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Influence of Freshwater Inflows on Estuarine Productivity

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Introduction

Coastal waters, estuaries, wetlands, and rivers are important spawning, nursery, and forage habitats for many fish and shellfish species harvested in U.S. commercial and recreational fisheries. Many human activities adversely affect these fishery-related habitats. For example, between the 1950's and 1970's, an average 18,000 acres of estuarine wetlands were lost annually in the United States (Tiner, 1984). Although coastal marsh losses were attributed primarily to subsidence in the Gulf of Mexico, elsewhere urban development involving dredge and fill activities significantly contributed to the loss of wetlands.

The National Marine Fisheries Service (NMFS) recognizes the significance of both tidal and non-tidal wetlands and other riverine, estuarine, and coastal habitats as a basis for survival and health of some living marine resources. These habitats are interrelated in a complex ecological continuum, so each contributes an integral role in fishery resource production. Hence, an ecosystem approach is essential in the assessment of impacts of human activities on fishery resources and associated habitats.

The NMFS has primary responsibility for the conservation, management, and development of living marine resources and the protection of certain marine mammals and endangered species. NMFS also recognizes its responsibility to conserve, restore, and enhance productive marine, estuarine, coastal, and riverine habitats that contribute to sustaining the living marine resources of national interest. In 1983, the NMFS implemented the Habitat Conservation Policy (48 Federal Register 53142) to address the agency objective to conserve fishery habitats and biological communities, and to define the role of the NMFS in addressing habitat conservation activities through federal legislative mandates. Under the Fish and Wildlife Coordination Act (16 U.S.C. 661 et seq.), for example, the NMFS provides an essential consultative service on regulatory and construction actions under purview of other federal agencies. The participation by NMFS in the federal regulatory reform process is essential to help ensure that regulators fully consider habitat issues in their decisions. Integral to this concept is the early involvement of all participants in the decision-making process, to minimize habitat alteration.

In estuarine and riverine environments, the NMFS is particularly concerned with alterations of freshwater inflows which have adverse effects on wetland and open-water habitats and fish stocks. Instream flow modifications causing environmental problems include changes in water quality and quantity, creation of physical barriers, and reductions in flows. Changes in quantity include modification in total volumes, seasonal discharges, and rates or timing of flows. The introduction of contaminants including toxic organic compounds, heavy metals, and pathogens, and alterations in fluxes of nutrients and sediments contribute to changes in water quality. Water quality degradation could also occur as diminished freshwater inflow exacerbates pollution by reducing the amount of dilution in estuarine waters. In addition, alterations in water quality include reductions in the amount of dissolved and particulate (detrital) material in the freshwaters entering estuaries via non-tidal wetlands and other floodplain ecosystems. Physical barriers reduce downstream flow of food material and sediments necessary to nourish marshes, submerged aquatic vegetation and other estuarine species, and prevent or impede the upstream spawning migration of anadromous fish resources.

Activities including water diversion projects for agricultural irrigation under federal purview of the Bureau of Reclamation; dam construction for water supply and flood control under permit authority of the Army Corps of Engineers; and hydroelectric development under authority of the Federal Energy Regulatory Commission have contributed to alterations of freshwater inflow to estuaries. Although large projects such as hydropower dams on the Pacific Northwest's Columbia River and water diversion projects within the Colorado River Basin have adversely affected living marine resources, the NMFS is also concerned that projects of lesser magnitude similarly alter instream flows within smaller watersheds. These activities have equally adverse impacts on fishery resources and the marine ecosystem when considered cumulatively. Consequently, effective freshwater inflow planning requires that all human activities modifying the water quality, quantity, or seasonal flow regimes entering the ocean be adequately assessed to determine synergistic effects and cumulative impacts on fishery-related habitats.

An example of this approach occurs in the Pacific Northwest, where the NMFS interacts with other agencies and organizations through legislative mandate of the Pacific Northwest Electric Power Planning and Conservation Act (16 U.S.C. 839 et seq.) to ensure full consideration of habitat conservation in hydroelectric development. The law includes specific provisions for adequate water flows and fish passage facilities prior to construction, as well as the assurance that fish protection and mitigation measures are operational at the time of initial project operation. The NMFS advocates the need for early involvement by all participants in regulatory processes to ensure that impacts to fishery-related habitats are minimized.

