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Effects of river regulation and diversion on marine fish and invertebrates

KENNETH F. DRINKWATER and KENNETH T. FRANK
Department of Fisheries and Oceans, Bedford Institute of Oceanography, Box 1006, Dartmouth,
Nova Scotia, Canada B2Y 4A2

ABSTRACT

1. The effects of freshwater regulation and diversion on the adult and larval stages of fish and invertebrates in coastal marine waters are reviewed.

2. Potential impacts of river modification are highlighted based on our present understanding of the role of fresh water on the physical, chemical and biological processes on the marine environment. These include effects on migration patterns, spawning habitat, species diversity, water quality and distribution and production of lower trophic levels. The effect of dams on anadromous and catadromous fish are also presented.

3. We discuss in detail the marine response to specific river regulation projects on the Nile, Indus and rivers flowing into the Black Sea, San Francisco Bay and James Bay in Canada. A decline in some coastal fisheries with an overall negative impact on the biota is generally associated with reductions in freshwater flow.

4. Extensive ecological considerations are needed during the planning stage of large-scale freshwater modification projects to minimize potential impacts.

INTRODUCTION

The abundance and distribution of marine fish and invertebrate stocks exhibit large temporal fluctuations which, in part, are determined by changes in environmental conditions (Bakun *et al.*, 1982; Shepherd *et al.*, 1984; Sissenwine, 1984; Hamilton, 1987). One important environmental factor in this regard is river run-off. This is not surprising given the profound effect freshwater discharge has upon the physical, chemical and biological processes in coastal regions (Skreslet, 1986). Fresh water affects circulation patterns and vertical stability, modifies mixing and nutrient exchange processes, influences sea-ice formation in high latitude regions, and regulates primary production. Particulate organic and inorganic compounds, as well as living organisms, carried seaward by rivers, are incorporated into marine food chains. The seasonal and interannual variability of the inflowing rivers are often reflected in the physical and biological characteristics of coastal waters. The effects of fresh water on the marine environment often extend well beyond the region adjacent to river mouths, upwards of a thousand kilometres 'downstream' in the case of rivers such as the Amazon (Moore *et al.*, 1988), the Zaire (Eisma and van Bennekom, 1978) and the St Lawrence (Sutcliffe *et al.*, 1976).

Man has long regulated river flows, initially for irrigation of agricultural lands, flood control and navigational purposes. Recently, dams have been built for hydroelectric generation and today most major river systems are regulated to some degree (Halim, 1991). Barrages have also been built within estuaries,

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initially for flood protection or water storage but more recently for tidal power generation. River regulation by dams or barrages can result in major alterations to the natural seasonal discharge cycle of fresh water and, in the case of interbasin diversion schemes, even the total annual discharge is altered. These changes can result in significant and sometimes detrimental effects not only to the riverine system but also to large areas of adjacent coastal waters (Davies *et al.*, 1992). It has been common practice not to consider the marine environment when planning freshwater management projects and although its importance is now being recognized, some developers, engineers and politicians still consider water that reaches the ocean to be a 'lost' resource (e.g. Bourassa, 1985). Unfortunately, this narrow perspective was also expounded in an editorial in the journal *Science* as recently as 1985 (Abelson, 1985). Effective management of freshwater resources *must* consider the potential impacts upon the marine environment given the ever-increasing demands for large-scale water regulation and diversion.

The purpose of this paper is two-fold: (1) to provide a brief overview of the general effects that freshwater regulation and diversion may have on fish and invertebrates in coastal and marine waters and (2) to examine the physical and biological responses that occurred during five different freshwater management projects.

GENERAL OVERVIEW

Freshwater regulation and diversion affect coastal fish and invertebrate species in a variety of ways. Migration and spawning patterns, survival of young, species distribution and competition, food production and water quality can all be altered.

Direct effects of dams and barrages

Freshwater regulation is principally achieved through the building of dams. One obvious direct effect of such barriers is the blockage of migration routes for anadromous and catadromous fish species. Anadromous species, which include members of Salmonidae and Clupeidae (e.g. shad), are those that live much of their adult lives in salt water but spawn in fresh water. Catadromous species, such as eels (F. Anguillidae), spawn in marine waters but spend most of their life in fresh water. Populations of anadromous fish that fail to reach their spawning grounds because of blockage due to barriers will eventually die out (Watt, 1989). In many instances steps have been taken to avoid such local extinction by constructing fishways or ladders to allow the fish to pass around the dams. These have proven successful in some locations (e.g. the Connecticut River in the eastern United States; Moffit *et al.*, 1982) but their general usefulness in both temperate and tropical regions is in doubt (Baxter, 1977; Scudder and Conelly, 1985). Even where fishways are successful, delays in migration occur below the dams (Haynes and Gray, 1980). Further delays can occur in the reservoirs behind the dams due to the absence of navigational cues such as strong currents that aid fish in their search for an upstream channel (Brett, 1957). Such delays result in a decrease in energy reserves. For the many anadromous species that do not feed during migration excess expenditure of energy can jeopardize spawning success as energy reserves are closely tied to the requirements necessary for successful migration and spawning (Brett, 1957; Geen, 1974; Glebe and Leggett, 1981).

