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Review and Assessment of Biotic Variables and Analytical Methods Used in Estuarine Inflow Studies

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ABSTRACT: Published and gray literature, and works in progress, were reviewed to identify biotic variables and analytical methods used in studying freshwater inflow needs of estuaries. Landings, CPUE, and other measures of single-species abundance are most often used, especially for shellfish and finfish. These efforts work best when biomass is used and lag times are allowed for recruitment, but neither method is always used, and most efforts have assumed that physical habitat availability is constant. Efforts employing habitat and community-level variables are used less often but more recent attempts are using dynamic as well as stationary definitions of habitat. Even stationary habitat methods have given less attention to tidal freshwater and brackish estuarine reaches, than to other reaches. Natural long-period climate cycles (El Niño Southern Oscillation; North Atlantic Multi-Decadal Oscillation) are not factored into most inflow studies. Three promising approaches are encouraged: a mixture of variables representing different levels of ecological organization should be used, the natural non-linear geometry of estuaries (especially tidal rivers) should be exploited to identify critical thresholds of inflow, and the validity of using instream flow methods to calculate estuarine requirements by proxy should be determined.

Introduction

Estuarine scientists and resource managers are increasingly asked to answer two basic questions concerning freshwater inflows, By how much or little must damaging flow regimes be moderated? and By how much can natural flows be changed without causing harm? No uniform scientific methods exist to answer these questions owing in part to the diversity of specific historic or proposed flow changes involved, and in part to the natural variability observed within and between estuaries. There is, however, considerable interest in the success and failure of tried methods, and in emerging ones, especially where living resources are concerned. The pace of method development and application will quicken as competition grows for limited water resources, even more so in those areas where climate change reduces rainfall, surface runoff, or groundwater discharge to estuaries. Presently, competition for the water that forms estuaries is greatest where issues of coastal river management are involved.

Changes to rivers represent one of the most extensive and severe ecosystem alterations on the planet, with flow regulation the most pervasive change wrought by humans on rivers world-wide (Stanford et al. 1996). At the end of the 20th century there were about 40,000 large dams in the world and on average one new large dam was commissioned daily (Dynesius and Nilsson 1994). In the United States alone there are 75,000 dams higher than 8 m. River flows have been altered profoundly. All of the larger rivers in the northern third of the world are regulated, and approximately two-thirds of world river discharge is controlled. Sufficient freshwater is stored on and in the ground to equal several centimeters of world ocean elevation. So extensive are changes to river ecosystems caused by flow alteration that limnologists have recently rallied behind The Freshwater Imperative, a synthesis of research directions to understand and predict effects of flow regulation on integrity and resiliency of aquatic ecosystems (Stanford et al. 1996). The program responds to a major disconnect of social policy and public literacy relative to America's freshwater resources by identifying national priorities for rivers on the basis of scientific significance, sociopolitical relevance, and needs of decision makers (Naiman et al. 1995).

Altered river flow has not been regarded by river or estuary scientists or managers as so large an issue facing estuaries. River science has tended to ignore estuarine consequences of flow alteration (Petts 1984; Gore and Petts 1989) and such oversight is understandable given their lotic priorities. More remarkable has been the relative silence of estuarine scientists and managers on the matter of inflow alterations. Despite a seminal 1980 national symposium on freshwater inflow to estuaries (Cross and Williams 1981), textbooks on estuarine ecology in that decade and the early 1990s emphasized

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other forms of disturbances (Kennish 1992). Major reviews by the National Research Council (1992, 1994) on restoration of aquatic ecosystems, and environmental research issues in the coastal zone, also overlooked inflow alterations. Whitfield and Woolridge (1994) report that the issue of altered freshwater inflow to estuaries of South Africa has largely been ignored.