Although the influence of freshwater inflows on estuarine productivity has been documented, the NMFS believes that further research is necessary to identify cumulative impacts to the marine ecosystem. The River Continuum Concept (Vannote et al., 1980), conceptualizing the entire fluvial system as an integrated series of physical gradients and associated biotic adjustments, is the current paradigm addressing the ecology of flowing waters. This holistic approach, including linkages between streams and their terrestrial setting, and identifying biotic interactions and integration of ecological principles, helps to identify cause-and-effect relationships between freshwater inflow and estuarine productivity. The NMFS believes that holistic research would document such relationships.

We have reviewed pertinent technical literature and provide reference lists regarding the following: (1) the contribution of wetland and estuarine habitats to fishery production; (2) case studies of altered freshwater inflows; (3) biotic changes attributed to altered salinity regimes; and (4) the role of freshwater inflows in estuarine nutrient cycling (Appendix 1). In addition we provide a brief summary of the references in the following narrative.

Each section summarizes the available information, although discussion is generally limited to site-specific studies relevant to the contribution of freshwater inflows to estuarine productivity and fishery resource production. We provide this compilation for consideration by all regulatory agencies having authority over projects that would result in modified freshwater flows to marine and estuarine ecosystems. We recommend that the reader consult additional reviews addressing the issue of altered freshwater inflows (e.g., Copeland (1966), Baxter (1977), Armitage (1978), Pandian (1980), Benson (1981), and Peters (1982)).

Literature Reviews

The Contribution of Wetland and Estuarine Habitats to Fishery Production

Estuaries are semi-enclosed bodies of water with an opening to the sea measurably diluted with freshwater derived from land drainage (Pritchard, 1967). Rivers draining terrestrial ecosystems transport freshwater, sediments, organic detritus, dissolved organic and inorganic materials, and pollutants to the marine environment. Thus, riverine, estuarine, and coastal waters are integrally linked to terrestrial ecosystems via freshwater inflows.

Estuaries are among the most biologically productive ecosystems in the world (Odum, 1971), possessing mean annual primary production rates of 1500 grams (dry matter) per square meter (gm/m^2) as compared with values of 125, 360,400, and 650 gm/m^2 for open ocean, continental shelf water, lakes and cultivated land, respectively (Whitaker and Likens, 1975). Estuarine production results from five types of autotrophs: emergent vegetation, phytoplankton, benthic algae, periphyton, and submerged aquatic vegetation (Correll, 1978). Biomass and energy produced by these autotrophs is then consumed by herbivores and other secondary producers. Adult Atlantic menhaden (Brevoortia tyrannus) populations in Atlantic and Gulf of Mexico waters consume large quantities of phytoplankton and benthic algae (Peters and Schaaf, 1981), although vascular plant detritus was identified as the primary constituent in the diet of juvenile B. tyrannus (Lewis and Peters, 1984). Hence, there is a direct link from primary production to fishery utilization.

McHugh (1966, 1976) estimated that more than 69 percent of the total U.S. commercial and recreational fin- and shellfish landings (in weight) are estuarine-dependent. In the Gulf of Mexico, approximately 98 percent of the fish species of commercial value utilize estuaries during one or more of their life stages (Gunter, 1967). The 1984 U.S. commercial landings of estuarine-dependent shrimp, menhaden, and blue crabs, for example, were valued at $488 million, $117 million, and $56 million, respectively (U.S. Dept. of Commerce, 1985). Commercial landings of wetland-dependent species had an ex-vessel price exceeding $700 million in 1976, while recreational fishermen spent $13.1 billion on fishery activities directed toward wetland-associated fishes (Peters et al., 1978).

Empirical studies on the abundance of larval and juvenile fishes have identified that shallow tidal creeks and marsh shoals support dense populations of juvenile marine species such as flounder, menhaden, croaker, seatrout and spot (Conner and Truesdale, 1973; Chao and Musick, 1977; Shenker and Dean, 1979; Bozeman and Dean, 1980; Weinstein and Brooks, 1983). Statistical relationships indicated that in some Texas estuaries at least 60 kg of penaeid shrimp are harvested per acre of intertidal marsh (Turner, 1977). In addition, estuaries also contain habitats such as seagrass (e.g., Zostera, Ruppia spp.) meadows that enhance nursery habitat for both fin- and shellfish species (Adams, 1976; Heck and Orth, 1980).

Estuarine and coastal waters serving as nursery habitats have a direct relationship with primary production. Nixon (1982) identified a statistically significant positive correlation between estuarine fisheries yield per unit area with the primary production per unit area of the estuary, while Bahr et al. (1982) quantified a positive correlation between gross primary production and secondary fish production. Other studies have revealed that food supplies to fish species are limited in estuaries (Peters and Kjelson, 1975; Weinstein, 1979), and may be a cause of mortality in juvenile fishes. Polgar (1982), for example, identified food availability as the primary cause of differential mortality in the striped bass (Morone saxatilis) in the Potomac River.

