FISH POPULATIONS AND POLLUTION

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Technical Note 04/96

June 10, 1996

1. Introduction.

Fish stocks in the North Sea are, without doubt, in a critical condition. Over the last few years, populations of cod, plaice and herring have fallen below the limits regarded as the biological minimum required to ensure their future safety. Haddock and coley populations are fluctuating around this minimum threshold while sprat stocks are declining. Mackerel populations have declined very markedly. Of the fish consumed by humans, only the stocks of sole and whiting are thought to be relatively healthy. Sand-eels are present in relatively healthy numbers, but these too are threatened by the scale of the industrial fisheries in the North Sea [67]. There is little doubt that the root cause of the decline in fisheries is overfishing. A great deal of research has been directed at the problems caused by this and indeed it has now been widely recognised that unless exploitation of stocks is better controlled, sea fishing is unlikely to prove sustainable [32]. It is estimated that of the total mass of fish in the North Sea of ten million tonnes, five million tonnes are fished annually [35].

Despite the immense pressure on fish stocks caused by over-exploitation, other factors also influence fish populations. Water temperature is, perhaps, the most obvious one yet even this factor is very poorly understood. Temperature can affect the abundance of fish from year to year, and not always in a predictable manner. In a study of flatfish in the River Severn in the UK the abundance of sole was found to be positively correlated with water temperature at the time of spawning of the adult fish the previous year. By contrast,in dab and flounder abundance was negatively correlated with temperature at this time [42]. The precise reason for this remains unknown but may relate to changes in predator activity in relation to temperature. Direct negative effects upon the reproduction of fish have also been shown in populations exposed to thermal discharges from power stations. Egg producing capacity in female roach was severely reduced by exposure to the hot effluent [44]. Fish populations, therefore can be extremely sensitive to changes in environmental conditions and even slight changes in such basic factors such as the temperature of the sea can produce wide variations of response.

Arguably, one of the most important impacts of human activity upon the marine environment is caused by the release and discharge of chemicals. Recent research has shown that chemical pollution of the sea can adversely affect both individual fish and fish populations. Chemical pollution, for example, can result in disease and reproductive disturbance. The information concerning pollution effects upon fish is reasonably accessible in the scientific literature. Nonetheless, the North Sea States have not routinely considered such data in their periodic reviews of the North Sea environment. The most recent of these is the 1994 North Sea Quality Status Report [68]. Consistently in such reports two important questions are not addressed in relation to chemical pollutants in the North Sea. Firstly, what effect is pollution having on the fish themselves? Secondly, how could this affect fish populations and their recovery from over-exploitation? Accordingly, this document presents some of the information which can be found in the open literature and summarises some of the scientific insights into these problem areas.

2. Pollution of the North Sea.

Pollution can, of course, exert catastrophic effects upon fish populations. Massive fish kills often result from spillages of chemicals and oils, while agricultural pollution is an increasing cause of fish kills in rivers. A fire in a chemical warehouse on the River Rhine in 1986 caused a massive mortality of fish and invertebrates [1]. If such kills take place during the spawning season at a sensitive site then a whole year class of fish may be lost to the population. This was a real concern in the case of the Braer oil spill which took place in the Shetlands. This happened during the spawning of the sand-eel population which is a highly important food resource for local bird populations. The impacts on sand-eels are still not clear but the effects of this spill are still evident in the intertidal zone [30]. Such incidents are highly visible and spectacular. Quite rightly, they attract a lot of media attention.

The impacts of such incidents upon fish populations, however, are probably exceeded by the less visible impacts of the constant, chronic, inputs of pollutants into the North Sea. These chemicals enter the sea in various ways. Rivers carry industrial and agricultural chemicals to the sea. Pipelines discharge industrial effluents and sewage into estuaries and coastal waters. Direct dumping of industrial wastes is declining, but contaminated harbour dredgings are dumped in large quantities at sea. The offshore oil industry is a source of toxic hydrocarbons together with discharges from ships. Nuclear power and fuel reprocessing discharge radioactive substances.

The sheer variety of chemicals to which fish populations may be exposed is staggering: It is estimated that in the EC alone 50,000 chemical substances are in common use of which around 4,500 could attract priority listing since they are toxic, do not degrade readily in the environment and may accumulate in the tissues of aquatic animals. Moreover, some chemicals can be transported long distances by the atmosphere from the places in which they are used and manufactured. The pesticide Toxaphene, for example, is used in the Caribbean. It is subsequently transported in the atmosphere to the more northern latitudes and has been found in fish caught in North Sea waters [37]. This is a problem of some magnitude [33] and is the subject of growing international concerns.