The situation began to change at the close of the millennium. The national symposium on freshwater inflow to estuaries consolidated a sparse and dispersed literature, documented cases of estuarine harm caused by inflow changes, pointed out major research deficiencies and needed directions, and began a dialogue among scientists, managers, and policy makers. In an essay in the National Research Council's *Environmental Science in the Coastal Zone: Issues for Further Research,* Shubel (1994) stated a concern for manipulation of river discharge as an overlooked problem. During the 1990s the issue of freshwater inflow figured prominently in the Gulf of Mexico Program, National Estuary Program, National Estuarine Research Reserve Program, and Comprehensive Everglades Restoration Program. The last milestone of the decade for American attention to estuarine inflows was a 1995 workshop, ''Historical freshwater inflow alteration and its potential effect on estuarine biota in Gulf of Mexico estuaries,'' sponsored by the National Oceanic and Atmospheric Administration Strategic Environmental Assessments Division and Gulf of Mexico Program's Freshwater Inflow Committee (National Ocean Service 1995). Five estuaries were chosen among Gulf systems as most altered with respect to inflows. Salinity changes were classified and candidate indicator species were recommended (submerged aquatic vegetation [SAV], oyster, penaeid shrimp, and spotted seatrout).

Despite the early call of the prescient freshwater symposium for a national program to protect estuaries from inflow change, coastal scientists and managers seem unready to declare an Estuarine Imperative to define research priorities or span the great gulf between science, public understanding, and policy. But consider the parallels between estuarine and lotic conditions: ''Scientists, managers, and politicians are routinely called upon to address competing demands on freshwater supplies and ecosystems, but they are increasingly unable to respond at scales commensurate with the issues. Why? Policy development and management activities are frequently undertaken without an adequate empirical foundation; inappropriately short-term, single-focus approaches are accepted with little question; human-caused change is often difficult to discern from natural variation; and even when relevant data are available to guide decision making, the legal and regulatory framework is inadequate. Consequently, the criteria for effective management and policy decisions are ambiguous at a time when degradation of water supplies and aquatic resources is accelerating'' (Naiman et al. 1995, p. 584).

This paper provides an overview of the work of estuarine ecologists to develop empirical foundations for coastal river regulation, giving attention to models taken from river management, insights from success in basic estuarine ecology, documentation of estuaries harmed by inflow change, and past and ongoing efforts to develop useful scientific tools. Approximately 300 citations were retrieved in literature searches. The median year of publication was 1992, signifying that half of the citations are relatively recent (produced in the last 10 years). The majority of the literature originated from North America and Europe although there is an important South African literature. Few citations concerned individual species; most literature dealt with living resources concerning habitats, communities, and ecosystems. Readers interested in the core literature on freshwater inflows to estuaries, prior to 1992, may consult Copeland (1966), Aleem (1972), Hopkins (1973), Gunter et al. (1974), Snedaker et al. (1977), Benson (1981), Cross and Williams (1981), Mahmud (1985), Skreslet (1986), Rozengurt and Hedgpeth (1989), and Halim (1990a,b).

Insights from Basic and Applied Estuarine Ecology

If estuarine scientists and managers do not have a kit full of methodological tools for minimum flow and related inflow studies, perhaps useful tools can be inferred from a review of estuarine structure and function related to inflows. Emphasis is given to living resources and tidal river settings although other information is included.

PHYSICAL, GEOLOGICAL, AND CHEMICAL ACCOUNTS

Minimum flows to South African estuaries are set primarily on the basis of geological and chemical considerations. Approximately half of South African estuaries tend to lose their connection to the sea (Whitfield 1992; Slinger et al. 1994). Effects of flow reduction in South African estuaries include a loss of the river's erosion capacity, growth of flood tidal deltas, a decrease in the size of the estuary, and hypersalinity. River regulation in South African systems eliminates floods of small magnitude and truncates the extent of large floods. Changes to regulation are based largely on two criteria: prevention of hypersalinity in the estuary and sufficient discharge and erosion to maintain an open mouth of the estuary to the sea. Experimental releases have had mixed outcomes. In one case a flushing flow failed to eliminate hypoxic and saline bottom waters, and aggravated bacterial pollution. The closure finally breached and improvements were due mostly to mixing with sea water (Slinger et al. 1994). Ecological considerations are made in setting minimum flows to South African estuaries but geological considerations are paramount. Except for sedimentation caused by the Santee Cooper (South Carolina) rediversion project (Kjerfve 1976) and work in Texas, geological studies or criteria are not otherwise prominent in older estuarine minimum flows. More recently, Jay and Simenstad (1994) accounted for delta erosion and losses of low intertidal area (by 40%) and SAV area (18%) as a result of sediment lost because of a 40% river diversion in the Skokomish River and estuary. Noel et al. (1995) accounted for the marine provenance of a flood tidal shoal in the tidal Loxahatchee River and found that high regulatory flows lowered total suspended solid (TSS) loads in the upper estuary but increased TSS in the middle estuary where mixing with salt water occurred. Diversions of Mississippi River flow to augment sediment delivery to delta marshes are actively under study.