Significant injury and even death can result if migrating anadromous fish pass through hydroelectric turbines. This occurs either from direct contact with the turbine components or through changes in hydrostatic pressure of the water as it flows through the turbines (Davies, 1988). Shearing and turbulence in the water can also cause injury. Bell and Kynard (1985) measured nearly 22% mortality for downstream migrating American shad (*Alosa sapidissima*) that passed through the turbines at the Holyoke Dam on the Connecticut River. Upwards of 46% mortality was estimated for shad at the tidal power barrage on the Annapolis River in the Bay of Fundy (Dadswell *et al.*, 1986). Juvenile salmon (*Oncorhynchus tshawytscha*) and steelhead (*Salmo gairdneri*) in the Columbia River must pass eight dams on route to the ocean; characteristically low numbers of returning adults can be attributed to high mortality rates of the juveniles when passing through turbines at the dams, delays in migration in low-flow years and exposure to lethal concentrations of dissolved gases caused by spilling at dams during high-flow years (Raymond, 1979). The survival rates of salmon and steelhead juveniles that were trucked past seven of these dams were 1.1 to 15 times those of naturally migrating salmon (Ebel, 1980).

Dams have less of a negative effect on catadromous fish (Baxter, 1977). Although eels may be killed in turbines, they are able to successfully negotiate spaces that adult anadromous species such as salmon cannot. Also, eels are not restricted to specific rivers and can colonize new rivers if their migration route is blocked by dams.

Effects of changes in river discharge

Changes in run-off also influence marine fisheries as suggested from studies showing strong covariation between river discharge and subsequent fish landings or abundance. Sutcliffe (1972, 1973) found statistically significant positive correlations between lagged landings of halibut, haddock, soft-shell clams, and lobster in the Gulf of St Lawrence (Canada) and St Lawrence River discharge. The lag time in years was species dependent and equalled the approximate age at maturity, i.e. when the cohort entered the fishery. This suggests an influence during the fish's first year of life and is consistent with other biological studies that indicate fish abundance is largely determined during the egg and larval stage. Empirical relationships between recruitment and catch of fish or shellfish and freshwater run-off or rain have been observed in many other regions for a variety of species, e.g. cod (*Gadus morhua*) in Norway (Skreslet, 1976) and off eastern Canada (Drinkwater, 1987), striped bass (*Morone saxatilis*) and chinook salmon (*Oncorhynchus tshawytscha*) in San Francisco Bay (Rozengurt *et al.*, 1985), striped bass (*Morone saxatilis*) in the Potomac, Delaware and Hudson estuaries in the northeastern United States (Summers and Rose, 1987), several varieties of pelagic fish off India (Pati, 1984), brown shrimp (*Crangon crangon*) off southern England (Driver, 1976), pink shrimp off Florida (Browder, 1985), shallow-water shrimp (*Penaeus indicus*) off Central Mozambique (Jorge da Silva, 1986; Gammelsrød, 1992), prawns (*Metapenaeus macleayi*) in Australia (Ruello, 1973; Glaister, 1978), blue crab (*Callinectes sapidus*) in Chesapeake Bay (Tang, 1985), oysters (*Crassostrea virginica*) and blue crab in Apalachicola estuary in Florida (Meeter *et al.*, 1979; Wilber, 1992), etc. Most correlative studies show a positive relationship between fish abundance or landings and river discharge although occasionally it is negative (Sutcliffe *et al.*, 1983). While there is always the possibility of spurious correlations and some of the relationships have not stood the test of time (Drinkwater and Myers, 1987; Drinkwater *et al.*, 1991), the number and geographical extent of these examples strongly support a linkage between freshwater flow and the production of certain species of fish and shellfish.

Freshwater regulation for flood control or hydroelectric power production primarily changes the seasonal discharge cycle. Water is held back during times of high run-off and released later, in the case of flood control, or when power consumption is low and released when power requirements are high, in the case of hydroelectric developments. The annual discharge rate will generally not differ greatly from the unregulated case, except initially as reservoirs are filled. Exceptions occur where significant amounts of fresh water are diverted from one river basin to another. The annual discharge may also be reduced where water is removed for industrial, residential or agricultural purposes, or where extensive evaporation occurs from the reservoirs.

Migration

Variations in river run-off are believed to induce upstream spawning migrations in many anadromous fish stocks (Fraser, 1972; Northcote, 1982). Most salmon migrations occur at times of increasing or peak run-off. Also, the downstream migration of many juvenile salmon stocks tends to be associated with high freshwater discharge (Northcote, 1982; Youngson *et al.*, 1983). A temporal shift in the normal discharge cycle due to regulation or an overall decrease resulting from diversions could alter migrational cues. Indeed, Ganapati (1973) suggested that the construction of dams reduced upstream migrations of shad (*Hilsa ilisha*) in several rivers in southern India through reductions of high freshwater flow rates.

