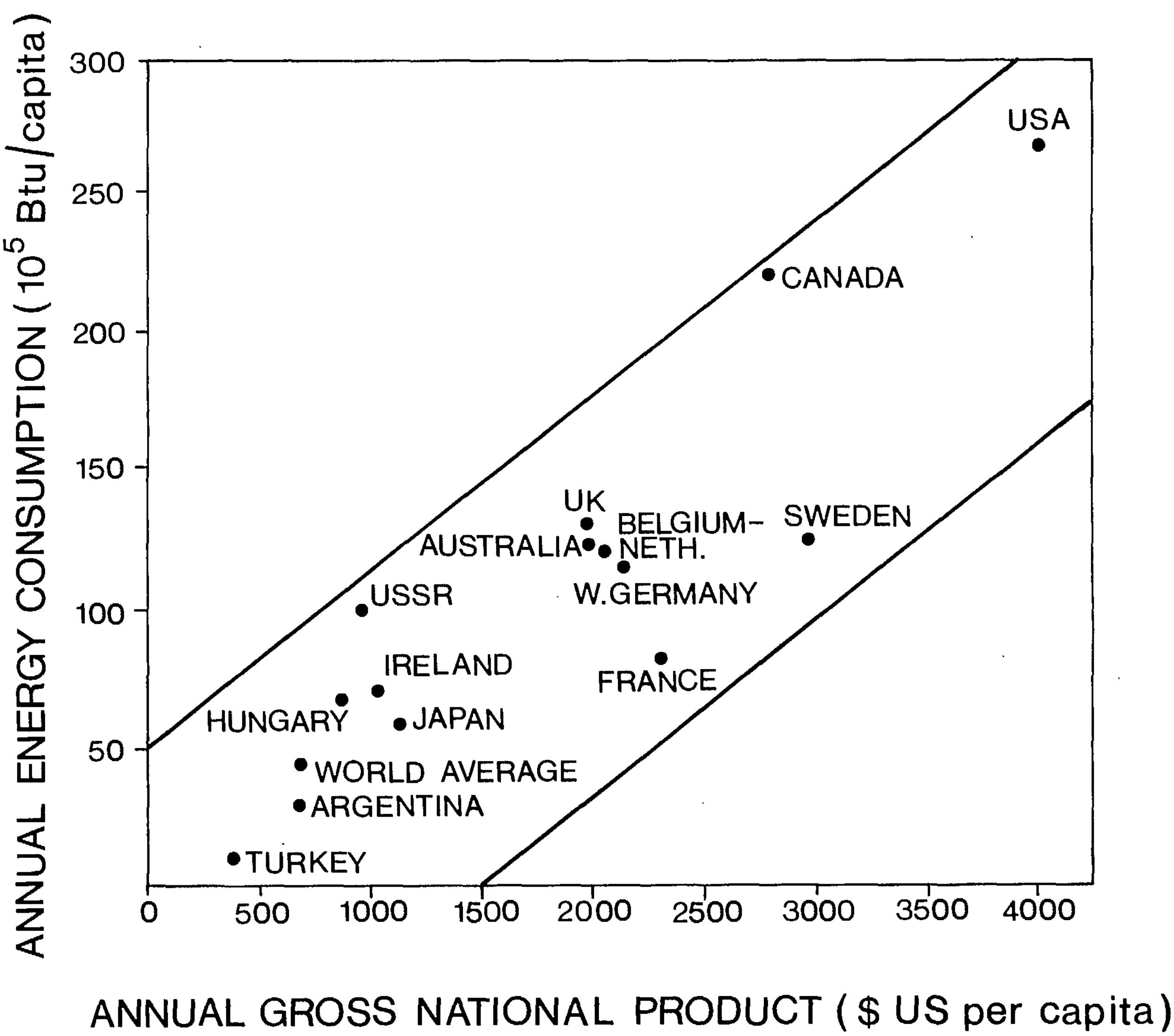

Figure 3. Annual energy consumption of 14 nations in relation to gross national product.
Source: Internat. Atomic Energy Agency (1973).

