See also

Primary Production Distribution. Primary Production Methods. Primary Production Processes. River Inputs. Trapped Particulate Flux. Upper Ocean Mixing Processes. Upper Ocean Time and Space Variability.

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THERMAL DISCHARGES AND POLLUTION

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Sources of Thermal Discharges

The largest single source of heat to most water bodies, including the sea, is the sun. Natural thermal springs also occur in many parts of the world, almost all as fresh water, some of which discharge to the sea. In the deep oceans hydrothermal vents discharge mineral-rich hot water at temperatures greatly exceeding any natural temperatures either at depth or at the surface. To add to these natural sources of heat, industrial processes have discharged heated effluents into coastal waters in many parts of the world for at least 150 years. By far the largest volumes of these heated effluents reaching the sea in the past 60 years have originated from the electricity generation industry (power industry). Indeed more than 80% of the volume of heated effluents to the sea originate from the power industry compared with 3–5% from the petroleum industries and up to 7% (in the USA) from chemical and steel industries.

The process known as 'thermal' power generation, in which a fuel such as oil or coal or the process of nuclear fission is used to heat water to steam to drive turbines, requires large volumes of cooling water to remove the waste heat produced in the process. Where power stations are sited on or near the coast all of this waste heat, representing some 60–65% of that used in the process, is discharged to the sea. The heat is then dissipated through dilution, conduction, or convection. In a few, atypical coastal situations, where the receiving water does not have the capacity to dissipate the heat, artificial means of cooling the effluent such as ponds or cooling-towers are used. Here the effluent is cooled prior to discharge and much of the heat dissipated to the air.

The waste heat is related to the theoretical thermal efficiency of the Rankine cycle, which is the modification of the Carnot thermodynamic cycle on which the process is based. This has a maximum theoretical efficiency of about 60% but because of environmental temperatures and material properties the practical efficiency is around 40%. Given this level of efficiency and the normal operating conditions of a modern coal- or oil-fired power station, namely steam at 550°C and a pressure of 10.3×10^6 kg cm^{-2} with corresponding heat rates of 2200 kg cal kWh^{-1} of electricity, some 1400 kg cal kWh^{-1} of heat is discharged to the environment, usually in cooling water at coastal sites. This assumes a natural water temperature of 10°C. Nuclear power stations usually reject about 50% more heat per unit of electricity generated because they operate at lower temperatures and pressures. Since the 1920s efficiencies have increased from about 20% to 38–40% today with a corresponding reduction by up to 50% of the rate of heat loss. The massive expansion of the industry since the 1920s has, however, increased the total amounts of heat discharged to the sea.

Thus for each conventional modern power station of 2000 MW capacity some 63 m^3 s^{-1} of cooling water is required to remove the heat. Modern developments such as the combined cycle gas turbine (CCGT) power stations with increased thermal efficiencies have reduced water requirements and heat loss further so that a 500 MW power station may require about 9–10 $m^3 s^{-1}$ to remove the heat, a reduction of over 30% on conventional thermal stations.

Water Temperatures

Natural sea surface temperatures vary widely both spatially and temporally throughout the world with overall ranges recorded from -2°C to 30°C in open oceans and -2°C to 43°C in coastal waters. Diurnal fluctuations at the sea surface are rarely more than 1°C though records of up to 1.9°C have been made in shallow seas. The highest temperatures have been recorded in sheltered tropical embayments where there is little exchange with open waters. Most thermal effluents are discharged into coastal waters and these are therefore most exposed to both physical and biological effects. In deeper waters vertical thermal stratification can often exceed 10°C and a natural maximum difference of over 23°C between surface and bottom has been recorded in some tropical waters.

The temperatures of thermal discharges from power stations are typically 8–12°C higher than the natural ambient water temperature though at some sites, particularly nuclear power stations, temperature rises can exceed 15°C (**Figure 1**). Maximum discharge temperatures in some tropical coastal waters have reached 42°C though 35–38°C is more typical. There are seasonal and diurnal fluctuations at many sites related to the natural seasonal temperature cycles and to the operating cycles of the power station.