Ultimately an environment may become so degraded by continued inputs of toxic chemicals and pollution insults that major changes in the balance of species present in the ecosystem may occur [5]. In the Black Sea ecosystem, major shifts in the taxonomic composition have been observed. This situation may favour species such as comb jellies and jellyfish which cannot be used as a commercial resource or as a food resource for fish [35, 65]. Not only will commercial fisheries collapse, but the stocks are then effectively prevented from regenerating by lack of suitable food. How great a concern this is in the North Sea is simply unkown but analytical chemistry techniques have clearly shown that chemical inputs are detectable over the whole of the North Sea [68].

Many more fish, therefore, are exposed to chronic pollution than are affected by catastrophic spills of chemicals and oil. While there are obvious health concerns attached to the human consumption of contaminated fish [36], fish from the North Sea are still regarded as fit for human consumption. Rather, it is the effects of these chemicals upon the fish themselves which give the most immediate causes for concern. The chemicals to which fish populations in the North Sea are exposed are present as a complex complex mixture. Even regulatory agencies admit that the toxicological impacts of chemical mixtures are impossible to predict given the current state of scientific knowledge [69]. Some impacts of chemical pollution identified in fish, such as skin damage and liver malfunction, have been known for some time. Other, newly identified effects are more subtle. Suppression of the immune system of fish, damage to their reproductive systems and reduced viability of fish larvae have received little attention from regulatory authorities. Yet these impacts may well be contributing significantly to the decline in fish populations.

3. Impacts of pollution on fish health

Fish exposed to sub-lethal industrial pollution may become diseased and stressed. Like all organisms, fish suffer naturally from disease and infestation with parasites. More recently, however, it has become apparent that exposure to chemical pollution can also exert serious effects upon the health of individual fish and hence upon fish populations [14, 31]. The longer term exposure of fish populations to certain industrial effluents has resulted in much more subtle effects than the catastrophic kills often associated with pollution incidents. The observed effects range from alterations in the behaviour of fish, the appearance of deformities and to the appearance of obvious diseases of the skin, liver and other organs. Although the apparent seriousness of these effects spans a wide spectrum, each can negatively affect individual fish and ultimately whole fish populations.

i) Liver disease

Fish have a number of biochemical responses to toxic chemicals. One of the most studied responses of fish to chemical pollutants involves the functions of the liver. The mechanisms for chemical detoxification are sited in this organ which can produce enzymes known as the mixed function oxidases. For example induction of the cytochrome P4501A1 enzyme system, may take place as fish deploy natural mechanisms in an attempt to detoxify chemicals [6]. The activity of these liver enzymes increases with increasing exposure to the chemicals until the system becomes overwhelmed [7, 8, 9] and damage to the liver results.

The induction of liver enzymes by toxic chemicals has been proposed as an indicator of chemical exposure in fish [46,47,]. Bottom dwelling flatfish are particularly affected by constant exposure to chemicals in the sediments. Positive correlations have been established between the occurrence of liver cancer in fish and the levels of toxic chemicals in sediment [10, 71, 72]. An increase in liver abnormalities and liver enzyme activity in dab has also been documented along a North Sea pollution gradient [46, 72] extending out as far as the Dogger Bank where chemical pollutants build up in the sediments which are deposited there. The detoxification of chemicals in the liver involves enzyme systems that are normally involved in hormone, steroid and fatty acid metabolism [29]. This then allows the direct interaction of foreign chemicals with physiological processes. Some chemicals such as the polynuclear aromatic hydrocarbon benzo[a]pyrene (B[a]P) are converted to their most carcinogenic form [11] by these processes. The chemical metabolite of B[a]P can combine directly with the genetic material DNA. The severity of liver lesions in flatfish in Europe and the US have been shown to closely correlate with the accumulation of a range of chlorinated, toxic and carcinogenic chemicals [12, 13].

ii) Skin Ulcerations

One disease of finfish has attracted attention because its unsightly appearance affects fish marketability. Highly visible ulcerations of the skin appear to be pollution related. Skin ulcers occur on a wide range of fish and have been described from the North Sea and the eastern seaboard of the US. The species distribution and occurrence of these lesions appears to be expanding and in the US at least they are considered to be a problem of regional scale [15]. Skin lesions have been reported from Atlantic menhaden, weakfish, southern flounder and American eels in the US, while in the North Sea the problem has been identified in dab exposed to metal rich wastes from the titanium dioxide industry [16].