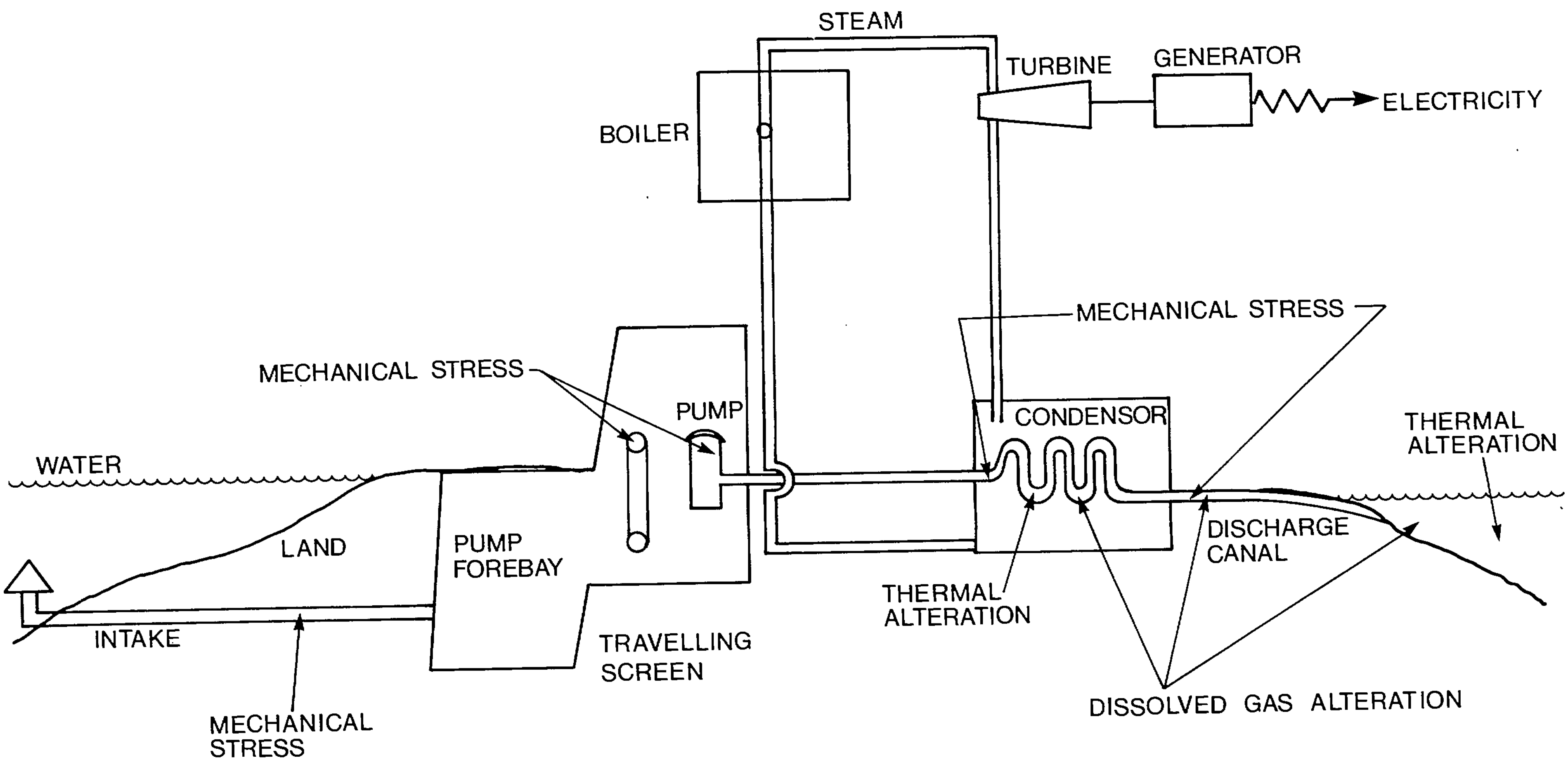

Figure 4. Schematic configuration of a thermal electric generating station and probable loci of effect.

furnace of a fossil-fueled power plant (Fig. 4). Since neither method of converting heat to electricity uses all the energy available, steam, decreased in temperature and pressure after having passed through the turbines, must be condensed before reheating for maximum efficiency (Fig. 4). It is from the condenser cooling system where aquatic environmental concerns due to heat arise.

Steam turbines using fossil fuels may attain thermal efficiencies of ≈40% while nuclear power plants are less efficient although comparable to the average thermal efficiency, about 30%, of fossil fueled plants (International Atomic Energy Agency 1973). Ontario Hydro (1973) has estimated that the Lennox station, oil-fired, will attain a conversion efficiency of 37% while the nuclear fueled Pickering station attains an efficiency of 29%.

Typically, then, thermal electric stations consist of a steam cycle and a steam cooling cycle, the contents of which do not physically mix (Fig. 4). Nuclear and fossil fuel plants consist of a heat source, boiler, turbines, generator and a condenser system. The most economical method of steam condensation is by passing cooling water from a natural source through the condenser system and back into the source at a subsequently elevated temperature (once-through cooling). Heat exchange takes place in the condenser unit consisting of banks of several thousand tubes, each approximately 2.5cm in diameter and about 25 m in length. Since the cooling water is pumped through the condensers at a rate of about 2 m/s, heat addition occurs in less than 0.5 min.

The change in temperature of the cooling waters, ΔT, ranges from 5.6 to 18.6 C (Schubel 1975) with a mean somewhere near 10 C. Since the conversion efficiencies of nuclear power plants are lower than conventional fossil units, larger quantities, about 1.5 times, of cooling water are required to maintain similar ΔT's. Conversely if the same volume of cooling water is required, heat rejection to it is proportionately greater. Irrespective of the ΔT and volume, the time course of temperature change in cooling water is dramatic although variable (Fig. 5). The maximum change in temperature occurs during the first few seconds and return to ambient may take any number of hours. In the Great Lakes, natural surface temperatures are normally regained within eight hours (R. V. Elliott personal communication). Although elevated discharge temperatures are attenuated by increasing length of discharge canals, the short discharge canals used in Canada generally promote rapid return to ambient temperatures.

Characteristics of the Discharge

Water, after passing through condensers, is returned to the source via either an onshore surface discharge canal or, in some cases, an offshore submerged diffuser. Since the

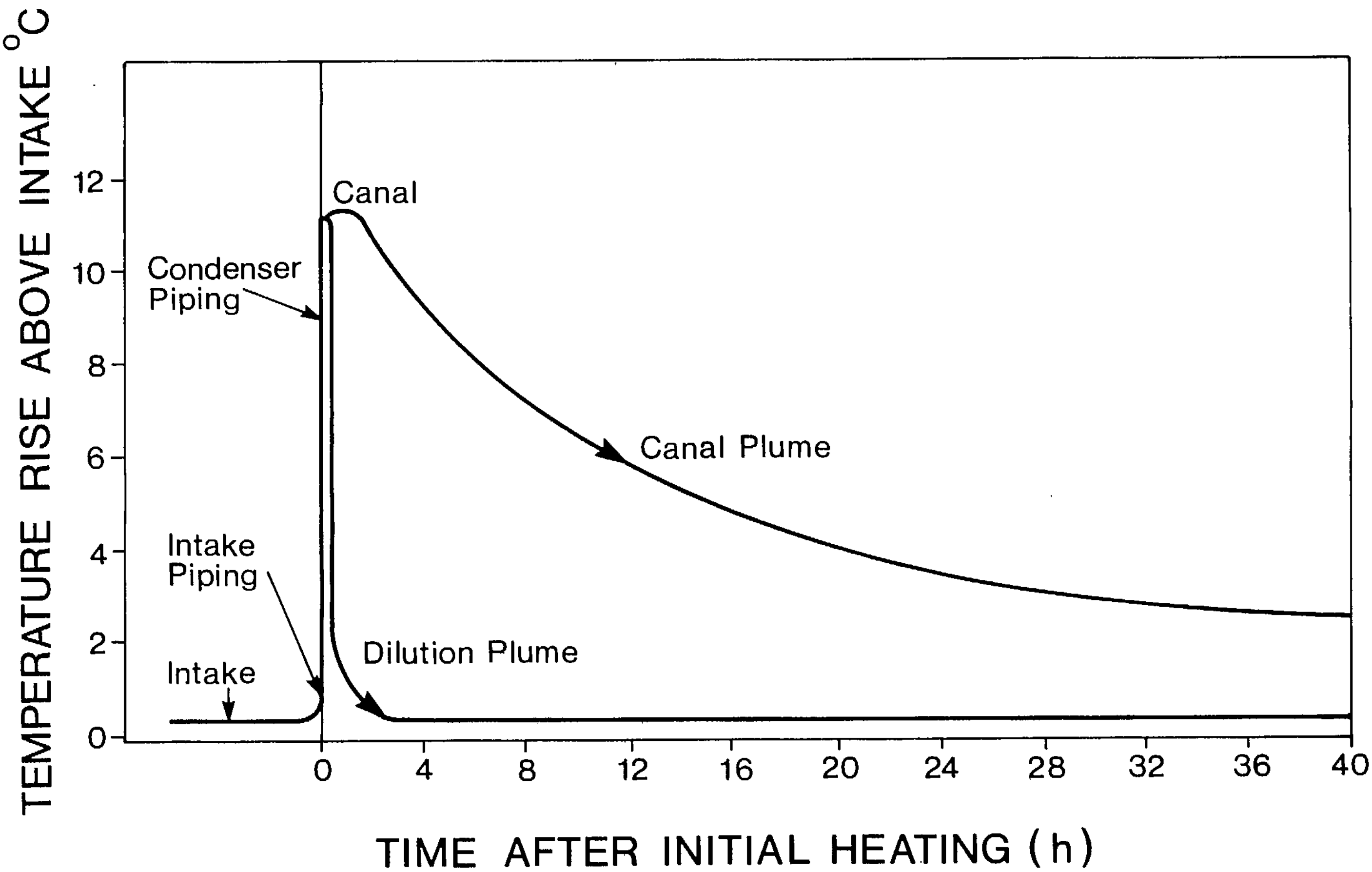

Figure 5. Time course of temperature change in cooling water passing through a hypothetical generating station.