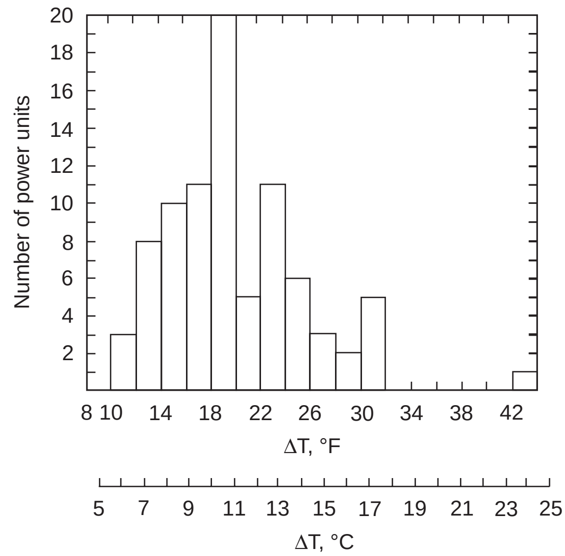

Figure 1 Frequency distribution of designed temperature rises for thermal discharges in US power station cooling water systems. (Reproduced with permission from Langford, 1990.)

Thermal Plumes and Mixing Zones

Once discharged into the sea a typical thermal effluent will spread and form a three-dimensional layer with the temperature decreasing with distance from the outfall. The behavior and size of the plume will depend on the design and siting of the outfall, the tidal currents, the degree of exposure and the volume and temperature of the effluent itself. Very few effluents are discharged more than 1 km from the shore. Effects on the shore are, however, maximized by shoreline discharge (**Figure 2**).

The concept of the mixing zone, usually in three components, near field, mid-field and far-field, related to the distance from the outfall, has mainly been used in determining legislative limits on the effluents. Most ecological studies have dealt with near and mid-field effects. The boundary of the mixing zone is, for most ecological limits, set where the water is at 0.5°C above natural ambients though this tends to be an arbitrary limit and not based on ecological data. Mixing zones for coastal discharges can be highly variable in both temperature and area of effect (**Figure 3**).

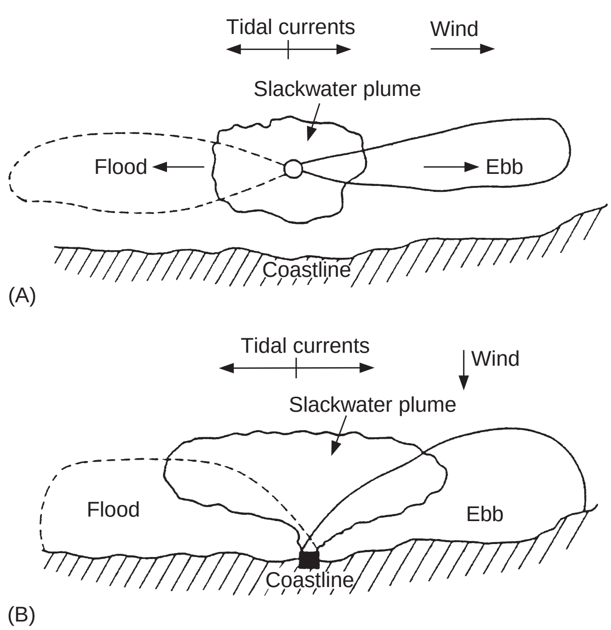

Figure 2 Movements of thermal plumes in tidal waters. (A) Offshore outfall; (B) onshore outfall. (Reproduced with permission from Langford, 1990.)