Monitoring activities conducted by the International Council for the Exploration of the Sea (ICES) have revealed that ulcerative lesions are more numerous in flatfishes from coastal waters adjacent to large urban populations, and these findings were paralleled in the US [17]. Nonetheless, the effects of ulcerative lesions on the viability of commercial stocks are unknown although the stressed conditions of the fish could affect reproduction by affecting survival and metabolic processes. There is also some evidence that the conditions favouring the development of these skin ulcers in fish also suppress the immune system [18]. Immune responses of a variety of marine organisms are known to be affected by pollution [41]. In turn, this may affect the ability of fish to resist bacterial disease and parasitic infection although relatively little empirical evidence of this has been gathered to date.

i) Behavioural alterations

Alterations to the behaviour of schools of fish have been observed following exposure to industrial effluents. The schooling behaviour of vendace (*Coregona albula*) is changed by exposure to pulp and paper bleachery effluents. By increasing predation pressure on the fish, such changes may be of great significance to fish populations [4]. As noted earlier much larger numbers are exposed to sublethal levels of chemicals than are acutely poisoned. In addition, sub-lethal levels of pollutants are known to interfere with the sensory systems of aquatic animals [38] affecting their ability to avoid predators and their ability to locate food. Under some circumstances, the feeding rate of fish exposed to chemicals may be reduced [39]. This is independent of pollution effects which may be exerted directly upon the food organisms themselves. This may alter the availability of preferred food organisms to the fish. Importantly, fish may not show avoidance behaviour towards areas areas where they are chronically exposed to pollution. Some juvenile fish will elect to live on contaminated sediments rather than clean ones on the grounds of preferring the size of the contaminated sediment grains [41]. This behavioural pattern will maximise their exposure to pollutants and increase the likelihood of other pollution related impacts.

Changes in the quality and quantity of food resources available to fish, together with changes in their ability to locate and utilise food resources have profound implications for individual fish and their populations. The growth and maturation of fish depends very greatly on the food that is available to them. Any fall in the quality of their food is likely to stress fish making them less likely to breed successfully. If their numbers are reduced by predation following changes in their schooling behaviour, then this too will mean that fewer individuals will reach reproductive age and be capable of regenerating depleted stocks.

iii) Deformities

Gross external deformities have been observed in fish exposed to the chemicals present in pulp and paper effluents. Baltic perch exposed to chlorine bleach effluents have been shown to suffer from fin erosion [2]. Fin erosion has also been observed in fish living in the highly contaminated waters of the New York Bight [60]. Pike exposed to chlorine bleach effluents are found to suffer from severe skeletal deformities of the jaw and similar deformities have been recorded in other fish species chronically exposed to pollution [3]. Such deformities may affect the ability of fish to escape predators or to exploit food resources and thus affect the size of the breeding population.

iv) Pollutant exposure, disease and population genetics

Overall, several clear links have emerged between disease in fish and their exposure to pollution. Gross deformity and behavioural alterations lie at opposite ends of a spectrum of demonstrated effects of pollution on fish health [28]. In most cases gross disease in fish is relatively easy to detect by examination of the whole fish or their internal organs. There is no doubt that ill health, by reducing the condition of the fish will affect their ability to avoid predation. Fish in poor health due to pollution exposure are less likely to breed successfully and the population will suffer as a result. Overall, sub-chronic pollution can stress individual fish to a high degree. By impairing the immune system and making the fish more vulnerable to disease, and by compromising the function of the liver, pollution stress could seriously impair the condition and reproductive capacity of a fish population.

One aspect that has been little investigated to date, but which is of great potential importance is the possible effect of pollution on the genetic diversity of fish populations. Genetic changes do not only lead to cancerous diseases of organs such as the liver. In many species of aquatic animals exposed to pollution, genetic diversity is reduced. Pollution effectively acts as a factor in natural selection by selecting for populations of animals which can withstand the polluted conditions. The characteristics which allow adaptation to other changes in environmental conditions may be selected against. Hence, while fish may appear to adapt to polluted conditions it may be at the expense of the long term ability of the population to accomodate other changes in environmental conditions. Although this may be important as this may be, [34] such changes in genetic diversity in fish have received very little attention, and so any conclusions are, necessarily, highly speculative. At worst, it could lead to a form of insidious chemical extinction of fish populations.