Upper estuarine reaches with very low salinity represent areas of transition from lotic to estuarine water quality conditions. Ionic ratios vary more at low salinities than elsewhere in the estuary (Deaton and Greenberg 1986). The response of salinity to flow is strongly non-linear in such estuarine reaches, such that small changes in flow can cause large changes in salinity (Sklar and Browder 1998). Upper estuaries tend to have greater relative variation in salinity as a result (Schroeder 1978) although down-estuary salinity fields can also be affected by flow changes. Diversions and other alterations to estuarine inflows often cause water quality problems, but there are cases where large inflow changes have biological impacts but not especially large water quality impacts. Where water quality impacts occur the most involved parameters (other than salinity) tend to be water temperature, dissolved oxygen, and bacterial contamination. Water quality may improve as a result of inflow alterations, which are sometimes made for that purpose. In Breton Sound estuary (Louisiana) additions of Mississippi River water decreased nitrogen and salinity but increased TSS, the effect desired to offset rapidly subsiding wetlands (Lane et al. 1999).

FLORA AND FAUNA

Responses of estuarine plants to river flow alteration are complex. Reductions in flow tend to promote blooms of phytoplankton because residence times of nutrients and cells are increased. A 90% reduction of flows in the Eastman River (James Bay) stimulated large population flushes in resident diatom species and also caused blooms of dinoflagellates (*Gymnodinium*) not previously common to the flora (Ingram et al. 1985). Phytoplankton responses may be more complex depending on estuary geometry and stratification. Increased flows promote counter-current bottom circulation and upwelling which can promote blooms or kill entrained, higher salinity species or export estuarine species (Hawes and Perry 1978; Madariaga et al. 1992). A natural drought in Apalachicola Bay transformed the trophic structure of the Bay as light penetrated to the bottom and stimulated phytoplankton, benthic algae, and other plants. The trophic switch took months to develop and persisted once normal flows resumed, illustrating the lag effects common to estuarine inflows. The drought-induced shift in carbon sources drove the Bay toward a high diversity, low productivity system, analogous to effects of prolonged flow diversion (Livingston et al. 1997).

Benthic macrophytes often map gradients in flows, salinity, and transparency across the length of an estuary. Adams et al. (1992) noted that freshwater gradients correspond to zonation patterns of SAV in South African estuaries, but that the patterns are lost in low-flow, high-salinity systems. Zonation patterns in SAV were also lost in the tidal Suwannee River during a period of drought (Estevez et al. 2002). Tomasko and Hall (1999) caution that SAV salinity tolerances may be difficult to discern where water clarity is positively associated with salinity. Increased flows often eliminate more marine species which flourish in estuaries affected by decreased flows. *Zostera* increased four-fold in the Kromme estuary (South Africa) after large flow reductions in the Kromme River (Adams and Talbot 1992), but was set back tremendously by large freshwater flows in the Kwelera and Nahoon estuaries (South Africa). *Zostera* recovery may take at least four years from that event (Talbot et al. 1990). This and other case studies documenting SAV impacts to inflow alteration have not analyzed fully the separate impacts of changing average salinity conditions versus impacts of changing patterns of salinity variation. Montague and Ley (1993) studied SAV responses to salinity variation in Florida Bay and found that total plant biomass decreased for every 3‰ increase in standard deviation of salinity. Estevez (2000) has suggested that salinity variation could be used in understanding SAV responses to inflow alterations.