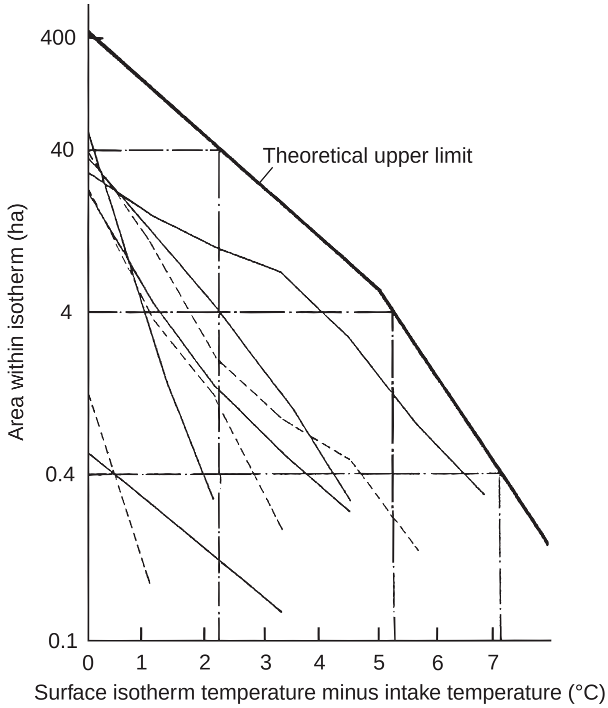

Figure 3 Relationship between surface-temperature elevation and surface area affected for nine different surveys at Moro Bay Power Plant, California. (Reproduced with permission from Langford, 1990.)

In addition to heat effects, thermal discharges also contain chemicals, mainly those used for the control of marine fouling in pipework and culverts. Chlorine compounds are the most common and because of its strong biocidal properties, the effects of chlorine are of primary concern in many coastal discharges, irrespective of the temperature. Measured chlorine residuals immediately after application vary between 0.5 and 10 mg l^{-1} throughout the world but most are within the 0.5–1.0 mg l^{-1} range. Because of the complex chemical reactions in sea water free chlorine residuals in discharges are usually a factor of 10 lower than the initial dosing rate. Even so, concentrations of chlorine compounds can exceed lethal limits for organisms at some sites.

Biological Effects of Temperature

The biological effects of temperature on marine and coastal organisms have been reviewed by a number of authors. Most animals and plants can survive ranges of temperature which are essentially genetically determined. The ultimate lethal temperature varies within poikilothermic groups but there is a trend of tolerance which is inversely related to the structural complexity of the organism (**Table 1**). Thus groups of microorganisms tend to contain species which have much higher tolerances than invertebrates, fish, or vascular plants. Because the life processes and survival of many organisms is so dependent on water temperature many species have developed physiological or behavioral strategies for optimizing temperature exposure and for survival in extremes of heat or cold. Examples are to be found among intertidal species and in polar fish.

The effects of temperature on organisms can be classified mainly from experimental data as lethal, controlling, direct, and indirect and all are relevant to the effects of thermal discharges in the marine environment. These effects can be defined briefly as follows.

- *Lethal*: high or low temperatures which will kill an organism within a finite time, usually less than its normal life span. The lethal temperature for any one organism depends on many factors within genetic limits. These include acclimatization, rate of change of temperature, physiological state (health) of the organism and any adaptive mechanisms.
- *Controlling*: temperatures below lethal temperatures which affect life processes, i.e., growth, oxygen consumption, digestive rates, or reproduction. There is a general trend for most organisms to show increases in metabolic activity with increasing temperature up to a threshold after which it declines sharply.
- *Direct*: temperatures causing behavioral responses such as avoidance or selection, movements, or migrations. Such effects have been amply demonstrated in experiments but for some work *in situ* the effects are not always clear.

Table 1 Upper temperature limits for aquatic organisms. Data from studies of geothermal waters[a]

Group	*Temperature* (°C)
Animals	
Fish and other aquatic vertebrates	38
Insects	45–50
Ostracods (crustaceans)	49–50
Protozoa	50
Plants	
Vascular plants	45
Mosses	50
Eukaryotic algae	56
Fungi	60
Prokaryotic microorganisms	
Blue–green algae	70–73
Photosynthetic bacteria	70–73
Nonphotosynthetic bacteria	>99

[a]Reproduced with permission from Langford (1990).

- *Indirect*: where temperatures do not act directly but through another agent, for example poisons or oxygen levels or through effects on prey or predators. Temperature acts synergistically with toxic substances which can be important to its effects on chlorine toxicity *in situ* in thermal plumes. Where temperature immobilizes or kills prey animals they can become much more vulnerable to predation.

Biological Effects of Thermal Discharges

The translation of data obtained from experimental studies to field sites is often not simple. The complexity of the natural environment can mask or exacerbate effects so that they bear little relation to experimental conditions and this has occurred in many studies of thermal discharges *in situ*. Further, factors other than that being studied may be responsible for the observed effects. Examples relevant to thermal discharges are discussed later in this article.