There is a question as to what degree fishery production and composition are limited by estuarine food sources. Some believe that production within an ecosystem is primarily based on detrital flux or phytoplankton production. Studies have shown that wetlands detritus is a primary food source, both directly and indirectly, for estuarine fishes (Darnell, 1961; Odum and Heald, 1975; Lewis and Peters, 1984). Conversely, Haines and Monteque (1979) identified phytoplankton, rather than marsh grass, as the major factor in shellfish production in a Georgia estuary. In fact, estuarine food webs are likely a mixture of detrital- and phytoplankton-based pathways, with the source and extent of primary production highly variable among estuaries (Deegan and Day, 1984).

Case Studies of Altered Freshwater Inflows

Numerous studies have correlated freshwater inflows and fishery resource production. Aleem (1972) described the impacts on coastal life near the Nile Delta from construction of the Aswan Dam in Egypt. The disappearance of nearshore phytoplankton blooms was attributed to a reduced net annual loss of 35 billion cubic meters of freshwater to the Mediterranean, reducing catches in the Sardinella fishery along the delta coast from 4600 metric tons (mt) in 1965 to 544 mt in 1966.

Sutcliffe (1972) identified positive relationships between the flux of particulate nitrogen and carbon material to St. Margaret's Bay, Nova Scotia (a large estuary located in the St. Lawrence River drainage) and the catch of four commercially important fish species in the Gulf of St. Lawrence. In another study (Sutcliffe, 1973), river discharge was positively correlated with local landings of the American lobster (Homarus americanus) and the Atlantic halibut (Hippoglossus hippoglossus) in the Gulf of St. Lawrence.

Seven major and several smaller estuarine systems along 370 miles of Texas coastline have been affected by significant reductions in freshwater inflow due to upstream water diversion projects (Texas Department of Water Resources, 1981). Consequently, regulations were passed (Texas Water Codes, Sections 11.147 and 16.051, as amended), requiring the Texas Department of Water Resources to base management decisions upon the cumulative impacts of upstream water resource developments and the probable impacts of all new applications for water right permits on the fishery resources and associated habitats of the Texas bays and estuaries.

Models were also developed to evaluate the effects of freshwater inflow on fish production and habitats in the seven Texas estuaries: (1) the Sabine-Neches system, (2) the Trinity-San Jacinto system, (3) the Lavaca-Tres Palacios system, (4) the Guadalupe estuary, (5) the Mission-Aransas system, (6) the Nueces system, and (7) the Laguna Madre system. Technical analyses quantified the annual and seasonal inflow needs in relation to nutrient supplies, habitat maintenance, and production of fishery resources in an effort to maintain the fisheries that generate an estimated $153 million (1980$) in annual personal income in Texas (Texas Department of Water Resources, 1981).

Analyses produced over 115 statistically significant multiple regression harvest equations. Major seasonal response differences were noted among the species, particularly between fisheries populations inhabitating the upper (high rainfall) coast versus lower (low rainfall) coast of Texas. Overall, 86 percent of harvest correlations were positively linked to spring inflows, while 57 and 76 percent were related positively to early and late fall inflows, respectively.

The U.S. Army Corps of Engineers (1984) evaluated the effects of reduced freshwater inflow on environmental and socioeconomic values of the Chesapeake Bay. Major objectives of the study were to assess existing physicochemical, biological, and environmental conditions of Chesapeake Bay and to project future water resource needs to the year 2020. Utilizing life history information on 57 Chesapeake Bay species, hydraulic modelling identified potential short- and long-term spatial impacts attributed to salinity changes on the biota and commercial fisheries of the Bay.

San Francisco Bay and the Sacramento-San Joaquin Delta have been adversely affected by water diversions from the tidal basin. Since 1951, freshwater flow entering the Bay via the San Joaquin and Sacramento Rivers has been reduced by 50 percent as federal and state projects have diverted river water to irrigate agricultural lands (Johns, 1981). Populations of spawning salmon in the Sacramento River have declined by more than 50 percent between 1960 and 1979. In addition, freshwater diversion projects have contributed to the large decline in numbers of striped bass in the San Francisco estuary, and have significantly altered the salinity balance in the estuarine zone of the Sacramento-San Joaquin Delta (Orlob, 1976).