4) Effects of pollution on fish reproduction

i) Survival of embryos, larvae and juvenile fish

The embryos and larvae of fish are known to be much more highly sensitive to the effects of pollution than the adults [19, 60]. One study outside a petrochemical complex has shown that fish recruitment into contaminated areas is lower than at reference sites [70]. Individual fish from adult populations close to the complex were larger in size but much smaller in number as a result. Developmental defects in fish larvae have also been reported and attributed to pollution. Aberrant development of Baltic fish was found to range between 18% and 44% depending upon species for larvae sampled in the western Baltic [22]. Malformation rates of fish larvae in the Eastern North Sea were found to be highest in the centre of the German Bight and off the Dutch coast. Both areas are highly impacted by contaminant input from rivers [23].

More recently, in the North Sea, the number of deformed fish embryos was positively correlated with contaminant levels along a transect from the inner German Bight to the Dogger Bank.

Abnormalities fell with increasing distance offshore, rising again over the Dogger Bank, where pollutants tend to accumulate in the sediments [61]. Similar results have been reported from California [24] and the New York Bight [25] where the highest rates of larval malformations were reported from the most seriously polluted areas. This work agreed with earlier work identifying the marine microlayer as a critical component of the ecosystem. This thin layer of lipid rich material at the sea surface can concentrate organic pollutants which in turn can adversely affect the fish larvae which develop in contact with it [26].

There is some evidence that the survival of fish larvae is determined to some degree by the exposure of the adults to toxic chemicals. For example, in a polluted area of San Francisco Bay, more highly exposed female starry flounder laid fewer viable eggs. These were less successfully fertilised and aberrant embryological developments were more common than in eggs laid by less exposed fish [48]. Such findings imply considerable disruption of biochemical and physiological controls and recent findings have highlighted the ability of some chemicals to disrupt the hormone systems which control fundamental aspects of fish reproduction.

ii) Endocrine disruption

A growing number of chemicals have been shown to interfere with hormone pathways in a wide range of species, including humans. This should come as no surprise in the case of many pesticides which are actually designed to interfere with these systems. The trichlorophenoxyacetic acid herbicides (2,4-D; 2,4,5-T; MCPA), for example work by disrupting the normal growth hormone systems of plants. Various insecticides also disrupt the hormonal systems controlling moulting and development of insects [63]. TBT is another well known chemical which interferes with the hormonal systems of marine molluscs [60]. The herbicides atrazine and simazine have also been shown to exert powerful disruption of oestrogen hormone systems [64]. Not surprisingly disruption of fish endocrine systems has been detected in fish exposed to pollutants. The reproduction of affected fish has been found to be particularly seriously affected.

iii) Effects on reproduction

Many chemicals are capable of disrupting endocrine systems [49,50] partly as a result of their ability to induce liver enzymes normally involved in regulating the oestrogen-like hormones or by otherwise affecting levels of circulating hormones. A recent extensive review has concluded that the effects of chemicals upon fish include lesions, haemorrhage or malformations in the gonads. Malformations of these organs together with the pituitary and liver can inhibit the secretion, production and metabolism of hormones by the endocrine system [74]. A wide range of environmental contaminants, in fact, are known to have the potential to disrupt endocrine systems. The major known group are representatives of the class of organochlorines although these are by no means the only ones. Accordingly, in benthic fish exposed to contaminated sediments levels of circulating hormones were found to be reduced and the females found to be less likely to spawn [51].

Winter flounder exposed to contaminated sediments were less able to manufacture egg yolk, vital to the survival of the larvae [52]. This leads, in turn, to the reduced egg and larval viability noted above [48, 53]. These effects can be maintained over long periods and consistent low egg viability, and larval size has been observed over three consecutive years in one population of winter flounder. Hence, this is not a transient, but a chronic long term, response [54]. The contaminants present were varied in nature but included PAHs, other hydrocarbons and PCBs.The chlorinated dioxins too, are powerful endocrine disrupters and act on liver enzyme pathways. In higher vertebrates at least twenty two other groups of halogenated chemicals with similar properties have also been identified [62].