Intertidal estuarine vegetation seems resilient to inflow changes (Smalley and Thien 1976) but impacts will occur when physical and chemical extremes surpass the tolerances of particular species. Short-term variations in salinity can play important controlling effects on the structure of marsh communities (Zedler and Beare 1986). In South Africa, SAV is much more sensitive to short-term inflow alteration than riparian vegetation (Talbot et al. 1990; Adams et al. 1992). Riparian impacts may take longer to manifest, as in the case of the Manamo River (Venezuela), where persistently reduced inflows allowed mangroves to colonize oligohaline reaches, and the distribution of other halophytes was affected throughout the system (Colonnello and Medina 1998). A similar upstream movement of mangroves into reaches dominated by cypress was documented in the Loxahatchee River by McPherson et al. (1982). Over longer periods, indirect impacts can accumulate. Coops et al. (1999) found that intertidal marshes deteriorated in two regulated estuaries in the Netherlands as the result of erosion, predation, and invasion by terrestrial species.

Estuarine fauna are affected profoundly by inflows and salinity, as well as by factors directly and indirectly affected by them. Secondary production in estuaries has been surprisingly difficult to relate to freshwater inflow in statistically meaningful ways. Even modern efforts sometimes fail (Ardisson and Bourget 1997). A clearer picture is emerging based on appreciation of the roles of habitat and faunal development rates. Habitat has long been known to regulate secondary production; more habitat generally means more production. Stocks (as landings, CPUE, absolute abundances, etc.) have been harder to relate to freshwater inflow but Deegan et al. (1986) demonstrated that stocks normalized by unit-habitat area are positively associated with freshwater inflow, suggesting that inflows fuel secondary production to limits set by habitat availability. A second breakthrough has been the discovery of significant relationships between inflows and stocks of estuaries when stock data are lagged by the time required for the species to enter the sample population. First observed by Russian scientists working in the Caspian Sea before World War II (see Izhevskii 1961), good fits were produced by matching the flows of a given year to benthic biomass data of the subsequent year. An early American demonstration was provided by Copeland (1966), who lagged fish landings in relation to inflows in five Texas bays. Various European fish stocks were successfully lagged against inflows in subsequent decades (Skreslet 1986), as were stocks of particular species in Texas estuaries (Longley 1994). In Florida, Browder (1985) time-lagged pink shrimp landings to Everglades water levels, and Wilber (1992) time-lagged oyster landings in Apalachicola Bay to flows of the Apalachicola River.

Spatial and temporal patterns of secondary production in an estuary were elegantly combined by Jassby et al. (1995) in a study of striped bass production in San Francisco Bay. An index of freshwater inflow, which could not be measured directly with precision, was developed using the position downstream from an arbitrary place of the 2‰ isohaline. Components of the striped bass food web were analyzed against the inflow estimator. Significant relationships were developed for each food-web component (particulate organic carbon, mollusks, crustaceans, smelt, flounder), as well as juvenile and adult striped bass. Several aspects make this work interesting. The 2‰ isohaline was defined for near-bottom conditions, and was chosen because it was an accurate descriptor of the Bay's salinity field. It (or more precisely, its downstream distance from the reference point) often occurred near the estuarine turbidity maximum, also the location of highest zooplankton abundance. The 2‰ distance was relevant both physically and ecologically, although Jassby et al. (1995) noted that its usefulness may be peculiar to San Francisco Bay.