Dam construction and altered instream flows have contributed to significant declines or elimination of many salmon runs in the Pacific Northwest (Pacific Fishery Management Council, 1979). The Columbia-Snake River System has 39 federal, 19 non-federal, and 3 international treaty dams in operation or under construction (Wandschneider, 1984). Dam construction, the primary factor in the decline of the Pacific Northwest's anadromous fish resources, has altered seasonal and annual river flow regimes, created delays in migration, and increased mortalities in juvenile fish as they pass through turbines and over spillways.

Prior to 1941, the Santee River in South Carolina had the fourth largest river discharge of any East Coast river. However, increased energy needs resulted in hydroelectric development which diverted approximately 88 percent of the Santee River's flow to the nearby Cooper River (Kjerfve, 1976). As a result salinity regimes, sediment deposition and erosion patterns, flooding characteristics, and floral and faunal communities were drastically altered. A hard clam fishery and extensive seed oyster beds in the lower Santee River were eliminated by the effects of the diversion project.

Biotic Changes Attributed to Altered Salinity Regimes

Salinity is a primary ecological factor regulating the distribution and survival of marine organisms (Gunter, 1967). Gunter (1961) and Hopkins (1973) reviewed the relationships of salinity to all organisms living in coastal waters with emphasis on Gulf and Atlantic coast estuaries, particularly those influenced by water diversion projects which alter salinity regimes.

The amount of freshwater entering an estuary determines physicochemical variables (e.g., salinity, temperature, and turbidity) directly affecting physiological processes in organisms. Previous studies on freshwater inflow alterations to estuaries identified effects on physicochemical processes (Orlob, 1976; Schroeder, 1978), and also on the physiological effects on estuarine organisms (Kinne, 1967). Estuarine fauna must adjust to fluctuating osmotic conditions either by tolerating considerable variation in blood concentration or by efficient osmoregulation. Hence, the lower salinity limit of an organism is primarily a physiological response; the upper salinity limit is either ecological or behavioral rather than physiological. The increase of predator/competitor species and disease with increasing salinity is one reason why many animals are not found in higher salinities which the species can, otherwise, physiologically tolerate (Gunter et al., 1973).

Salinity is a primary factor regulating estuarine primary production. Adams (1963), for example, found that salinity is a major factor in the zonation of vascular plants in saltmarshes. Direct effects of freshwater inflow/salinity fluctuations are primarily physiological, affecting seed germination, plant growth, and biomass, and these responses are ultimately reflected in the competitive balance among emergent plant species and the presence of plant zonation in marshes (Nestler, 1977; Smart and Barko, 1978).

Submerged aquatic vegetation (SAV) species, providing valuable habitats to marine organisms, reducing shoreline erosion by trapping sediments and dissipating wave energy, and acting as important sources of primary production, are limited in distribution by salinity regimes (Dierner, 1975). Aquatic vegetation such as coontail (<u>Ceratophyllum dermersum</u>), sago pondweed (<u>Potamogeton pectinatus</u>), and redhead grass (<u>P. perfoliatus</u>) have upper salinity tolerances of 7, 13, and 12 parts per thousand (ppt), respectively (Stevenson and Confer, 1978). Stewart (1962) documented a dramatic increase in the number of SAV species from higher to lower salinity regimes in Chesapeake Bay estuaries. Hence, distributional patterns of seagrasses are at least partially related to the species-specific salinity tolerances, and freshwater inflow reductions could be detrimental to species growing near upper salinity limits.

Species may increase or decline in abundance, become extinct, or migrate to other suitable estuarine areas in response to salinity changes. Shifts in abundance or distribution imply new trophic relationships that may alter estuarine primary production. Phytoplankton production may be significantly altered by changes in freshwater influx. If inflow is decreased, the most dominant group in the phytoplankton community will shift towards a more marine form. The amount of freshwater influx also dictates estuarine salinity gradients that influence phytoplankton distribution. Modelling of the lower Hudson estuary by Malone et al. (1980) and Neale et al. (1981) indicated that peaks in netplankton biomass occur between pulses in freshwater flow. During peaks of high river flow, estuarine circulation and the pycnocline (boundary layer of sharp vertical density change) are altered as denser marine bottom water moves up into estuarine surface waters. Consequently, diatoms entrained in the boundary layer are advected into the upper water column of the estuary. Hence, biomass fluxes in terms of chlorophyll *a* are dominated by boundary inputs during high flow, and by growth and grazing by more euryhaline plankton species during low flow.