Homing in some anadromous species such as salmon is believed to be triggered by the chemical make-up of the river water. This ability to 'smell' the fresh water has been termed the olfactory hypothesis (Harden Jones, 1968). Both the olfactory sensitivity in fish (Hasler, 1954; Hara, 1970) and its use to identify particular streams (Cooper *et al.*, 1976; Cooper and Hasler, 1976) have been demonstrated. The offshore location where fish are able to detect stream odours depends upon several factors including river discharge rates (Leggett, 1977). The effects of the Connecticut River have been traced onto the continental shelf a distance of 65 km from the river mouth, where it is believed to initiate the final stages of homing in American shad, *Alosa sapidissima* (Doodson and Leggett, 1974). Clearly, in the case of low flow rates the offshore limits of the freshwater influence would be reduced. This would probably delay detection of the home stream, increasing the probability of straying and result in a later migration for those species dependent upon such cues.

Spawning success

Many marine fish species spawn in estuaries or flood plains, generally at times near peak run-off. Significant shifts in the timing of flood waters may result in asynchrony between peak run-off and spawning time. An increase in sediment concentrations or settling rates of the river-borne materials resulting from alterations in the quantity of freshwater discharge rates may cause the spawning grounds to become covered with sediment thereby suffocating the eggs. Conversely, insufficient sediment transport could reduce food levels for emerging larvae. Low flow rates may result in reduced oxygenation of eggs attached to the bottom causing increased stress and possibly higher mortality. For other species, dams may reduce current speeds below critical levels needed to keep their eggs in suspension and the eggs may settle to the bottom (Zimpfer *et al.*, 1987). The presence of high salinity water through reduced river flow may also be detrimental to the eggs of some species (Peters, 1982). Under severe reductions in freshwater flow spawning sites may dry out. Declines in fish abundance in the estuaries along the northwestern Black Sea (Tolmazin, 1985) and within San Francisco Bay (Kjelson *et al.*, 1982) have been partially attributed to deterioration of spawning sites through reduced freshwater flows.

Advection of eggs and larvae

Many fish species have evolved behaviour that in combination with horizontal circulation patterns maximize their potential of reaching favourable habitat in later life stages. For example, currents may advect eggs or larvae towards distant nursery grounds or conversely act to retain them within a region if the spawning and nursery grounds overlap (Boicourt, 1982, 1988; Norcross and Shaw, 1984; Weinstein, 1988). In coastal regions strongly influenced by river discharge, such as estuaries, the residual circulation pattern tends to be dominated by a surface outflow driven by the river run-off with a compensating subsurface inflow. Many species of zooplankton and fish have been found to spawn near the head of estuaries, their eggs and larvae drifting seaward, descending as late stage larvae or juveniles into the lower layer near the mouth of the estuary, and eventually returning back up the estuary to spawn (Bousfield, 1955; Tyler and Seliger, 1978). Other species are known to use outflowing surface currents from estuaries to transport larvae onto the adjacent shelf where they reside before returning to the estuary as adults (e.g. the blue crab, *Calinectes sapidus*, in Chesapeake Bay; Johnson and Hester, 1989). Regulated flow rates can effect the strength of the residual currents and hence the time the larvae reside within a region, i.e. the larvae may be transported beyond the nursery areas in the case of increased run-off or not reach these areas in the case of lower flow rates. Mitchell (1976), studying the recruitment of the bivalve, *Mercenaria mercenaria*, in an estuary on the south coast of England, observed an apparent positive correlation with the presence of low river flows during its spawning time. The low flows were interpreted as reducing the flushing time of the estuary, thereby decreasing the loss of larvae from the river system.

Species competition and distribution

Freshwater-dominated estuaries and deltas, including saltwater marshes and mangrove swamps, are well known as important nursery areas for large numbers of marine fish species (McHugh, 1967; Haedrich, 1983). Houde and Rutherford (1993) estimated that over 50% by weight of the total fish and shellfish landed in the United States spend a portion of their life in estuaries. In certain areas such as the Gulf of Mexico the percentage is even higher (McHugh, 1967). The principal advantages to juvenile fish of these nearshore nurseries are lower predation pressure and increased food supply (Miller *et al.*, 1985). Adult fish, which may prey upon the young, are less able to tolerate salinity extremes, less likely to swim into very shallow waters, and may not be able to see the small fish due to high turbidity (Miller *et al.*, 1985). A decrease in sediment load and an increase in salinity through reduction of fresh water may thus lead to increased access of adult fishes to nearshore areas with a concomitant reduction in juvenile abundance.

Nursery habitat can also be physically modified by changes in freshwater flow. Intrusions of salinity induced by decreases in river flow can destroy habitat as in the case of coastal mangrove forests (Snedaker, 1984) or may be beneficial in the case of saltwater marshes (Boesch and Turner, 1984). Tidal barrages usually result in a rise in the mean sea level behind the barrier with the subsequent loss of intertidal areas (Gray, 1992).

Species abundance and distributions are partially controlled by salinity and salinity gradients. Increased river run-off can result in a territorial expansion and higher abundance levels for estuarine species whereas marine oriented species are more likely to contract their geographical distribution and decrease in abundance. The opposite responses will occur in the case of a decrease in river run-off. In extreme situations, such as river diversions, salinity changes can be large enough to eliminate resident species and introduce new ones. In addition to direct influences on fish and shellfish, salinity changes can affect them indirectly through effects on food, predators and parasites (Copeland 1966). Interbasin water transfers can potentially introduce new species of flora or fauna into the receiving river basin, including diseases and parasites (Davies *et al.*, 1992).