added heat is not dissipated instantaneously, a thermal plume develops. The excess temperature is primarily dissipated by way of horizontal mixing. Direct heat transfer from the plume to the atmosphere has been estimated to be around 10% of the outfall heat load. Dissipation in the vertical plane is negligible as the heated water is less dense than the receiving water and consequently tends to float. The vertical mixing rate is usually 2 or 3 orders of magnitude less than horizontal mixing in aquatic environments (Smith 1975).

Thermal plumes are usually defined as the mass of water confined by a convenient isotherm, 0.5 or 1 C, above the prevailing ambient conditions. It should be noted that ambient temperature is often not easy to define in the vicinity of an outfall, where a 1 or 2 C variation is not unusual. Within a plume, two zones can be recognized: 1) A small volume of high turbulence and velocity induced by the discharge in the immediate vicinity, and 2) a volume where, although temperatures are still elevated above ambient, the turbulence and velocity levels approximate those of the receiving water body (Fig. 6).

The discharge-induced characteristics of the plume result from the combined effects of the flow rate, the heat-induced density difference relative to the ambient receiving water, and the discharge velocity which in turn is determined by the characteristics of the outfall i.e. position, width, depth, etc. Asbury and Frigo (1971) have shown that the surface

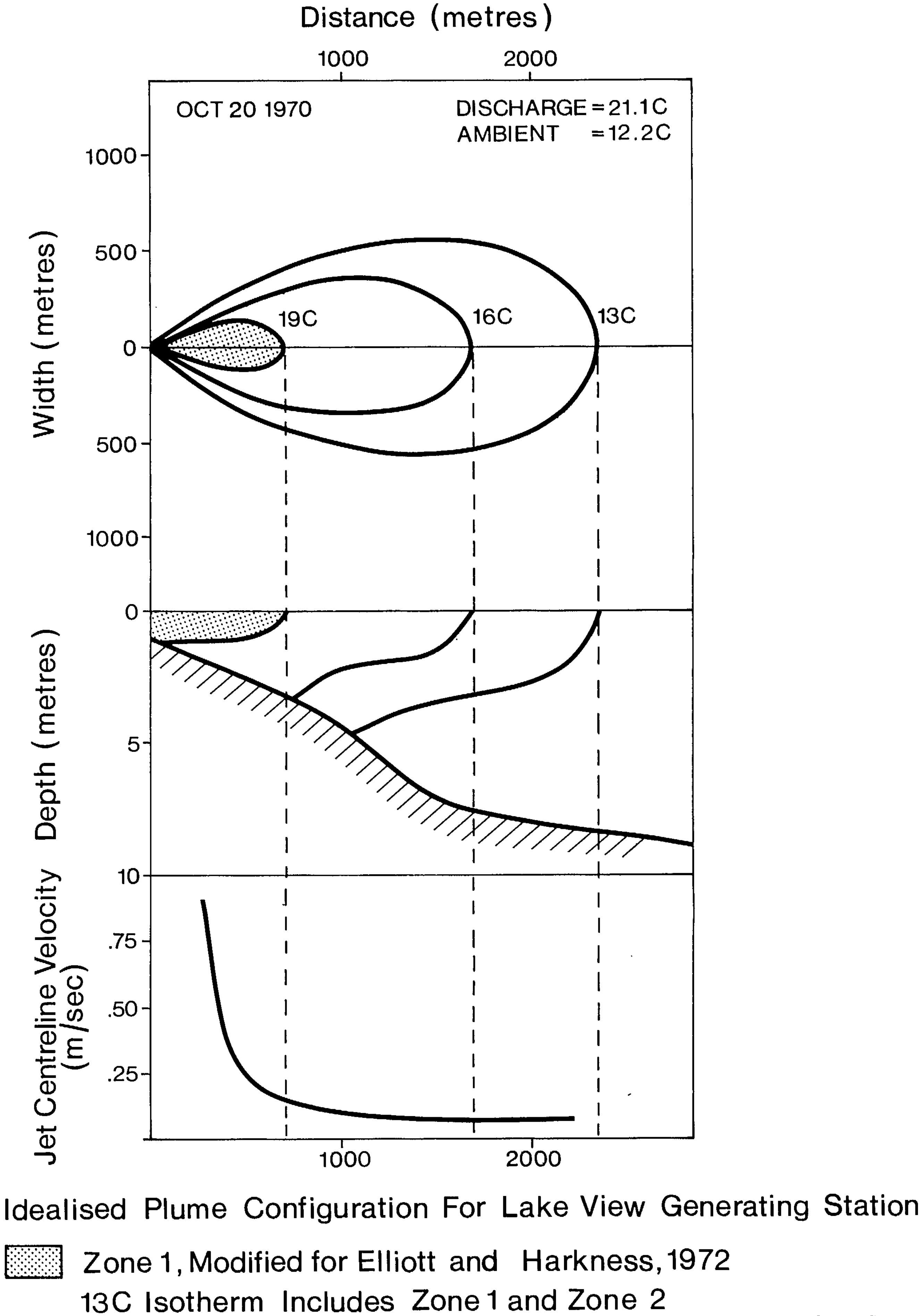

Figure 6. Idealized plume configuration for Lakeview Generating Station, Ontario, modified from Elliott and Harkness (1972).