Herbivorous zooplankton which consume a major portion of phytoplankton are a key link in energy transfer to higher trophic levels. The calanoid copepod, *Acartia tonsa*, is a widespread, seasonally dominant zooplankton species in Chesapeake Bay, and is estimated to consume approximately half of the phytoplankton production in the Patuxent River, Maryland during the summer months (U.S. Army Corps of Engineers, 1984). Estuarine zooplankton populations are sensitive to salinity and temperature changes such that optimal conditions for growth and survival occur at different times during the year for each species. In the Nueces-Corpus Christi and Copano-Aransas estuarine systems in Texas, freshwater inflows resulted in replacement of estuarine species with oligotrophic species. Consequently, populations of *A. tonsa* were lowest during maximum inflow but sharply increased following salinity increases by as little as 1 to 3 ppt (Kalke, 1981). In addition, estuarine zooplankton composition and abundance are also influenced by development rates versus flushing time (Perkins, 1974).

Adult benthic organisms have limited motility; thus, biomass, distribution, and diversity fluctuations are strongly correlated with salinity variability. Benthic species distribution may be determined primarily by the rate and magnitude of salinity change rather than the salinity gradient. Hence, a species would have a greater salinity tolerance in an estuary with a smaller rate of salinity change. Further, sediment salinity is likely the more critical factor limiting species distribution than water column salinity, because most benthic organisms live in rather than on the sediment surface (Sanders et al., 1965).

Holland (1985) identified salinity as a primary factor regulating macrobenthic recruitment in a mesohaline region of Chesapeake Bay, as the early developmental stages of macrobenthic species have narrower tolerances to environmental conditions, particularly salinity. Castagna and Chanley (1973) identified salinity tolerances of the bivalves endemic to mid-Atlantic coastal waters. Cain (1975) found that salinity has a controlling effect on the spawning and recruitment of brackish water clam (Rangia cuneata) populations in the James River, Virginia. A seasonal salinity change from fresh to 5 ppt induced spawning in upstream populations of R. cuneata. The American oyster (Crassostrea virginica) flourishes in a wide range of salinities, although survival and growth of larvae are physiologically (Davis, 1958) and ecologically (Manzi, 1970) controlled by salinity. For example, the distribution of some oyster predators, such as drills (Eupleura caudata and Urosalpinx cinerea), and pathogens, including MSX (Minchinia nelsoni), are limited to higher salinities in Chesapeake Bay (Andrews and Wood, 1967).

Fluctuations in salinity affect growth and recruitment of other benthic invertebrates. Pearson (1948) identified a positive correlation between low river discharge, salinity and survival and recruitment of the blue crab (Callinectes sapidus). Bowler and Seidenberg (1971) found the grass shrimp (Palaemonetes vulgaris) to be less tolerant of low salinities (less than 3 ppt), but more tolerant of high salinities (36 and 40 ppt) than its cogener, P. pugio. Corresponding to this relationship, the composition of the Palaemonetes population made up by P. vulgaris decreased markedly with decreased salinity in the York River, Virginia. Further, salinity change is a mechanism contributing to tidal transport of post larvae and juvenile pink shrimp (Penaeus duorarum) from inshore nursery areas to offshore waters of the Gulf of Mexico (Hughes, 1968). Copeland (1966) detailed the effects of decreased river flow and salinity on oyster, shrimp, and blue crab production in several major estuaries.

Finfish production, growth, recruitment, and distribution in estuaries are controlled by altered freshwater inflows and salinity. Primary effects of inflow/salinity on finfish production are physiological and play an important role in survival of early life stages, metabolic stress of adult populations, and adaptability rates by juveniles. Distribution of juvenile fishes within primary nursery areas has been correlated with salinity (Gunter, 1961). In addition, salinity governs fish distribution by secondarily restricting predator distribution (Joseph, 1973; Blaber and Blaber, 1980). Extreme temperature and salinity fluctuations in shallow embayments and creeks may exclude large adult predators, but not juvenile fishes (Hyatt, 1979). Weinstein and Walters (1981) identified salinity as the primary factor controlling mortality of the spot (Leiostomus xanthurus) by limiting stenohaline predator distribution.

Changes in freshwater inflow/salinity alter the amount of habitat. For example, more estuarine area is available during periods of high river flow and may represent increased habitat availability (Deegan and Day, 1984). Salinity may also interact with temperature to alter the areal extent of habitat available for an individual species.