Entrainment

The biological effects of any thermal discharge on marine organisms begin before the effluent is discharged. Cooling water abstracted from the sea usually contains many planktonic organisms notably bacteria, algae, small crustacea, and fish larvae. Within the power station cooling system these organisms experience a sudden increase in temperature (10–20°C, depending on the station) as they pass through the cooling condensers. They will also experience changes in pressure (1–2 atm) and be dosed with chlorine (0.5–5 mg l^{-1}) during this entrainment, with the effect that many organisms may be killed before they are discharged to the receiving water. Estimates for power stations in various countries have shown that if the ultimate temperatures are less than 23°C the photosynthesis of entrained planktonic marine algae may increase, but at 27–28°C a decrease of 20% was recorded. At 29–34°C the rates decreased by 61–84% at one US power station. Only at temperatures exceeding 40°C has total mortality been recorded. Concentrations of chlorine (total residual) of 1.0 mg l^{-1} have been found to depress carbon fixation in entrained algae by over 90% irrespective of temperature (**Figure 4**). Diatoms were less affected than other groups and the effects in open coastal waters were less marked than in estuarine waters. Unless the dose was high enough to cause complete mortality many algae showed evidence of recovery.

The mean mortality rates for marine zooplankton entrained through cooling-water systems were shown to be less than 30% except in unusual cases where extreme temperatures and high chlorine doses caused 100% mortality. High mortalities can also occur where the entrained organisms are exposed to high temperatures in cooling ponds after discharge from the cooling system. In general, zooplankton do not suffer percentage mortalities as high as those of phytoplankton under typical cooling-water conditions. After passing through the cooling system at a US power station the dead or dying zooplankton were observed being eaten by large numbers of fish gathered at the outfall and hence passed into the food chain.

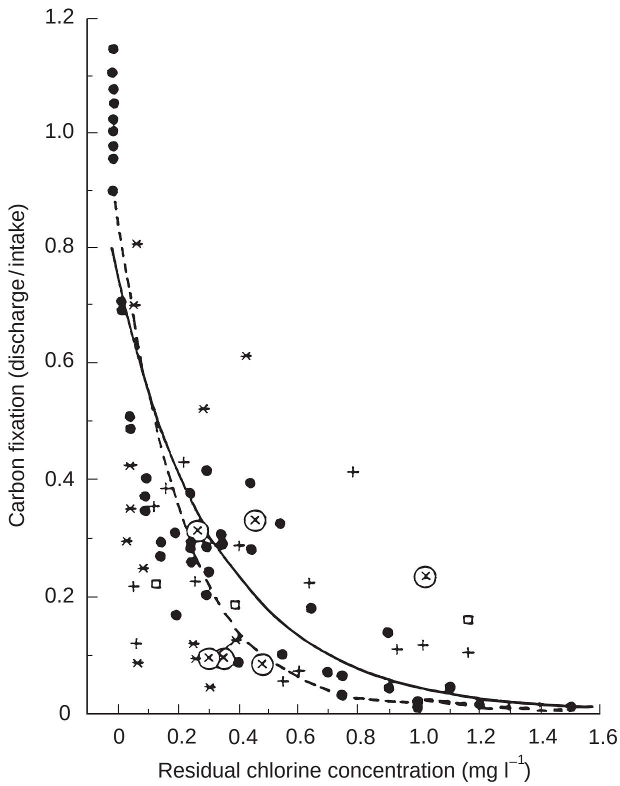

Figure 4 The effect of cooling water chlorination on carbon fixation in marine phytoplankton. ⊗ , San Onofre; + , Morgantown; *, Hudson River; ●, Fawley; □, Dunkerque. (Reproduced with permission from Langford, 1990.)

There are few published observations of marine macro-invertebrates entrained in cooling-water systems though at a site in the UK, field experiments showed that specimens of the prawn *Palaemonetes varians* were killed by mechanical damage as they passed through a cooling system. Larval fish are probably most vulnerable to the effects of entrainment, mostly killed by the combination of mechanical, chemical, and temperature effects. Mortalities of ichthyoplankton have varied from 27 to 100% at sites in the US and UK. Many of these were, however, on estuaries or tidal reaches of rivers. At a coastal site in California the mortality rate increased from 10 to

100% as temperatures rose from 31 to 38°C. Some 13% mortalities occurred with no heat, mainly as a result of pressure and abrasion in the system. The significance of 20% larval mortalities to the natural populations of flounders (*Platichthyes americanus*) calculated for a site on Long Island Sound indicated that the annual mortality was estimated at a factor of 0.01 which might cause a reduction of 9% of the adult population over 35 years provided the fish showed no compensatory reproductive or survival mechanism, or no immigration occurred.