General productivity and food supply

Freshwater flow affects the general productivity of the coastal regions. Primary production at the mouths of rivers and downstream in coastal areas can be enhanced through an influx of natural river-borne nutrients, as was suggested for the Columbia River by Stefánsson and Richards (1963) and for the Mississippi in the early years by Riley (1937). River-induced entrainment of nutrient-rich subsurface sea water also can enhance surface nutrient levels (Neu, 1976). A reduction in river outflow, annually or seasonally, could lead to less phytoplankton production through reduction of these nutrient fluxes. In highly populated and industrialized countries, such as those in northern Europe, the large nutrient loads carried by the rivers have produced dramatic increases in phytoplankton production, as well as changes in the species compositions and seasonal patterns of the nearshore algal blooms (Postma, 1985; Cadée, 1986; Radach, 1992). The nutrient supply to the coastal regions depends not only upon nutrient concentrations in the river but also upon the rate of freshwater discharge (Schaub and Gieskes, 1991). The biological response in the coastal region to river-induced nutrient loading will depend upon several factors, foremost among them being the strength of the tidal mixing (Monbet, 1992).

The relationship between primary production and run-off is not simply through the river's influence on nutrients. For example, increased turbidity caused by river-borne sediments can reduce light levels, thereby depressing phytoplankton production, as occurs off the Zaire River (Cadée, 1978). In other regions during flood conditions the current speeds may exceed those necessary to maintain a plankton population and production becomes limited (e.g. the St Lawrence Estuary; Therriault and Levasseur, 1986). Where there are sufficient nutrients and light to promote phytoplankton growth, the high vertical stability of the water column produced by river outflows allows development of phytoplankton blooms by maintaining the plankton in the euphotic zone. Initiation of the bloom following stratification induced by run-off has been observed off Iceland (Thórdardóttir, 1986; Stefánsson and Ólafsson, 1991), Norway (Peinert, 1986), and in the St Lawrence Estuary (Therriault and Levasseur, 1986). On the other hand, the reduced vertical exchange due to stratification may prevent phytoplankton cells that overwinter in the deep waters from seeding the surface mixed layer, thus delaying the spring bloom as has been suggested in the Lower St Lawrence Estuary (Therriault and Levasseur, 1986).

Changes in sediment load, settling velocities and bottom scouring caused by river regulation may affect sedimentation rates in coastal areas. These in turn can cause changes in the distribution and characteristics of bottom dwelling fauna and flora in coastal regions. Vertical stratification of the water column, enhanced by freshwater addition, also influences the vertical transfer of primary production. Under strongly stratified conditions most of the primary production is consumed or recycled within the upper layers whereas under weak stratification more energy is deposited to the ocean floor (Smetacek, 1986).

Detritus is important as food for fish and shellfish (de Sylva, 1975) and is the dominant source in tropical regions. The latter is primarily derived from decaying mangroves (Snedaker, 1984). The amount and type of detrital material carried by the river waters to the coastal regions often reflect the strength of the freshwater discharge.

Water quality

Large quantities of chemicals are added to rivers through waste disposal from industrial and urban sources and through drainage of agricultural lands. These include nutrients, as well as contaminants such as PCBs, heavy metals, pulp mill effluent, etc. As discussed earlier, river-borne nutrients can lead to increased primary production where light is not limiting. In the southern Bight of the North Sea eutrophication has also changed phytoplankton species diversity (Gieskes and Kraay, 1977), produced obnoxious blooms of algae (Cadée, 1986) and caused oxygen depletion due to algal decomposition (Schaub and Gieskes, 1991). Such changes can lead to reductions in the abundance of shell and finfish, although this will tend to be species dependent (Valiela *et al.*, 1992).

If river run-off is reduced, pollution problems can develop or worsen. The concentration of contaminants may increase because less water is available for dilution and because of longer residence times due to weaker mean currents. Slower currents may also lead to more rapid deposition of the river-borne materials and a build-up of toxins at the bottom of estuaries and nearshore coastal regions, with serious negative impacts on benthic organisms and bottom-feeding fish (Tolmazin, 1985). Toxin accumulation through the food chain can occur such to make commercial fish feeding in heavily polluted areas unfit for human consumption.

River-induced stratification can also effect water quality. Extreme stability of the water column can prevent reoxygenation of the subsurface waters resulting in hypoxia ($<2\,\mathrm{mg\,L^{-1}}$) or even anoxia ($<0.1\,\mathrm{mg\,L^{-1}}$). Oxygen depletion in the near-bottom waters is reduced further by decomposition of river-borne organic material. Hypoxia and anoxia are common in summer along the north coast of the Gulf of Mexico due to the influence of the Mississippi and Atchafalaya Rivers (Gaston, 1985; Pokryfki and Randall, 1987). Reductions in the abundance of shrimp and demersal fish in the region have been linked to the river-induced oxygen depletion (Pavela *et al.*, 1983). Similar events in Chesapeake Bay have led to mortality of oysters (Seliger *et al.*, 1985).