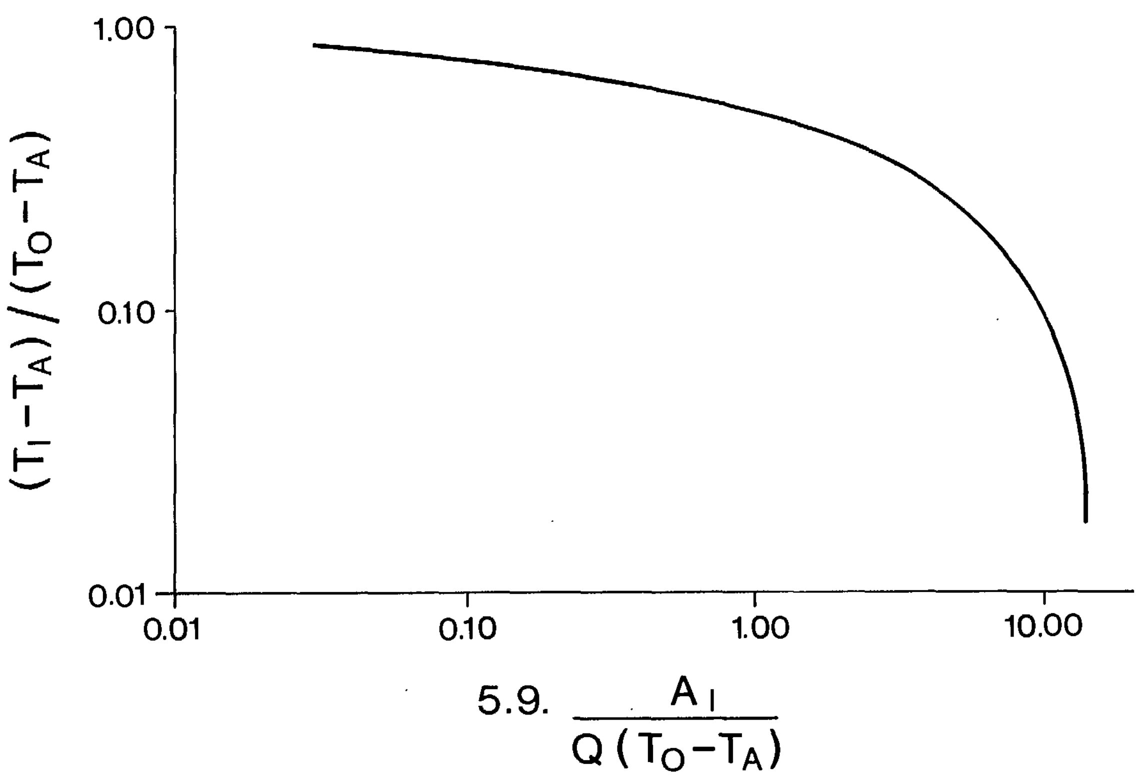

Figure 7. Surface plume area decay from Elliott and Harkness (1972).

plume area relative to temperature decay, conforms to a simple empirical model. An equation was fitted to the available data (Fig. 7) by Elliott and Harkness (1972):

$$\frac{T_I - T_A}{T_o - T_A} = 1.0 - 0.0972 \left(\frac{A_I}{Q(T_o - T_A)}\right)^{0.297}$$

where T_o - Temperature C at outfall

T_A - Temperature C at ambient

T_I - Temperature C at bounding isotherm

A_I - Area m^2 within T_I

Q - Discharge m^3/s

This relationship has been found to be applicable to most power plant studies irrespective of whether the discharge is into a lake, a river or the ocean. In the area of turbulent mixing, the most severely affected by the discharge, temperature increases are greatest; however, from Fig. 6 and 8 it is apparent that less than 1% of the area subject to thermal alteration is affected.

In the absence of any current in the receiving water body a plume would develop with an axis in line with the direction of the discharge jet (Fig. 6). However, all natural water bodies receiving heated cooling water have currents. There are generally three classes of receiving water body: 1) rivers and estuaries, 2) small lakes and reservoirs and 3) large lakes and oceans.

In rivers and estuaries, the extent of thermal alteration

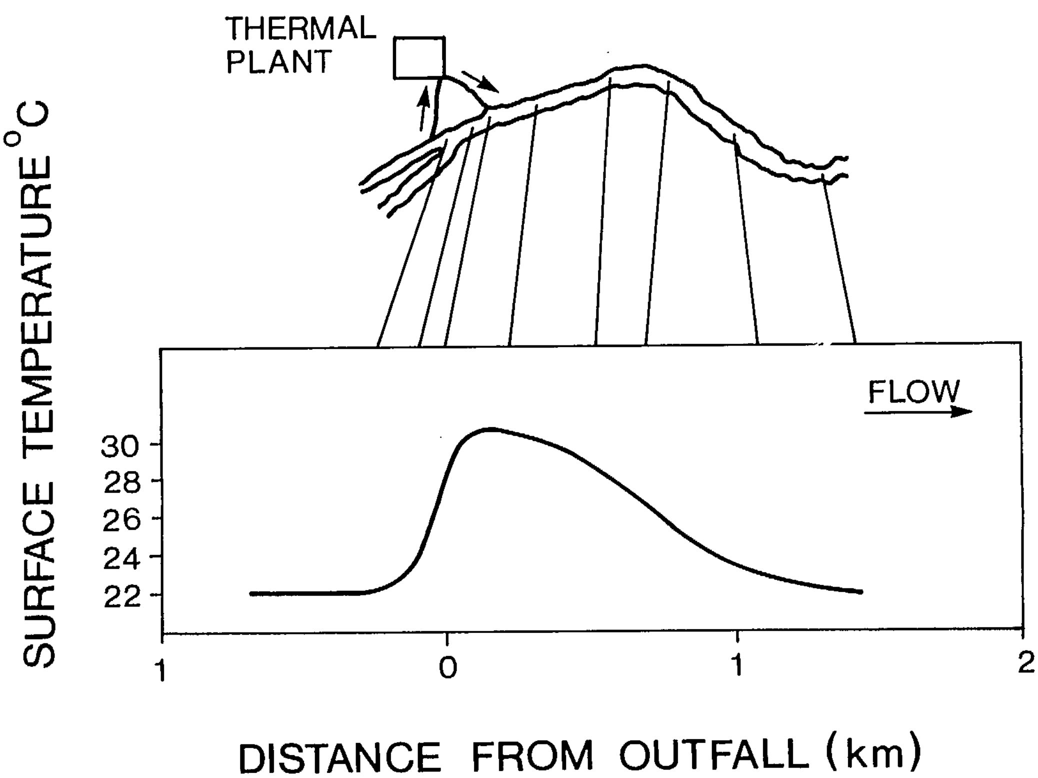

Figure 8. Characteristics of a thermal discharge on a small river, River Ouse, England.