Effects of Discharges in Receiving Waters

Algae

At some US power stations the metabolism of phytoplankton was found to be inhibited by chlorine as far as 200 m from the outfall. Also, intermittent chlorination caused reductions of 80–90% of the photosynthetic activity some 50 m from the outfall at a site on the Californian coast. From an assessment of the total entrainment and discharge effects, however, it was reported that where dilution was 300 times per second the effect of even a 100% kill of phytoplankton would not be detectable in the receiving water. In Southampton Water in the UK, mortality rates of 60% were estimated as causing about 1.2–3% reduction in the productivity of the tidal exchange volume where a power station used 6% of this for cooling. The main problem with most assessments is that replication of samples was typically low and estimates suggest that 88 samples would be needed from control and affected areas to detect a difference of 5% in productivity at a site, 22 samples for a 10% change and at least six for a 20% change. Such replication is rarely recorded in site studies.

Temperatures of 35–36°C killed shore algae at a coastal site in Florida, particularly *Halimeda* sp. and *Penicillus* spp. but factors other than temperature, most likely chlorine and scour, removed macroalgae at another tropical site. Blue–green algae were found where temperatures reached 40°C intermittently and *Enteromorpha* sp. occurred where temperatures of 39°C were recorded. In more temperate waters the algae *Ascophyllum* and *Fucus* were eliminated where temperatures reached 27–30°C at an outfall but no data on chlorination were shown. Replacing the shoreline outfall with an offshore diffuser outfall (which increased dilution and cooling rates) allowed algae to recolonize and recover at a coastal power station in Maine (US). On the Californian coast one of the potentially most vulnerable algal systems, the kelps *Macrocystis*, were predicted to be badly affected by power station effluents, but data suggest that at one site only about 0.7 ha was affected near the outfall.

The seagrass systems (*Thalassia* spp.) of the Florida coastal bays appeared to be affected markedly by the effluents from the Turkey Point power stations and a long series of studies indicated that within the + 3 to + 4°C isotherm in the plume, seagrass cover declined by 50% over an area of 10–12 ha. However, the results from two sets of studies were unequivocal as to the effects of temperature. The data are outlined briefly in the following summary. First, the effluent was chlorinated. Second it contained high levels of copper and iron. Third, the main bare patch denuded of seagrass, according to some observations, may have been caused by the digging of the effluent canal. Although one set of data concluded that the threshold temperature for adverse effects on seagrass was + 1.5°C (summer 33–35°C) a second series of observations noted that *Thalassia* persisted apparently unharmed in areas affected by the thermal discharge, though temperatures rarely exceed 35°C. From an objective analysis, it would appear that the effects were caused mainly by a combination of thermal and chemical stresses.

Zooplankton and Microcrustacea

In Southampton Water in the UK, the barnacle *Elminius modestus* formed large colonies in culverts at the Marchwood power station and discharged large numbers of nauplii into the effluent stream increasing total zooplankton densities. Similar increases occurred where fouling mussels (*Mytilus* sp.) released veliger larvae into effluent streams. Data from 10 US coastal power stations were inconclusive about the effects of thermal discharges on zooplankton in receiving waters with some showing increases and others the reverse. Changes in community composition in some areas receiving thermal discharges were a result of the transport of species from littoral zones to offshore outfalls or vice versa. At Tampa Bay in Florida no living specimens of the benthic ostracod *Haplocytheridea setipunctata* were found when the temperature in the thermal plume exceeded 35°C. Similarly the benthic ostracod *Sarsiella zostericola* was absent from the area of a power effluent channel in the UK experiencing the highest temperature range.

Macro-invertebrates

As with other organisms there is no general pattern of change in invertebrate communities associated with thermal discharges to the sea which can be solely related to temperature. Some of the earliest studies in enclosed temperate saline waters in the UK showed that no species was consistently absent from areas affected by thermal plumes and the studies at Bradwell power station on the east coast showed no evidence of a decline in species richness over some 20 years though changes in methodology could have obscured changes in the fauna. No changes in bottom fauna were recorded at other sites affected by thermal plumes in both Europe and the US. The polychaete *Heteromastus filiformis* was found to be common to many of the thermal plume zones in several countries. In these temperate waters temperatures rarely exceeded 33–35°C.