The building of dams can themselves cause severe water quality problems. The flooding of soils and vegetation in boreal forest lands during reservoir formation adds inorganic mercury and organic nutrients to the water. Both of these increase microbial methyl-mercury production elevating mercury levels within the water which is then transported downstream (Johnson *et al.*, 1991). Ultimately, the mercury is incorporated into the food chain causing mercury contamination of the local fish populations. High levels of mercury may remain in the water and fish populations for periods of up to 20 years or more.

CASE STUDIES

The preceding brief overview clearly shows that modifications to freshwater inflow can potentially produce a wide range of responses, with a negative impact on the biota generally, but not always, associated with reductions in freshwater flow. We now examine the marine response to five specific freshwater regulation and diversion schemes.

Nile River

The building of the High Aswan dam in Egypt had important impacts on the marine life in the southeastern Mediterranean Sea. Prior to the dam construction, the Nile River entered the sea through two main tributaries with a mean discharge of about 40 $km^3 y^{-1}$ (Gerges, 1976). The main period of river flow was between July to January with the peak in September–October. The flood waters spread over the sea surface and were deflected eastward along the coast, their influence reaching at least as far as Lebanon and southern Cyprus (Aleem, 1972). The strong vertical stability, high nutrient levels, and large quantities of organic matter introduced to the sea by the influx of Nile flood waters contributed to an intense phytoplankton bloom (Pandian, 1980). It primarily consisted of diatoms (Halim, 1960) and gave rise to increased zooplankton biomass (Aleem, 1972). Sardines (F. Clupeidae) migrated into the area to feed on the zooplankton. During this time the fat content of the sardines increased substantially (Aleem, 1972). An extensive fishery developed, based on this migratory stock. Another important commercial fishery whose production was also linked to the Nile flood waters was shrimp (F. Penaeidae).

Construction began in 1960 and the High Aswan dam was fully operational in 1965. By 1968 the river discharge had dropped to one-tenth of the pre-dam level, with over 50% of the flow occurring in January–February (Gerges, 1976). The large decrease in fresh water resulted in increased salinity in the coastal region off the Nile delta, a deeper mixed layer, and a sharp decrease in both suspended sediments and nutrient concentrations (Aleem, 1972; Gerges, 1976). The autumn phytoplankton bloom, when the biomass was traditionally at a maximum, decreased to 10% of its pre-dam levels by 1964, to less than 1% by 1969–70 and has remained low (Gerges, 1976; Dowidar, 1984). Zooplankton production and standing crop decreased an order of magnitude and the fat content of the sardines dropped substantially (Aleem, 1972; Dowidar, 1988). The average weights of the sardines were 10%–15% lower in the post-dam years compared with pre-dam years for corresponding lengths, and the length-at-age decreased (Dowidar, 1988). The total catch of sardines declined by 90% and has remained well below pre-dam values (Halim, 1976; Dowidar, 1988). Although fishing effort increased by a factor of 19 between 1952 and 1962 (Bebars and Lasserre, 1983), the decrease in sardine catch is generally attributed to alterations in Nile outflow rather than to excessive human exploitation (White, 1988; Dowidar, 1984, 1988).

A 75% reduction in Egypt's annual shrimp landings also occurred after completion of the dam and the catch has remained low (Aleem, 1972; Wadie and Abdel Razek, 1985). The four dominant species of shrimp decreased in both body size and numbers and were eventually replaced in importance by a smaller, less productive shrimp species. These changes have been attributed to reduced mud and silt deposition caused by the dam which in turn decreased the benthic food supply for the large shrimp and possibly destroyed breeding areas through increased coastal erosion (Wadie and Abdel Razek, 1985).

It is important to note two other far-reaching consequences of the High Aswan dam. After completion of the dam there was increased flow from the Suez Canal into the Mediterranean Sea (Gerges, 1976). Previously the Nile flood waters raised sea levels in the southeastern Mediterranean higher than those in the Red Sea which produced a southward flow during flood conditions. With the reduction in Nile outflow the sea surface slope reversed, causing northward flow that facilitated further migration of Red Sea fauna to the Mediterranean. Second, a simplified hydraulic model that assumes the circulation in the Mediterranean is largely controlled by exchange through the Straits of Gibraltar, predicts that the temperature and salinity of the water flowing from the Mediterranean Sea into the Atlantic Ocean would increase (because of the reduced freshwater run-off) and the transport would increase by an amount equal to approximately eight times the volume of the diverted discharge (Nof, 1979). Similar predictions were made by Hassan (1975). Although oversimplified and difficult to confirm because of variability in the transport and hydographic properties due to other processes, the model results illustrate the possible far reaching effects of river diversion.