Case Studies of Impacts from Altered Inflow

Reports mount on varied ecological responses of estuaries to altered inflow. These can be interpreted in terms of species intolerances, trophic effects, and higher-order processes. The intolerance of oyster drills to low salinity is well-known. Andrews (1964) based minimum estuarine inflows (184 m^3 s^{-1} for 20 d beginning May 1 to the Rappahannock River, Virginia) on control of the oyster drill line in order to optimize oyster yields. The intolerance of striped bass eggs to high salinity resulted in stock declines when reduced flows allowed salt intrusion in the Savannah River (Van Den Avyle and Maynard 1994). Species-specific tolerances to variable salinities explained a finding by Serafy et al. (1997) that more fish species occupied stable salinity waters, than waters affected by the discharge of a freshwater canal. Canal discharges in Uruguay were responsible for significant changes in sex ratios, size classes, weights, and fecundity of *Emerita brasiliensis,* a sandy-beach mole crab (Lercari and Defeo 1999). Canal freshets also killed urchins but not gastropods and laboratory exposures to salinity changes typical of those caused by water management structures verified urchin vulnerability. Urchin grazing was also depressed whereas snail grazing was increased by variable salinity (Irlandi et al. 1997). As the urchin study revealed, feeding behavior and larger-scale trophic effects may accompany altered freshwater inflow. A dam across the

Mbashe estuary (South Africa) starved the system of silt and fine particulate organic matter, reducing fish diversity and abundance, especially for locally important mullet, *Mugil cephalus* (Plumstead 1990). Ecological effects of changed inflows can be difficult to separate from the structures causing the change, but the barrier effect of instream structures can cause significant impacts where the maintenance of metapopulations is involved. Holmquist et al. (1998) found that Puerto Rican dams with zero discharge eliminated all native fish and shrimp fauna from upstream reaches. Dams with some discharge had diminished upstream populations. Most seriously affected were amphidromous species. The extirpation of freshwater crab species from the Naktong estuary (South Korea), as well as precipitous declines in commercial bivalve catches, was attributed to the barrier effect of a dam (Jang and Kim 1992).

COMMUNITIES, ECOSYSTEMS, AND LANDSCAPES

Flow alterations can play out at large scales. Three reports from the Netherlands are instructive. Increased flows to the Krammer-Volkerak estuary reduced some species abundances immediately but they recovered. Valuable mussel stocks were not hurt though condition indices declined. Ammonia and bacteria levels increased but no water quality calamities resulted (Coosen and Leewis 1984). In a case of reduced flow, enclosure of the Rhine-Meuse estuary caused low ecological values, sediment contamination, the disappearance of intertidal areas, and the loss of nursery grounds for fishes (Smit et al. 1997). A third type of alteration occurred in the Oosterschelde estuary when it was isolated from both its river and the sea. It changed from a turbid estuary to a lagoonal system in which phytoplankton flourished, salt marshes declined, and populations of carnivorous wading birds contracted (Nienhuis and Smaal 1994).

Impacts of flow alteration occur at landscape scales within or among watersheds. In work presaged by Bradley et al. (1990), Estevez and Marshall (1997) developed a landscape method to investigate the larger range of ecological changes resulting from instream flow changes in estuaries. Salinity regimes before and after alteration of flow in the Manatee River, Florida were compared for habitat-overlap changes, following Browder and Moore (1981). Impacts of various types were more common in low salinity reaches below a dam in the tidal river, highlighting a particular, large area where flow mitigation was required. Sklar and Browder (1998) review overlap and more sophisticated landscape methods of statistical performance and dynamic landscape simulation. They ‘‘recommend that model structure match management goals . . . if it is important to manage an estuary within the viability limits of a few economically important species, then a performance curve is the best approach. If it is important to manage an estuary for biodiversity and spatial heterogeneity while predicting cumulative impacts of management, then a landscape simulation is best’’ (Sklar and Browder 1998, p. 558). Estuaries are affected by processes at very large scales. Morris et al. (1990) demonstrated that *Spartina* production increased during periods of relative sea level rise, translating into higher landings of shrimp and menhaden. But where have sea level signals been reckoned in estuarine inflow studies? Peterson et al. (1995) have shown that continental-scale climate patterns affect salinity in San Francisco Bay. Estuarine scientists will need to know when their research was performed relative to phases of El Niño cycles and longer-period cycles of oceanic and atmospheric processes, and be able to advise resource managers as to the range of climate conditions for which management advice such as minimum flows are meant to apply.