In contrast, in tropical coastal waters data suggest that species of invertebrates are excluded by thermal plumes. For example in Florida, surveys showed that some 60 ha of the area affected by the Turkey Point thermal plume showed reduced diversity and abundance of benthos in summer, but there was marked recovery in winter. The 60 ha represented 0.0023% of the total bay area. A rise of 4–5°C resulted in a dramatic reduction in the benthic community. Similarly, at Tampa Bay, 35 of the 104 indigenous invertebrate species were excluded from the thermal plume area. Removal of the vegetation was considered to be the primary cause of the loss of benthic invertebrates. In an extreme tropical case few species of macro-invertebrates survived in a thermal effluent where temperatures reached 40°C, 10 species occurred at the 37°C isotherm and the number at the control site was 87. Scour may have caused the absence of species from some areas nearer the outfall (**Figure 5**). The effluent was chlorinated but no data on chlorine concentrations were published. Corals suffered severe mortalities at the Kahe power station in Hawaii but the bleaching of the colonies suggested that again chlorine was the primary cause of deaths, despite temperatures of up to 35°C. It has been suggested that temperature increases of as little as 1–2°C could cause damage to tropical ecosystems but detailed scrutiny of the data indicate that it would be difficult to come to that conclusion from field data, especially where chlorination was used for antifouling.

The changes in the invertebrate faunas of rocky shores in thermal effluents have been less well studied. Minimal changes were found on breakwaters in the paths of thermal plumes at two Californian sites. Any measurable effects were within 200–300 m of the outfalls. In contrast in southern France a chlorinated thermal discharge reduced the numbers of species on rocks near the outfall though 11 species of Hydroida were found in the path of the effluent. In most of the studies, chlorine would appear to be the primary cause of reductions in

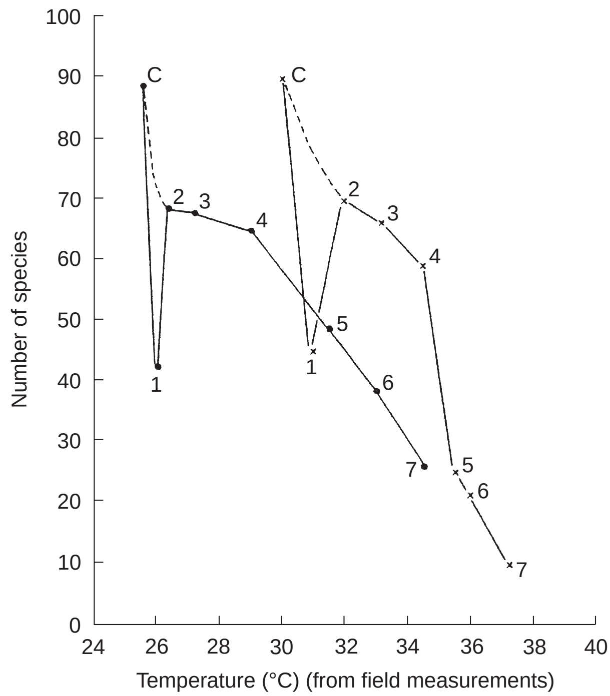

Figure 5 Numbers of invertebrate species recorded at various temperatures, taken from two separate surveys (×, October; ●, winter) at Guyanilla Bay. C, control sampling; 1–7, effluent sampling sites. (Reproduced with permission from Langford, 1990.)

species and abundance though where temperatures exceeded 37°C both factors were significant. There is some evidence that species showed advanced reproduction and growth in the thermal plumes areas of some power stations where neither temperature nor chlorine were sufficient to cause mortality. Also behavioral effects were demonstrated for invertebrates at a Texas coastal power station. Here, blue crabs (*Callinectes sapidus*) and shrimps (*Penaeus aztecus* and *P. setiferus*) avoided the highest temperatures (exceeding 38°C) in the discharge canal but recolonized as temperatures fell below 35°C. At another site in tropical waters, crabs (*Pachygrapsus transversus*) avoided the highest temperatures (and possibly chlorine) by climbing out of the water on to mangrove roots.