Estuarine hydrodynamics relating to salinity is altered by the influx of lower temperature river flow. Mihursky et al. (1981) identified correlations between year class strength of striped bass (<u>Morone saxatilis</u>) in the Potomac River estuary and above average spring freshwater runoff and colder than normal winters. Polgar et al. (1985) similarly identified positive correlations between climatic factors and the catch per unit effort of Potomac River striped bass and American shad over a long-term period (1929-1976), indicating freshwater inputs strongly influence survival of these species through critical periods in development. Survival rate of juvenile chinook salmon (<u>Oncorhynchus tshawytscha</u>) in the Sacramento-San Joaquin estuary and the numbers of fry and juvenile salmon are increased through releases of additional inflow at appropriate seasonal periods (Kjelson et al., 1981).

Freshwater discharge is also important to anadromous fishes which make use of rheotaxis in locating the mouth of their natal river or spawning stream. However, coinciding physical changes in salinity, temperature, and seston make identification of cause-and-effect relationships of these migrations difficult.

In summary, salinity is likely one of many physicochemical and biological factors regulating the amount of habitat available for fish production, although salinity tolerance limits may be the key mechanism needed to manage freshwater inflow to estuaries as previously suggested by Darnell (1981).

The Role of Freshwater Inflows in Estuarine Nutrient Cycling

Estuarine productivity is a result of maintenance of high nutrient levels in bottom sediments and the water column. However, controversy remains concerning the extent to which freshwater inflows contribute nutrients to estuarine waters. Nixon (1981) identified five major hypotheses that have been presented to account for estuarine production: (1) nutrient enrichment via freshwater inflow; (2) advection of nutrients from offshore waters; (3) nutrient entrapment in estuarine circulation; (4) outwelling of nutrients from saltmarshes and wetlands; and (5) recycling of nutrients within the estuary. Of these hypotheses, the author concluded that recycling and remineralization of nutrients and coupling of heterotrophic and autotrophic processes provide the greater contribution to estuarine productivity than does the contribution of nutrients derived from frehwater influx, although nutrients associated with freshwater inflows may be more influential over estuarine productivity in the long term. Armstrong (1982) calculated that less than 5 percent of the total external nutrient inputs to six major estuarine systems in Texas were derived from adjacent, upstream saltmarshes. Similarly, Ward et al. (1982) calculated that freshwater inflows accounted for only 2 and 5 percent of the total nitrogen (N) and phosphorus (P) (respectively) fixed by primary producers in Matagorda Bay, Texas, concluding that most of the nutrients were derived from recycling through the pelagic and benthic systems. Conversely, Correll (1978) suggested that a combination of the nutrient sources is responsible for estuarine productivity.

It is inferred that freshwater inflows provide at least some of the nutrients utilized in estuarine food webs, although great variability exists between estuarine systems. The amount of dissolved organic and inorganic nutrients and particulate detrital material transported to estuarine waters is related to a host of factors including hydrology, types of soil, vegetation and wetlands of the drainage basin, seasonality, and human intervention (Odum, 1985). Reduced freshwater inflows result in a decreased quantity of organics and inorganics imported to the estuary from the drainage basin, and productivity of estuarine food webs dependent on this source is thus limited (Copeland et al., 1972). Nutrients supplied by freshwater inflow support both detritus-based (Odum and Heald, 1975) and plankton/algae-based (Haines, 1977; Correll, 1978) estuarine food webs. However, excessive nutrient levels in estuaries exacerbated by reduced water exchange may limit phytoplankton production (Corliss and Trent, 1971). Thus, freshwater inflows influenced by upriver nutrient load, urban and agricultural runoff, wastewater discharges, and biochemical and chemical processes may enhance or limit overall estuarine productivity.

Wetlands have the ability to intercept and retain nutrients from the water which flows through and over them, although seasonal uptake pattern and length of time which the nutrients are retained vary greatly between wetland sites and types (Odum, 1985). The coupling of tidal and non-tidal wetlands form a vegetatively diverse continuum which influences nutrient cycling and transport from rivers to estuaries.

Bottomland hardwood swamps undergo cyclic wet/dry periods, creating a unique chemical environment which affects nutrient cycling. Flooding regulates chemical properties of floodplain soils by replenishing minerals, providing anaerobic soil conditions, importing particulate and dissolved organic matter, and exporting decomposing leaf litter and other detritus (Wharton et al., 1982). Livingston et al. (1976) demonstrated that the productivity of Apalachicola Bay, Florida was strongly influenced by the organic detrital source via bottomland hardwoods. Day et al. (1977) also found that a Louisiana hardwood swamp provided pulses of carbon, N, and P to Barataria Bay. Hence, large quantities of organic matter contributed by bottomland hardwood swamps may be transported to estuaries although dam construction or other modifications to floodplain swamps can significantly change mineral and detrital fluxes and seasonal flooding, and consequently, alter downstream nutrient movement (Wharton et al., 1982).