Indus River

The Indus River drains much of Pakistan and flows into the Arabian Sea. Significant alterations to this river began in the 1940s with major dams completed in 1956, 1967 and 1974. Prior to large-scale regulation the mean discharge was approximately 110 $km^3 y^{-1}$ with peak run-off occurring in July and August and minimum run-off during November to spring (Quraishee, 1988). Eighty percent of the flow occurred between May and October. Since regulation, the freshwater discharge reaching the Arabian Sea has fallen to 20% of its previous value and it occurs exclusively during the summer monsoon (Quraishee, 1988). The river is presently confined to one channel, compared with multiple channels prior to regulation. The low freshwater flows have resulted in a large reduction in the suspended sediment load and, therefore, reduced sediment reaching the sea (Milliman *et al.*, 1984). Salinity intrusions into many parts of the Indus delta caused reduction in the availability of drinking water and destruction of rice growing regions, resulting in emigration of people from the delta region (Quraishee, 1988).

In the waters around the delta, primary production has fallen and hypersalinity and nutrient impoverishment led to the deterioration of the mangrove forests (Snedaker, 1984; Quraishee, 1988). Fish and shrimp that utilized the mangrove ecosystem early in their life histories have been negatively affected. The shrimp fishery in Pakistan decreased 10-fold from the 1950s to the 1980s with large declines associated with the completion of each of the major dams or barrages (Quraishee, 1988). In addition, the catch rate of all fish species dropped significantly in the late 1950s following the completion of the first large barrage and have remained low (Milliman *et al.*, 1984; Quraishee, 1988).

Black Sea

Tolmazin (1979, 1985) has described changes in the Black Sea and adjacent estuaries resulting from inland water management projects. During the 1950s through to the 1970s the USSR built a large number of hydroelectric dams on the rivers flowing into the Black Sea, including the Danube, the Dnieper and the Dniester. Besides modifying the seasonal flow patterns to accommodate hydroelectric production, a significant reduction (10%–15%) in the annual discharge into the Black Sea occurred through both evaporation from the large reservoirs that were created behind the dams and increased consumption for industrial, agricultural and municipal purposes. Water problems were heightened by the intensive use of agricultural chemicals which reached the rivers through land run-off and irrigation seepage.

Changes became apparent in the adjacent coastal regions of the Black Sea. The lowering of the amplitude and the shift in the time of the peak seasonal discharge of the Dnieper River resulted in the low-lying marshes in the Dnieper Estuary not being flooded during the period of peak fish migration. The irregularity of the river discharge due to weekly and daily cycles in hydroelectric production produced associated fluctuations in the currents, particulate content and salinity which were deleterious for many of the estuarine species of fish and zooplankton. The average salinity in the Dnieper Estuary increased and there was an extension upstream of the near-bottom salinity layer. The reduction in the area of fresh and brackish water habitats, coupled with diminished reproductive capabilities, meant that many of the species left the estuary. Excessive phytoplankton blooms occurred in the estuary as a result of high nutrient levels from agricultural sources and sewage disposal that were carried by the river. Peak nutrient concentrations increased by a factor of 2 to 8 over normal conditions. The loss of planktonic herbivores, that normally grazed down the phytoplankton, also contributed to the large blooms. Eventually anoxic conditions occurred, causing the commercial fish landings in the Dnieper Estuary to drop by a factor of 5 and all but eliminated the fisheries in the Dniester Estuary.

The effects of river modifications were not limited to the estuaries. Increased river discharge during summer generated intense vertical stratification of the water column such that the lower layers in the coastal waters of the northwest shelf region of the Black Sea were deprived of oxygen replenishment. Coupled with increased deposition of organic-rich river-borne material, anoxia resulted with mass mortality of all living matter in the bottom layers of the Shelf. Although depletion of dissolved oxygen had been recorded in the pre-control era, the anoxic events and associated mortality increased dramatically in the late 1970s and early 1980s. This led to a sharp decrease in catches of turbot, flounder and crab, which have continued to remain at low levels.

The hydrographic changes in the Black Sea increased flow from the Aegean Sea (Hassan, 1975). Transport of Mediterranean organisms into the Black Sea increased after the major diversions of freshwater flow although the relative abundances remained low.

San Francisco Bay

Extensive modification of the Sacramento–San Joaquin River system, which flows into San Francisco Bay, has taken place over the past several decades. Of the 34 $km^3 y^{-1}$ that historically discharged into the Bay, 40% has been removed for local consumption and another 24% is diverted to central and southern California, leaving a mere 36% to enter the estuary (Nichols *et al.*, 1986).

The reduced freshwater inflow into San Francisco Bay has lowered the flushing time of the water in the Bay thereby reducing its ability to rid itself of industrial contaminants (Rozengurt, 1983). There also has been a rise in the mean salinity of the Bay and salinity intrusions have extended farther upstream in the Sacramento–San Joaquin Estuary (Rozengurt, 1983; Rozengurt *et al.*, 1985). It is estimated that the sediments have been reduced by 60% to 75% of the 8×10^6 tonnes previously discharged annually into the Bay (Krone, 1979). The most important changes have occurred in the biological community. The adult population of striped bass has decreased by 75% since the mid-1960s (Stevens *et al.*, 1985) and the chinook salmon population declined by 70% since the early 1950s (Kjelson *et al.*, 1982). These declines have been attributed to reductions in freshwater run-off through degradation of the spawning areas, reduction in their food supply through a general decrease in the biological productivity of the Bay, introduction of river-borne toxic substances, and mortality of young fish by entrainment into landward-directed water diversions (Kjelson *et al.*, 1982; Stevens *et al.*, 1985; Rozengurt *et al.*, 1985).