Fish

There are few records of marine fish mortalities caused by temperature in thermal discharges except where fish are trapped in effluent canals. For example mortalities of Gulf menhaden (*Brevoortia petronus*), sea catfish (*Arius felis*) occurred in the canal of a Texas power station when temperatures reached 39°C. Also a rapid rise of 15°C killed menhaden (*Alosa* sp.) in the effluent canal of the Northport power station in the US. Avoidance behavior prevents mortalities where fish can move freely.

The apparent attraction of many fish species to thermal discharges, widely reported, was originally associated with behavioral thermoregulation and the selection of preferred temperatures. Perhaps the best recorded example is the European seabass (*Dicentrarchus labrax*) found associated with cooling-water outfalls in Europe. Temperature selection is, however, not now believed to be the cause of the aggregations. Careful analysis and observations indicate clearly that the main cause of aggregation is the large amounts of food organisms discharged either dead or alive in the discharge. Millions of shrimps and small fish can be passed through into effluents and are readily consumed by the aggregated fish. Further where fish have gathered, usually in cooler weather, they remain active in the warmer water and are readily caught by anglers unlike the individuals outside the plume. This also gives the impression that there are more fish in the warmer water. Active tracking of fish has shown mainly short-term association with outfalls though some species have been shown as entering water at temperatures above their lethal maximum for very short periods to collect food. There is clear evidence, however, that fish avoid adversely high temperatures for most of the time and will return to a discharge area once the temperatures cool. Avoidance behavior is also apparent at high chlorine concentrations.

Where water temperatures and chemical conditions allow consistent residence, fish in thermal discharge canals show increased growth (**Figure 6**). At the Kingsnorth power station in the UK seabass (*D. labrax*) grew at twice the rate as in cold water, particularly in the first year. Fish showed varying residence times and sequential colonization of the canal at various ages. Winter growth occurred and the scales of older fish with long-term association with the discharge showed no evidence of annual winter growth checks. The fish were able to move into and out of the canal freely.

Occurrence of Exotic Species

Exotic or introduced marine invertebrate species have been recorded from thermal discharges in various parts of the world. Some of the earliest were from the enclosed docks heated by power station effluents near Swansea and Shoreham in the UK. The exotic barnacle *Balanus amphitrite* var. *denticulata* and the woodborer *Limnoria tripunctata* replaced the indigenous species in the heated areas but declined in abundance when the effluent ceased. The polyzoan *Bugula neritina* originally a favored immigrant species in the heated water disappeared completely as the waters cooled. In New Jersey (USA)

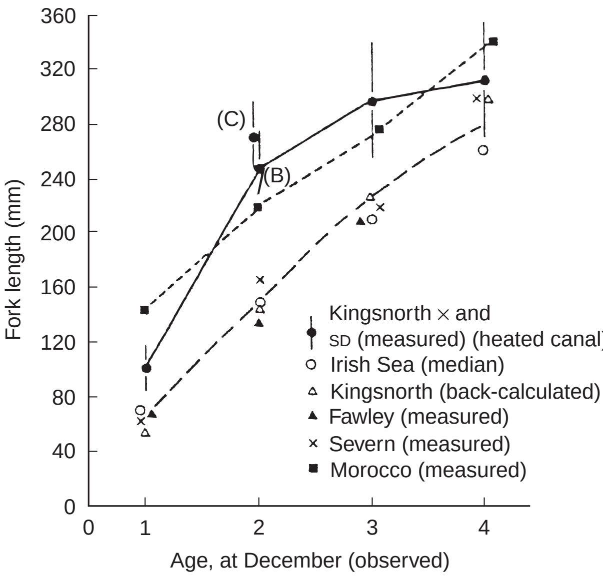

Figure 6 Growth of bass (*Dicentrarchus labrax*) in a thermal discharge canal in comparison to other locations. Note that back calculated lengths are smaller because they probably relate to cold water growth. (Reproduced with permission from Langford, 1990.)

subtropical species of *Teredo* bred in a heated effluent and both the ascidian *Styela clavata* and the copepod *Acartia tonsa* have both been regarded as immigrant species favored by heated effluents. However many immigrant species have survived in temperate waters without being associated with heated waters. In UK waters, only the crab *Brachynotus sexdentatus* and the barnacle *B. amphitrite* may be regarded as the only species truly associated with thermal discharges despite records of various other species.