Tidal freshwater wetlands contribute detritus (Odum et al., 1984), serve as sinks for nutrients (Kadlec and Kadlec, 1979), and provide mineral nutrients to estuaries (Simpson et al., 1983). These systems also function as nutrient transformers by importing dissolved oxidized forms of N (i.e., nitrite, nitrate) and P (i.e., phosphate) and exporting dissolved and particulate reduced forms (i.e., ammonium and organic forms) (Bowden, 1984). Overall, tidal freshwater wetlands act as either nutrient sinks or sources depending on local conditions such as hydrological variables (e.g., circulation, tidal range, precipitation), geomorphological characteristics (e.g., drainage area, elevation gradient), and the age of the wetland (Odum et al., 1979).

Nutrient and particulate fluxes in tidal freshwater wetlands result from the complex interaction of chemical, physical, and biological processes similar to processes occurring in saltmarshes (Nixon, 1980). Diurnal fluctuations act as additional nutrient flux mechanisms. Phosphorus may be removed from overlying water either by plant uptake or absorption into particulate matter and subsequently buried (Klopatek, 1978). Nitrogen imported into freshwater tidal wetlands may be retained, converted from nitrate to nitrite through denitrification, or exported. Tidal freshwater marshes have distinct seasonal nutrient exchange processes. Studies demonstrated that after dieback of plant vegetation in the fall and early winter, 80 percent or more of the N and P of standing dead litter may be lost within one to two months and exported out of some marsh systems (Richardson et al., 1978; Simpson et al., 1978). Because of an almost total lack of litter cover at the onset of the growing season, there is a net import of N and P into the system. Organic N and P occur in plant tissues during peak vegetative growth, while there is an export of reduced N and P following plant decomposition (Odum et al., 1984).

The volume of river flow has often been correlated positively with the presence of particulate organic material (Borman et al., 1974). Maximum organic matter concentrations are typically associated with high discharges related directly or indirectly to precipitation. Hence, the creation of impoundments in tidal freshwater wetlands can interrupt flux of organic matter and nutrients to the downstream estuary. For example, Anderson and Neilson (1985) identified that impounding some tidal freshwater wetlands on the Eastern Shore of Virginia had a trapping efficiency of 46.7 percent of the total P moving through a small drainage. Hence, even small dam construction may alter the nutrient flux from tidal and non-tidal freshwater wetlands to the marine environment. Overall, the source, velocity, renewal rate, and seasonal quantity of water in freshwater wetland ecosystems directly control nutrient loads transported to estuarine ecosystems (Gosselink and Turner, 1978).

Estuarine marshes act as nutrient (N and P) transformers, and function either as sources or sinks depending on a number of factors (Axelrad et al., 1976; Valiela and Teal, 1979; Nixon, 1980). Generally, coastal wetlands have a net import of nutrients at the beginning and during the plant growth period, whereas these marshes have a net export in the fall and winter. Stevenson et al. (1977) identified factors determining whether a marsh is importing materials or exporting nutrients to the estuary. Factors include: (1) successional stage of the marsh, (2) salinity and redox characteristics, (3) nutrients released from point sources, (4) nutrients released from non-point sources, (5) tidal energy input, and (6) stability and magnitude of the nutrient flux of the estuary to which the marsh is coupled.

Study results of a tidal marsh in the Choptank River, Maryland indicated that the wetland exported inorganic N and P to the estuary in the winter, while in the spring there was a net import of inorganic N and P to the marsh (Stevenson et al., 1977). Results also demonstrated that another tidal marsh located in the Patuxent River, Maryland imported dissolved inorganic N between May and July, although there was a net N flow to the estuary when dissolved organic N was included. Wilcox and Childress (1981) found that virtually all nutrient forms were directed out of a tidal marsh in Nueces Estuary, Texas during the fall and winter, but were directed into the marsh during the spring; thus, the wetland also acted as a nutrient sink. Axelrad et al. (1976) found that, in both a *Spartina cynosuroides* dominated marsh (Ware Creek) and *S. alterniflora* dominated marsh (Carter Creek), net dissolved inorganic and organic P were exported to the York River estuary, Virginia, while net particulate P was imported to both marshes. There was a net annual export of dissolved organic N from both marshes and a net import of particulate N into the *S. alterniflora* dominated marsh. A study by Jordan et al. (1983) indicated that a *Typha angustifolia* dominated brackish marsh retained only small amounts of N and P. The authors suggested that the marsh acts more as a nutrient transformer, while the adjacent mudflat functions as a sink for the nutrients.