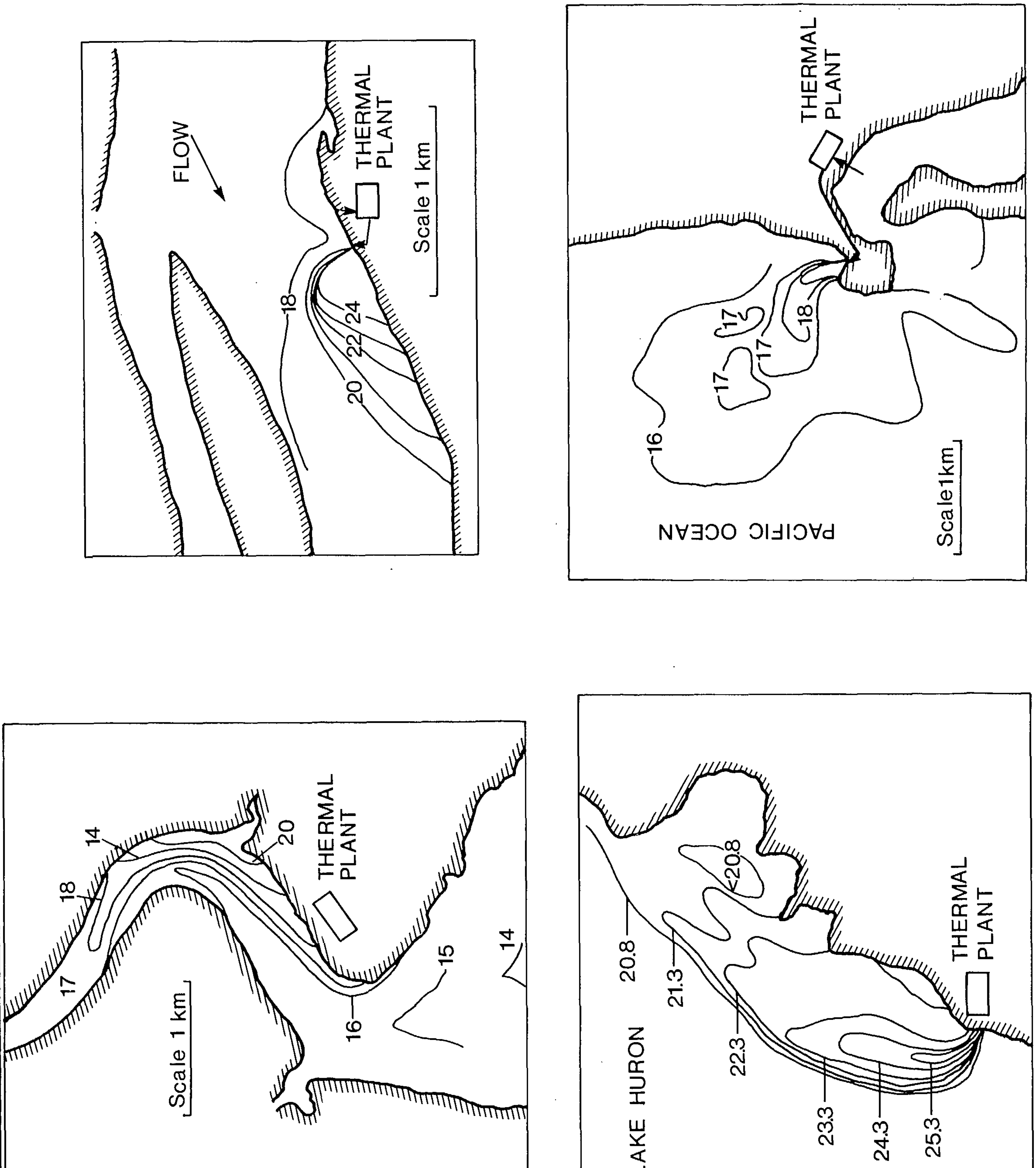

Figure 9. Typical plumes emanating from thermal generating stations in a river (upper left), estuary (upper right) and exposed shorelines (bottom).

depends on the fraction of natural flow utilized for cooling purposes and the morphometry of the receiving water body. The plume axis is deflected by the natural flow. In small rivers, the plume can occupy the full width as exemplified by the waste heat discharge into the River Ouse, England, of the Goldington Power Plant (Fig. 8). This example is typical of small river modifications though the heat load is intermittent here as cooling towers are in use. In larger rivers the plume will tend to hug the near bank when the discharge is a small fraction of natural flow. An example of this type is the plume at the Contra Costa Power Plant on the San Joaquin River, California (Fig. 9). Estuaries are affected in a similar fashion to rivers though the tidal ebb and flow modifies effects profoundly. In the example (Fig. 9) on the estuary of the River Usk, England, the plume of the Uskmouth Power Station migrates upstream at low slack water and the result is an accumulation of heated water which is confined to one bank of the estuary. In these situations, particularly smaller rivers, the plume will extend to the bottom and elevated temperatures are often present several kilometres downstream from the outfall. In estuaries the freshwater flows over saltwater and this will restrict the vertical extension of a thermal plume.

In many situations small lakes and reservoirs are used essentially as cooling ponds for power plants. Intake water is usually derived from a nearby river or lake or, if deep enough, from the hypolimnion of the receiving water body. The effects are continually elevated surface temperatures, deeper and longer stratification and in some cases, elimination of the hypolimnion (Sundaram and Rehn 1971).

In large lakes, nearshore currents generally run parallel to the shoreline, partly under the influence of local winds which tend to conform to the shoreline. Thus the plume is deflected to run parallel to the shore (Fig. 9). During current reversals, the plume is usually carried back on itself and reorganizes downstream. Reversals may occur in a matter of several hours (Csanady 1970). Generally speaking the nearshore parallel flow undergoes little exchange with the offshore, this is particularly true in the spring when thermal bar conditions develop in large temperate lakes. Thus the overall impact of heat loads in large lakes must be considered primarily in terms of the nearshore zone where there is the potential for the merging of many plume effects along an extensive section of shoreline. The oceanic coastal situation is similar (Fig. 9) though the ebb and flow of tides exert a considerable disruptive influence (Fig. 9).

Thus far we have only considered surface buoyant plumes. Under certain conditions a sinking plume is generated (Hoglund and Spigarelli 1972). If the ambient receiving water body (freshwater) has a temperature somewhat less than 4 C, as the plume develops the mixing will produce a plume segment which is at 4 C, when freshwater attains its greatest density. The plume will consequently sink and mix further below the surface. This sinking plume can impinge on the bottom of the receiving water body resulting in the elevation of temperature in sediments and the overlying water. Sinking plumes, however, may raise bottom temperatures only up to 4 C.