A period of extremely low flows in 1976–77 (summer discharges of less than 100 $m^3 s^{-1}$) have highlighted the importance of fresh water on the biology of the Bay. During the summer of 1977 the phytoplankton biomass dropped to 20% of normal levels (Cloern *et al.*, 1983), zooplankton and shrimp abundance decreased (Knutson and Orsi, 1983) and the striped bass declined severely (Stevens *et al.*, 1985). The shrimp and bass have remained at low levels. The data clearly show that fish production in the Bay depends on a high biomass of primary production which, in turn, is directly related to the freshwater inflow (Cloern, 1991). This is further supported by high correlations between the mean annual run-off and the commercial catches of salmon, striped bass and shad for pre-diversion years of 1915–1944 found by Rozengurt *et al.* (1985) and the June–July river flow with the late summer abundance of striped bass for the years 1959–70 found by Turner and Chadwick (1972). Rozengurt *et al.* (1985) suggested that to ensure successful commercial landings of the three species they studied approximately 70% of the long-term average run-off must be discharged i.e. about twice the present levels.

James Bay

Beginning in July 1980, over 90% of the Eastmain River in James Bay (Canada) was diverted northward into the LaGrande River system as part of the first phase of the James Bay Hydroelectric Development.

Prior to diversion the mean discharge of the Eastmain River was near 38 $km^3 y^{-1}$, with a maximum in June and minimum in March (Lepage and Ingram, 1986). The mean discharge after diversion has been about 2.5 $km^3 y^{-1}$ (Ingram *et al.*, 1985).

The changes to the physical regime of the Eastmain River have been described by Lepage and Ingram (1986). Prior to diversion, the Eastmain River was a salt-free estuary and the river produced an extensive (100 km^2) brackish plume 1 to 2 m deep in the adjacent coastal waters. Following diversion the surface flow in the lower estuary decreased almost 90% from approximately 0.4 to 0.05 $m s^{-1}$. Salt water penetrated 8 km upstream of its historical position, resulting in upwards of a 10-fold decrease in amplitude and reversal in the mean currents near bottom (upstream as opposed to downstream). At mid-depth, approximately 5 and 8 km upstream of the mouth, tidal current amplitudes increased by 75% and 100% respectively. Offshore, the smaller freshwater plume following the diversion resulted in reduced stratification, an increase in salinity throughout the summer and a decrease in the amplitude of the semidiurnal salinity variability.

Accompanying the salinity intrusion into the estuary was a major phytoplankton bloom and a change in the species composition from a freshwater dominated community to a more marine oriented one (Ingram *et al.*, 1985). The bloom was due primarily to the increased production of a strictly estuarine species; it is believed to have resulted from a combination of high nutrient levels, strong vertical stability of the water column, and low surface velocities that retained the bloom within the estuary (Ingram *et al.*, 1985). The cause of the high nutrient concentrations following diversion is unclear, but may have been through advection from offshore, regeneration from local sediments followed by vertical transport as a result of larger tidal currents, or lateral transport of materials resulting from wave erosion on newly exposed river banks, as the mean water level decreased by approximately 0.3 m near the mouth of the estuary. Fish larvae characteristic of James Bay and not collected previously in the Eastmain Estuary were observed immediately following diversion (Ochman and Dodson, 1982). However, two of the dominant species, lake whitefish (*Coregonus clupeaformis*) and cisco (*Coregonus artedii*), have not undergone major changes in growth, abundance or reproduction but their distribution has shifted upstream (Messier *et al.*, 1986).

Major changes have also been observed in the LaGrande River. In November of 1978 its flow was interrupted to fill the reservoir behind the largest dam in the James Bay development known as LG-2 (Messier *et al.*, 1986). The flow dropped immediately from a minimum of 340 $m^3 s^{-1}$ to a few tens of $m^3 s^{-1}$ and reached a minimum of 2 $m^3 s^{-1}$ in February, 1979. The flow was gradually restored between June and November, 1979. Since then the mean annual discharge has increased by a factor of 1.5 to 2 over pre-diversion rates with upwards of an 8-fold increase in winter. The natural spring freshet has been eliminated and the summer flow rates are similar to pre-dam conditions. The low-salinity plume under the winter ice has deepened and its areal extent has increased by a factor of three (Ingram and Larouche, 1987).

The impacts of the initial freshwater holdback on the local native subsistence fishery were discussed by Berkes (1982). Although species more characteristic of a higher salinity regime, such as Greenland cod (*Gadus ogac*), became more abundant in the estuary, the estuarine species of lake whitefish and cisco targeted by the local fishery continued to be present in relatively large numbers. Growth rates of both the whitefish and cisco initially decreased but have shown no long-term effects. Abundance and reproduction also seemed to be largely unaffected by the project (Messier *et al.*, 1986). However, mercury released because of the decomposition of forests flooded by the newly formed reservoirs caused levels in the fish within the LaGrande River to rise to several times pre-dam levels (Brouard *et al.*, 1989). Routine fish consumption has resulted in excessive levels of mercury in a majority of the local native community (Gorrie, 1990).