Not all such effects are produced by induction of liver enzymes and subsequent interference with hormonal pathways. Some chemical effects may be direct. Perhaps the most dramatic example of endocrine disruption in fish has been documented downstream of sewage effluent discharges into river systems [55]. In this case, male fish acquired pronounced female characteristics, in particular, the ability to produce a precursor to egg yolk. This process is normally under the control of oestrogens produced in the ovaries of females. The chemical or chemicals causing this are as yet unidentified and the mechanisms of action are unclear, but detergent breakdown products (nonyl phenols) are one of a number of priority suspects and are known endocrine disrupters. The detergents based on nonyl-phenols are in wide use and are known to be able to influence a wide range of biological functions, generally with negative effect [56]. Large quantities of surfactants are released in sewage discharges, and the nonyl-phenols are also released in large quantities by the factories which manufacture them [57, 58].

In addition, reproduction may be affected by the ovaries of fish taking up chemical contaminants directly. Even cod from relatively remote areas are known to have organochlorine contaminants in their ovaries [59]. Many organochlorines such as PCBs, DDT, toxaphene and mirex are known endocrine disrupters but may also act directly on the reproductive tissues. In the North and Baltic Seas positive correlations have been made between the levels of these contaminants and reproductive success. Contamination of the ovaries of fish by organochlorines has been correlated with a lower hatching success in a variety of fish species in the Baltic Sea [20,21]. The gametes themselves are known to be highly sensitive to toxic chemicals [74].

5) The significance of effects of chemicals at population level

There is no doubt, therefore, that pollution is capable of affecting fish in a variety of ways. The most important impacts are upon health and reproduction, compromising the ability of populations to replace and maintain themselves. A full understanding of stock/recruit relationships has proved elusive but reproduction and larval viability is regarded as a fundamental determinant of fish stocks. Impairment of reproductive potential of fish species, therefore could result in collapse of fish stocks. Population crashes have been recorded in birds of prey and seabirds as a result of pesticide use. Effects may be exerted on two levels. Reduction in the fecundity of breeding fish may result in fewer viable larvae. Pollution effects may also be exerted upon the juvenile stages which are the most sensitive to pollution [19, 60].

The degree to which these established effects are influencing fish stocks is a matter for conjecture. Lack of hard evidence at the population level in marine waters is merely a reflection of the natural size and variability of fish populations coupled with a lack of suitable techniques for the reliable detection of changes. It is likely that detection of any effects will result only from catastrophic decline of any given fishery. Modelling techniques however allow some appreciation of the scope for disaster.

One model collated the available life history data for eight species of fish. The model simulated a one-off 50% reduction in the survival of fish larvae at the first year. The model predicted that on average, equilibrium to 88% of pre-impact levels would take ten years [27]. Later work [66] modelled the effect of habitat destruction for Atlantic menhaden. This model takes into account potential impacts on adults. These spend winters away from the estuarine habitats which serve as breeding and nursery grounds. The results were startling. If 1% of the Atlantic menhaden habitat was destroyed, the model predicted that the population would fall by 8% over ten years. If this habitat loss took place in the estuaries, affecting juveniles also, then in ten years the population would be driven down to 58% of its normal level. Pollution of marine habitats can be regarded as a form of destruction insofar as it can prevent fish reaching their full reproductive potential. The possible impacts could be sufficient to not only prevent stocks recovering but in some cases to actually drive stocks down. The pollution of seas and coastal waters is a continual process and the progressive degradation of marine habitats in this way poses a threat to fish populations of immense scale.

6) Conclusion

Official evaluations of the state of the North Sea environment have signally failed to include a consideration of the potential effects of chronic exposure to low levels of toxic chemicals upon fish populations. This is a serious ommission given the fact that disease syndromes observed in both laboratory and field studies clearly demonstrate the potential negative impacts of pollution upon fish. Demonstrated effects include behavioural alterations, developmental abnormalities, liver disease, cancer, interference with sensory mechanisms and skin disease. There is a possibility also that reduction in the genetic diversity of fish populations exposed to toxic chemicals may also be an important factor. Recent findings of major importance to the population dynamics of fish include a reduced production of eggs from adult fish exposed to toxic chemicals, reduced viability of eggs and larvae and an increase in the numbers of deformed larvae.

Research into the consequences of long term low level exposure of fish to toxic chemicals is still very much in its infancy. Provisional modelling exercises, however, predict significant impacts upon fish populations and these are likely to be most serious in populations already under pressure from over fishing.

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