ECOLOGICAL EFFECTS

In the once-through cooling process, the only cooling procedure used in Canada to date, several major possibilities for adverse ecological effect, real or potential, exist (see Fig. 4). Ecological effects arising from thermal electric stations should not be abstracted into a catch-all, like "thermal pollution", an expression that is still popular. Rather, since the electrical generation process is a complex one, the environmental issue must be related to the causative agent in the electrical generating process. Many factors may become important depending upon the nature of the generating station and procedures used, of which a few are: mortality due to impingement, entrainment and temperature; acute and residual effects of biocides, primarily chlorine, used as an anti-fouling agent in condenser tubes; acute and residual effects from gas changes, oxygen and nitrogen; contaminants resulting from corrosion or cleaning of components in either steam or cooling cycles; fossil fuel emission products which are distributed via atmospheric fallout; leachates from coal piles, ash lagoons etc. Obviously the scope for ecological harm is broad but we choose to deal primarily with the area most often discussed and frequently the least understood; namely, the direct effects encountered as a result of using water for condenser cooling.

Impingement

Impingement refers to the forcing of nektonic species and, in some cases, benthic shellfish against screen meshes designed to eliminate entrainment of large items into the cooling system. The pumps controlling condenser cooling water flow (Fig. 4) generally create high velocity fields in forebays and observed impingement mortality arises usually when exhaustion of biota causes collision with screens and collecting devices (Fig. 4). Individuals fatigued to the point where they cannot remove themselves from the travelling screens are therefore carried into waste bins.

Of the freshwater biota, only fish have been impinged in quantity and losses are primarily controlled by the combination of nearshore fish density, intake location and intake structure. "Pollution" in ecosystems has been most commonly measured through gross observations, such as mortality; therefore, an area where adverse ecological effect from electrical generating stations is easy to relate to is mortality at intake screens. However, few adequate data series are available.

Ontario Hydro, in 1974, commenced monitoring fish mortality at intakes and found, for the thermal generating stations in Ontario, annual losses to fish standing stocks varying from 1 to 232,000 kg (Ontario Hydro 1975). Losses during 1975 covered a similar range with maximum of 328,840 kg (Ontario Hydro 1976). At these impingement rates, the losses appear significant in relation to commercial fish catches but are placed in perspective when examined by species, as few valued species are normally impinged. It is apparent from Table 2 that wide variability exists as to quantity impinged and periods of maximum loss. Further, impingement mortality is extremely variable as neighbouring plants e.g. Lakeview and Hearn have widely differing impingement rates. Generally, few species valued by commercial or sport groups are killed, comprising ≈2% of total impingement mortality. Direct losses of 500,000 kg occurred during 1975. Although this represents 4% of the annual total weight of commercial landings for the Great Lakes, losses to valued fish stocks is small because of the predominance of species such as alewife (<u>Alosa pseudoharengus</u>) in fish killed through impingement. Fish communities in the

Table 2. Impingement of fish (all in kg except Nanticoke where weight & number are provided) at several thermal generating stations in the Great Lakes, 1975.

Station, Ont.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Pickering	867	4,193	12,699	249,626	33,073	10,790	4,380	3,074	4,254	2,153	2,736	995
Douglas Point	5,415	910	0	85	935	553	1,048	0	0	0	0	2,405
Hearn	113	14	671	9,116	10,124	724	86	61	69	44	64	175
Lakeview	40	0	1,865	14,407	14,321	2,958	180	514	15	315	0	0
Lambton	11,252	40,563	3,822	5,689	945	440	177	154	95	162	278	11,127
Nanticoke:												
Smelt and Alewife (kg)	108	12	625	291	137	23	18	35	54	65	1,248	56
Other species (numbers)	207	253	239	237	90	226	82	32	34	55	103	102

Great Lakes have, however, been altered through time by a variety of factors and it is unknown whether rehabilitation of fish stocks will influence the species normally removed through impingement as power plants. Although the lakewide effect appears small, there is an obvious opportunity for local depletions to cause community changes.

Entrainment

Organisms may be caught up in cooling waters and exposed to elevated temperatures either during passage through condensers or following re-entry of the cooling water into the receiving body. Although intake placement strategy will influence taxa of entrained organisms, planktonic organisms are the most vulnerable. Planktonic organisms, including fish larvae and eggs, can therefore be drawn into the cooling water intake of a thermal generating station, passed through condensers and discharged back into the environment or they may be entrained into thermal plumes without passing through the power plant. Screens and collecting devices (Fig. 4) impose an upper size limit less than condenser tube size, 2.5 cm, for organisms prone to entrainment. Otherwise, intake location, intake design and water supply characteristics determine the taxonomic composition of non-screenable organisms passing through condensers.

Once entrained into the plant, organisms may be subjected to thermal, mechanical, pressure and biocidal stresses. Exposure to elevated temperature during entrainment varies according to plant operating conditions but severest exposures are for organisms following the full course from passage through the plant to a return to ambient conditions via the plume centreline trajectory (Fig. 5). The initial rise to maximum exposure generally requires less than one minute but the duration of maximum exposure depends primarily upon the time delay imposed by discharge structures which return cooling waters to the receiving water body. Time required for return to ambient temperatures obviously then may be from a few minutes to 8-12 h depending upon characteristics of the discharge structure and behavior of discharged water on entry into the receiving water body.

Field studies at thermal generating stations have been unable to determine causes of in-plant mortality. However residual effects such as susceptibility to predation (Coutant 1973) and not direct mortality may be as singularly important as immediate death.

Although losses of phytoplankton and zooplankton do occur, losses of ichthyoplankton represent a considerably larger impact primarily because of their longer generation time (Marcy 1975). In terms of the whole planktonic population, indications are that the consequences of entrainment are of minor importance particularly for phytoplankton and zooplankton.

Losses to phytoplankton and zooplankton communities can, however, be significant particularly when the aquatic system used for cooling purposes is either small or has limited circulation. The net productivity of phytoplankton can be reduced (Morgan and Stross 1969; Williams *et al*. MS 1971) but the effect is frequently not noticeable even a few km from discharges either because of the rapid population regeneration or rapid admixture of ambient water in the plume, or both. Marcy (1975) also indicates that mortality of zooplankton during entrainment can range from 15 to 100%. Dunstall (1976) found for the Pickering generating station on Lake Ontario that approximately 20% mortality was suffered by the cladoceran *Bosmina longirostris*. The entrained population appeared not to suffer from mechanical damage. Dunstall (1976) also found that for three generating stations in the Great Lakes only two occasions of significant difference between intake and outfall C^{14} primary production levels were found. It must be noted here that differences in mortality are bound to occur as differences in fragility and response to temperature are diverse and frequently temporally governed.