The decline of the American hard shell clam fishery (*Mercenaria mercenaria*) introduced to Southampton Water in the UK was reportedly caused by the closure of the Marchwood power station combined with overfishing. Recruitment of young clams and their early growth were maximized in the heated water and reproduction was advanced but all declined as the thermal discharge ceased.

Aquaculture in Marine Thermal Discharges

The use of marine thermal discharges from power stations for aquaculture has not been highly successful in most parts of the world. Although it is clear that some species will grow faster in warmer water, the presence and unpredictability of chlorination has been a major obstacle. It is not generally economically viable to allow a large power station to become fouled such that efficiency declines merely to allow fish to grow. In Japan some farming ventures are regarded as profitable at power stations but in Europe and the USA such schemes are rarely profitable. At the Hunterston power station in Scotland plaice (*Pleuronectes platessa*) and halibut (*Hippoglossus hippoglossus*) grew almost twice as fast in warm water as in natural ambient but the costs of pump maintenance and capital equipment caused the system to be uneconomic irrespective of chlorination problems. Optimization of temperature is also a problem especially where temperatures fluctuate diurnally or where they exceed optimal growth temperatures. The general conclusion is that commercial uses of heated effluents in marine systems are not yet proven and are unlikely to become large-scale global ventures.

Thermal Discharges and Future Developments

The closure of many older, less-efficient power stations, has led to an increase in the efficiency of the use of water and a decline in the discharge of heat to the sea per unit of electricity generated. However, the increasing industrialization of the developing countries, China, Malaysia, India and the African countries is leading to the construction of new, large power stations in areas not previously developed. The widespread use of CCGT stations can reduce the localized problems of heat loss and water use further as well as reducing emissions of carbon dioxide and sulphur dioxide to the air but the overall increase in power demand and generation will lead to an increase in the total aerial and aquatic emissions in some regions.

In some tropical countries the delicate coastal ecosystems will be vulnerable not only to heat and higher temperature but much more importantly to the biocides used for antifouling. There is as yet no practical alternative that is as economic as chlorine though different methods have been tried with varying success in some parts of the world. There is little doubt that the same problems will be recognized in the areas of new development but as in the past after they have occurred.

Conclusions

It is clear that the problems of the discharge of heated effluents are essentially local and depend on many factors. Although temperatures of over 37°C are lethal to many species which cannot avoid exposure, there are species which can tolerate such temperatures for short periods. Indeed it can be concluded for open coastal waters that discharge temperatures may exceed the lethal limits of mobile species at least for short periods. This, of course, would not apply if vulnerable sessile species were involved, though again some provisos may be acceptable. For example, an effluent which stratified at the surface in deep water would be unlikely to affect the benthos. On the other hand an effluent which impinges on the shore may need strict controls to protect the benthic community. From all the data it is clear that blanket temperature criteria intended to cover all situations would not protect the most vulnerable ecosystems and may be too harsh for those that are more tolerant or less exposed. Constraints should therefore be tailored to each specific site and ecosystem.

Irrespective of temperature it is also very clear that chlorination or other biocidal treatment has been responsible for many of the adverse ecological effects originally associated with temperature. The solution to fouling control and the reduction of chlorination of other antifouling chemicals is therefore probably more important than reducing heat loss and discharge temperatures particularly where vulnerable marine ecosystems are at risk.

See also

Deep-sea Ridges, Microbiology. Demersal Fishes. Dispersion from Hydrothermal Vents. Fish Ecophysiology. Geophysical Heat Flow. Heat and Momentum Fluxes at the Sea Surface. Hydrothermal Vent Biota. Hydrothermal Vent Deposits. Hydrothermal Vent Ecology. Hydrothermal Vent Fluids, Chemistry of. Mesopelagic Fishes. Ocean Thermal Energy Conversion (OTEC). Pelagic Fishes. Satellite Remote Sensing of Sea Surface Temperatures. Thermohaline Circulation. Upper Ocean Heat and Freshwater Budgets. Upper Ocean Mixing Processes. Wind and Buoyancy-forced Upper Ocean.

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