Saltmarshes have the ability to intercept and retain nutrients from incoming freshwaters. Haines et al. (1976) suggested that river water is the primary source of inorganic N in some unpolluted estuaries. Conversely, Nixon (1981) reasoned that freshwater inflow is a minor nutrient source to saltmarshes in comparison to the contribution attained from recycling, remineralization, and complex interactions between autotrophic and heterotrophic processes in estuarine waters. Rather, freshwater inflows likely provide a long-term contribution as a nutrient source by replenishing nutrients lost in benthic regeneration and complex biological processes. In addition, regeneration rates are significantly affected by physical and chemical parameters of the overlying water column (Edwards, 1981). Hence, freshwater inflow can result in salinity transitions to create changes in nutrient regeneration rates controlled by complex biological and physicochemical processes.

Seasonally high freshwater inflows transport organic matter from saltmarshes to estuarine waters. Some Spartina marshes provide significant quantities of detritus to estuaries (Teal, 1962), although few organisms are able to digest and directly utilize the material (Pomeroy et al., 1976). Consequently, microorganisms must convert plant detritus to soluble compounds utilized by detritivores. River flows provide a detrital transport mechanism allowing plant debris to reach decomposers at the sediment-water interface, and thus, contribute to overall estuarine productivity. Further, freshwater inflows transport algae, protozoa, fungi, and bacteria, thereby providing energy sources for detritivores (Odum, 1980).

Zedler et al. (1980) studied the influence of river inflow on saltmarsh productivity and concluded that higher productivity values were attributed to river inflow which physically altered an embayment area. In turn, alteration decreased soil salinity and retained nutrients in the marsh. Linthurst (1980) demonstrated that an increase in substrate salinity (from 15 ppt to 45 ppt) decreased S. alterniflora biomass by 66 percent, although the presence of N and aeration of the substrate reduced the effects of high salinity. Hence, freshwater flows also provide a circulatory mechanism that stimulates increased saltmarsh production.

Summary and Conclusions

Freshwater inflows draining terrestrial ecosystems transport sediments, nutrients, detritus, and dissolved inorganic materials to the marine environment and influence physicochemical estuarine conditions. Flowing waters link diverse physical gradients and associated biotic influences, thus providing energy-transfer pathways and an ecological continuum. Consequently, freshwaters moving from uplands thru bottomland hardwood swamps and vegetated and non-vegetated tidal and non-tidal wetlands to estuaries replenish, exchange, and transport matter and energy to sustain a balance throughout the ecosystem.

Estuaries and associated wetlands are valuable spawning, nursery, and feeding habitats for many commercially and recreationally important fishery resources and essential forage species. The quantity of freshwater inflow to estuaries affects the composition, abundance, and productivity of estuarine communities because life history strategies, migratory patterns, and feeding habits are keyed to salinity shifts and flushing patterns. Nutrients, sediments, detritus, toxins, and pathogens alter the quality of freshwater inflows ultimately influencing fishery resource production.

Many human activities have altered freshwater inflows. Consumptive uses decrease overall freshwater availability to estuaries while non-consumptive uses restrict natural flow of matter to estuaries. Dam and levee construction, stream channelization, navigational channel dredging, deforestation, and agricultural diversions modify total volumes, seasonal discharges, and rates or timing of flows. Additionally, these projects affect water quality and create physical barriers that ultimately influence fishery resource yield.

The NMFS is conducting comparative studies relating species (both vertebrate and invertebrate) composition, abundance, size, and food intake to water depth and salinity in estuaries influenced by both unaltered and altered freshwater inflows. In addition, the NMFS funds research projects addressing freshwater inflow issues through the Saltonstall-Kennedy Fisheries Development Grant Program, the Commercial Fisheries Research and Development Act (P.L. 88-309), and the Anadromous Fish Conservation Act (P.L. 89-304), while the National Oceanic and Atmospheric Administration supports additional projects through the Sea Grant Program. The NMFS recognizes research activities by the other federal agencies and recommends that both environmental and regulatory agencies continue to conduct or support research which aids in identifying cause-and-effect relationships between freshwater inflows and fishery resource production, and ultimately influences management decisions to conserve fishery-related habitats.

The NMFS believes that all federal and state agencies regulating projects which alter freshwater inflows should consider the cumulative effects to estuarine production in their decision-making processes. Permits and licenses issued must contain provisions for withdrawal, discharge, and the return of water that minimize adverse effects to the environment. Management decisions should be directed to meet societal needs while still maintaining adequate freshwater inflows that sustain estuarine and fishery resource production.

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APPENDIX 1

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