Schubel (1975) has summarized the thermal effects of power plants on fish eggs and survival and indicated that site studies have failed to establish cumulative effects from the stresses experienced during entrainment and that separation of these stresses into mortality components has rarely, if ever, been possible. From an environmentalist's viewpoint, the most informative studies, however, are those using real situations giving the end result of a variety of experiences - thermal, mechanical or biocidal. Mortalities to ichthyoplankton are generally high (Marcy 1975) although one instance of no apparent mortality is reported (Kerr 1953).

In the Great Lakes, few studies of entrainment effect are complete. However, as one would expect, there are seasonal differences (Teleki, 1976b; Kelso and Leslie, unpublished data; Dunstall 1976) and diel differences (Teleki, 1976b; Kelso and Leslie, unpublished data). Both Dunstall (1976) and Teleki (1976b) indicate that the impact of entrainment mortality upon stocks (generally smelt, alewife and carp) appears minimal.

Use of water for "tempering" (reducing) discharge temperature may well be a further source for in-plant mortality of organisms routinely entrained. Water from forebays has at times been combined, using condenser cooling pumps, with water passing through condensers in an effort to reduce discharge temperature. This practice, usually performed to meet temperature regulations for the discharge, appears to add one perturbation to another. Obviously, trade-offs exist between volume of water used for cooling and ΔT when regulations apply to either the discharge temperature or temperature rise across the condensers. Since in-plant mortality of, particularly, larval fishes is significant, the practice of "tempering" discharge temperatures, although meeting temperature regulations at the discharge, likely increases the adverse effect from the once-through cooling process by increasing in-plant entrainment and subsequent mortality rates.

Several remedial measures become apparent. Power plant siting could be such that non-productive water bodies, or portions of them, receive new sites. Also, in most ecosystems, ecological insight tells us that intake placement can be arranged such that entrainment is minimized or even eliminated. Since entrainment rate is essentially proportional to cooling water volume, intake volume could be restricted. This action, however, is problematic in that for those that are entrained, thermal conditions become more severe. A useful guideline to determine thermal related effects of entrainment is provided by NAS/NAE (1973) which also sheds some light upon the trade-offs between flow rate and temperature rise.

Discharge Oriented Effects

Fishes, like other organisms, are profoundly affected by temperature. Consequently the hue and cry raised over "waste heat", until recently at least, resulted from the increase in thermal load to aquatic ecosystems. Although concern is justified, the variety of ecological processes infringed upon vary in importance according to the cooling process and the water body in use.

In general, the composition of aquatic communities depends largely upon temperature characteristics of their environment. Biota occurring naturally in each body of water, or portion of it, compete with varying degrees of success determined by the interplay between habitat characteristics and preferences and tolerances of the biota. Consequently alterations in temperature can disturb natural balances.

Once condenser cooling waters are discharged into receiving water bodies, both passive and mobile biotic forms can experience altered thermal regimes. Planktonic forms, of course, experience thermal conditions essentially similar to that experienced by entrained organisms except that exposure times and duration depend upon behavior patterns of nearshore water masses. Sedentary communities experience the severest of discharge related conditions but it is with the mobile forms - fish - where our attention will rest.

Excellent reviews of temperature effects upon fish exist (Fry 1967; Brett 1970; and others) and have been used to predict responses of fish to thermally altered environments (NAS/NAE 1973). Few, however, have conducted definitive studies as to how fishes respond naturally to diverse environments having temperature as one of many factors determining behavior and success, notable exceptions being Ferguson (1958) and Neill and Magnuson (1974).

From Figs. 6, 7, 8 and 9, it is apparent that only portions of aquatic systems used as receiving waters are altered in their thermal regimes. Small lakes, reservoirs and embayments or larger lakes, however, are susceptible to whole system alteration. Fortunately, such instances are rare or at least limited in Canada. In the Great Lakes, discharges are usually on/near the shoreline and, with the exception of the Lennox Generating Station at the mouth of Bay of Quinte, Lake Ontario, Canadian power plants are located on high energy shorelines, connecting waterways or major tributaries (Fig. 10). The rest of Canada, representing about 60% of Canada's steam electric generating capacity, has plants associated with each of the possible locations discussed earlier. The most common situation still remains the one in which a segment of the environment is disrupted and discharges behave as plumes rather than alter the whole system.

Once heat is added to condenser cooling waters (Fig. 4) and discharged, plumes develop (Figs. 6, 8 and 9) having two recognizable zones: a volume of high turbulence and velocity and a volume in the immediate vicinity of the discharge where turbulence and velocity levels approximate those of the receiving water thus forming what is usually seen and termed as the thermal plume. It is in the region of high turbulence near the discharge and the discharge canal itself where observations of mortality, attractance, repulsion and other