DISCUSSION AND CONCLUSIONS

The response of the coastal regions to river regulation in the case studies of the Nile, the Indus, the Black Sea, San Francisco Bay and James Bay are summarized in Table 1. In all cases except the LaGrande River in James Bay the total annual freshwater discharge decreased and the seasonal run-off cycle was modified.

Table 1. Environmental and biological responses in the nearshore coastal regions to freshwater (FW) flow regulation at the five sites reviewed in the paper. The flow and the responses are categorized as having increased (I), decreased (D), been modified (M) or remained unchanged (U). ? indicates that we are unsure of the response.

	Nile	Indus	Black Sea	SF Bay	James Bay Eastmain	James Bay LaGrande
FW flow						
Total	D	D	D	D	D	I
Seasonal	M	M	M	M	M	M
Environment						
Salinity	I	I	I	I	I	D
Circulation	M	M	M	M	M	M
Sediments	D	D	D	D	I	I
Nutrients	D	D	I	D	I	I
Biology						
Primary Production	D	D	I	D	I	?
Secondary Production	D	D	D	D	?	?
Fish Production	D	D	D	D	U	U
Fish Distribution	M	M	M	M	M	M

Several similarities in the response to decreased river run-off at the different sites were observed. Salinity increased and circulation patterns were modified, including a reduction in the strength of the estuarine circulation and an increase in the importance of the tidal currents relative to the mean flow. The sediment load and nutrient fluxes generally decreased with subsequent decreases in the primary and secondary production. The commercial fish and shellfish production also typically decreased and often were accompanied by changes in composition or relative abundance levels of the coastal fish community. Exceptions did arise, however. In the Black Sea nutrients increased because of increases in sewage disposal and drainage off agricultural lands. This coupled with the increase in light levels associated with the decrease in sediment load caused higher primary production. Decomposition of these algal blooms led to anoxic conditions which caused mortality of the bottom dwelling fish and shellfish. Nutrient levels also increased in the Eastmain River in spite of greatly reduced freshwater flow rates. The nutrient levels rose because of increased erosion and resuspension in the upper reaches of the estuary due to stronger bottom currents. The higher bottom velocities resulted from the greater influence of the tidal currents. In the LaGrande River in James Bay where freshwater run-off increased and fish production remained relatively unchanged, the fish became contaminated from mercury released by processes associated with the filling of the reservoir.

Measurable changes in the species composition, distribution, abundance and health of fish and invertebrates in marine coastal waters that are directly or indirectly attributed to reduced or modified freshwater inflow are not unique to the five projects discussed above. The literature abounds with numerous other examples; most of the major estuaries in the United States (Chapman, 1972; Mahmud, 1985), the Sea of Azov and the Aral Sea in the former USSR (Tolmazin, 1985; Rozengurt *et al.*, 1985; Rozengurt and Haydock, 1981; Williams and Aladin, 1991), the Caspian Sea (Rozengurt and Hedgpeth, 1989), the Zambezi Delta in Africa (Rozengurt and Herz, 1981), off the Murray River in Australia (Harvey, 1988), in the coastal region of the Netherlands (Ferguson and Wolff, 1985; Nienhuis and Huis in 't Veld, 1985; Jong and Roelofs, 1985), French Mediterranean lagoons (Stora and Arnoux, 1988), etc. In other regions the impacts of modification on fish stocks have been masked by natural variability or fishing practices (Sinclair *et al.*, 1986). Where changes have been measured they represent an ecological readjustment to new environmental conditions imposed by freshwater regulation or diversion. In certain cases they have brought economic hardship to those segments of the population dependent upon the marine fisheries in the adjacent offshore regions.

It is clear from the above examples that massive reductions in freshwater discharge can alter, and in some cases destroy, the existing ecosystem in the adjacent coastal region. It is time for governments to legally recognize instream flows for fish and ecosystem conservation in planning freshwater resource strategies. Where possible, water releases should be used to maintain or even improve conditions for estuarine and marine fish and shellfish production (Peters, 1982). Multidisciplinary studies are required to determine at what level these releases should be. Much of the research to date has been qualitative. More quantitative research is needed including the development of integrated physical-biological models. As such models are still in their infancy, statistical analysis may have to suffice for a few years yet in determining the effects of changes in river run-off on fish production (Saila, 1979).

With continued modification of nearshore coastal regions from river regulation and other of man's activities such as land reclamation, dredging, building of harbours and breakwaters, etc., serious consideration should be given to protection of a series of natural marine reserves as proposed by Mitchell (1978).

Finally, the planning process for river regulation or diversion projects requires comprehensive ecological considerations in order to recognize, in advance, possible environmental problems, particularly downstream of the proposed project, and to take necessary steps to minimize any potential damage. This should not be limited to undertaking impact assessments but environmental and conservational issues should be considered throughout the building and management stages of river regulation projects as well. This would allow an adaptive environmental strategy responding to new developments, discoveries or unforeseen events associated with the project (Saeijs *et al.*, 1983).

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