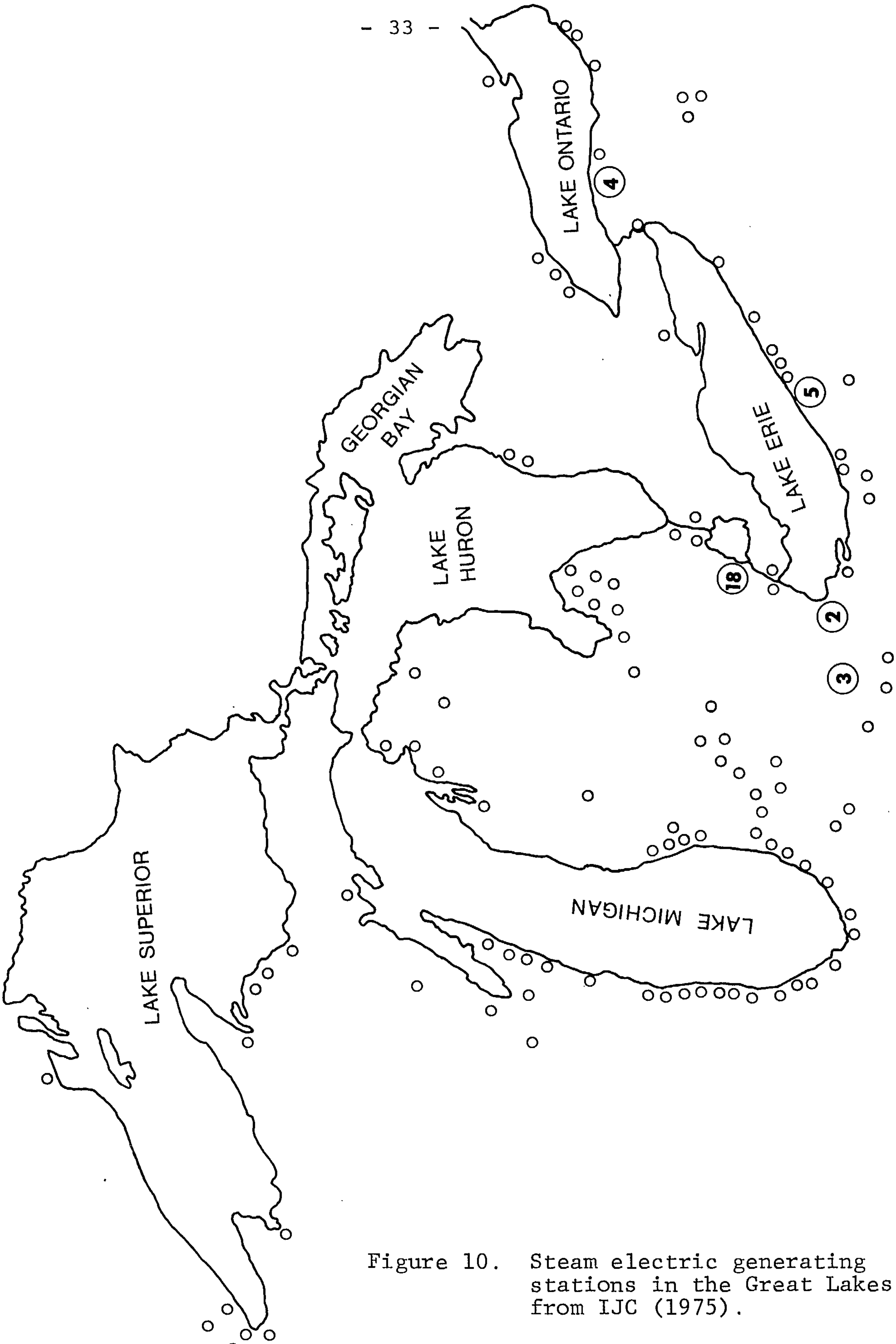

Figure 10. Steam electric generating stations in the Great Lakes from IJC (1975).

phenomenon attributable to temperature are apparent. Surface plumes generally exert minimal or undetectable influence upon fish (Kelso 1974; Neill and Magnuson 1974; Kelso and Minns 1975; Coutant 1975; Kelso 1976) likely because the association of fish with the top 1-2 m of the water column is at best tenuous. Consequently the primary loci of effect is restricted in comparison to the volume and area under the influence of elevated temperature (Fig. 6).

Neill and Magnuson (1974) in a noteworthy study in the laboratory and in Lake Monona, Wisconsin, found that fish were distributed in the outfall area according to their different temperature preferenda. They also found that neither laboratory nor field results suggested that thermoregulatory behavior was overridden by feeding behavior. Ferguson (1958) also found good agreement between laboratory and field preferenda with discrepancies explainable on the basis of size or day/night differences. Temperature in both these cases was a major factor governing fish distribution. In the Great Lakes, however, nearshore fish associations develop with the environment - benthic or pelagic - and fail to respond to temperature at least at the water surface where alteration is greatest (Kelso and Minns 1975). Further, species associations may develop strong segregation particularly during summer months and although fishes preferring higher temperature seek warmer waters, temperatures inhabited are significantly below their preferenda (Kelso and Minns 1975). These segregations are not always strong, however, and depend upon species compositions and how the variety of optimal conditions for fishes interact to produce observed distribution patterns (Kelso and Minns, unpublished data). Nearshore Great Lakes waters are exceptional though in that the temperature range is naturally narrow limiting options available.

Recent studies using ultrasonic telemetry (Kelso 1974; Coutant 1975; Kelso 1976; Teleki 1976a) further stress that the outfall area is the area of maximum effect and that, especially in the Great Lakes, associations with the outfall during ice free periods is limited. Also, data strongly suggest that current is implicated as strongly if not more so than temperature (Kelso 1976; Teleki 1976a). The discharges from both the Pickering and Nanticoke Generating Stations altered nearshore movement of Great Lakes fishes by causing them to increase the sharpness of their turns, decrease the distance between turns and to orient into the discharge. In other words, movement was abnormally localized in the vicinity of an outfall. Exposure of fish to the area of maximally elevated temperatures range from a few brief excursions to approximately 9 h (Kelso 1976). During these exposures, the three species of fish tracked (white sucker, yellow perch and brown bullhead) were offered temperatures close to, but below, their preferred temperatures. Also the response to the outfall was similar for these three widely differing species.

Ability of fishes to manifest choice by selection of suitable conditions leads one to expect an avoidance of lethal conditions. This appears to be the case, particularly during summer, and if temperatures from discharges approach avoidance levels or lethal conditions, an exodus occurs. In temperate climatic regions, however, "cold shock" is undoubtedly of greater significance than its counterpart. Although death due to cold shock is recognized in temperature criteria (NAS/NAE 1973), few examples of mortality are available. Ash et al. (1974), in one of the few studies available, documented a thermal fish kill due to cold shock in Lake Wabamun, Alberta, where mechanical failure in the generating station caused discharge temperatures to rapidly return to winter ambient conditions. These observations and Marcy (1976) indicate that strong attractions of fish to discharges of condenser cooling water develop during winter while during summer temperature preference, reaction to current and alongshore movement patterns minimize contact with overly elevated temperatures obviating death due to high temperatures.

Concluding Remarks

The main emphasis of biological research in waste heat has been to examine the response of ecosystems to added heat. This bias was no doubt encouraged by the fact that physical limnologists followed a similar approach though with a good deal more justification since they were concerned with the dissipation of heat and not waste heat effects. Only when it became apparent that in-plume effects were frequently a carryover from the entrainment process and that plume-related effects were of consequence only to large fish, and even then only marginally, did we look further.

The primary and dominant effects of once-through cooling are entrainment, particularly of icthyoplankton, and, to a lesser extent, fish impingement. Unfortunately it is these impacts that we are least able to assess since they are stock-based, i.e. a lakewide rather than plant by plant consideration. Fortunately these effects can be almost completely alleviated by appropriate siting with minimal change to available plant design. Basic ecological principles can be readily applied to locate sites, particularly in the Great Lakes, where the fewest organisms are likely to be entrained and where the fewest fish are prone to impingement and/or discharge related perturbations. Effects would be further minimized by the placement of intakes in sparsely inhabited waters (usually deep) and usually the placement of short onshore discharges on high energy shorelines.

Disturbingly it is only now becoming apparent that effects other than thermal (or even mechanical) are potentially far more serious. Fossil fuel combustion products, sulphur and metals in particular (Harvey 1976), along with nuclear waste disposal are problems which are only now beginning to be addressed in North America. This circumstance is indeed unfortunate in light of the enormous amount of attention that has been devoted to aquatic aspects of thermal power generation. The misdirection of effort here is perhaps made even more grave since the effects resulting from entrainment and impingement are far more severe than those resulting from addition of heat to aquatic ecosystems.

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