At the scale of total freshwater inflow to entire seas, Rozengurt and Hedgpeth (1989) drew world attention to the extent, severity, and complexity of impacts associated with altered river flow on the Caspian Sea. Other work addressed equally serious impacts in additional inland seas and, more recently, American estuaries. Rozengurt developed methods for computing differences between modern and virgin flows of fresh water to inland seas. Virgin flows must be scrupulously defined. Then departures from the virgin flows can be used to gage estuarine risk. Rozengurt independently derived the idea that human-caused inflow variations, in excess of natural inflow variation, will harm estuaries. With time, Rozengurt’s ideas have taken on other dimensions (Rozengurt 1999). Chief among these are the idea that the thermodynamics of closed systems apply to estuaries, and that as a consequence, annual water deprivation (annual entropy gain) accumulates through time in estuaries. Rozengurt’s lasting contributions will be the West’s education regarding the history and demise of eastern Europe’s inland seas, and the concept that forced inflow alterations in excess of an estuary’s natural and long-term inflow variability will cause it harm. Armed with new tools from river science (Richter et al. 1996), estuarine scientists will be able to evaluate what we may call The Rozengurt Rule in the fuller context of hydrological variation.

Insights from the Texas Estuaries Study

Early works of Gunter and others (see Gunter et al. 1974) set the stage for a key paper by Copeland (1966), who evaluated total commercial landings of all species within a given estuary in a particular year, relative to the total freshwater inflows received by the estuary in the previous year. Nonlinear relationships were found in four of the five systems. Given existing and projected flows, Copeland (1966, p. 1836) concluded, ''The minimum freshwater contribution required to maintain the present commercial fishery is not reached in some years in Matagorda, Aransas, and Corpus Christi Bays.'' Lambert and Fruh (1978) developed a method to demonstrate how estuarine needs can be determined. Using Corpus Christi Bay as a test case, they erected a hypothetical goal of providing an estuarine salinity environment conducive to the maintenance of spotted seatrout (maximum salinity of 27‰ from April to September). Lambert and Fruh (1978, p. 411) concluded that the use of only one species was ''unacceptable for actual inflow management,'' and that ''serious deficiencies existed in the ecological data base needed for serious inflow management.''

A 1975 Act of the Texas Legislature (64th Texas Legislature Senate Bill 137) mandated comprehensive studies of the effects of freshwater inflow upon the bays and estuaries of Texas to address the relationship of freshwater inflow to the health of living estuarine resources and to present methods of providing and maintaining a suitable ecological environment. The Legislature resolved that ''a sufficient inflow of freshwater is necessary to protect and maintain the ecological health of Texas estuaries and related living marine resources.'' Seven Texas bays and estuaries were studied in depth (Texas Department of Water Resources 1982). A major premise of the studies was that indicators can be used to examine interactions between freshwater inflow and estuarine productivity. Three were selected: frequency of marsh inundation, salinity, and commercial fishery landings (depending on the estuary, of spotted seatrout, red drum, white shrimp, blue crabs, and bay oysters; brown shrimp were added to a later coast-wide assessment of total flows). Data for indicators were analyzed in the context of three management scenarios. The first, a subsistence supply, addressed marsh inundation and salinity but not fisheries. A second maintenance supply continued fishery landings at levels no less than the 1962–1976 annual average landings. A third enhancement supply increased landings of estuary-specific indicator species.

Texas scientists and resource managers struggled with the issue of timing and frequency distributions of the annual flows calculated for each scenario, understanding the effects that impoundments can have on river hydroperiods. They concluded, ''the most satisfactory interpretation (would be) flows needed by the estuary with approximately the same frequency as historically entered the estuary'' (Texas Department of Water Resources 1982, p. 47). Because annual flow targets could increase the frequency of low flow events the team concluded, ''Such a situation could be overcome by applying an additional qualification . . . whereby the frequency of the very low inflows (such as those exceeded 90 percent of the time) be no less than that which has occurred over the historical period'' (p. 48). Texas modelers confronted important problems in the use of mathematical analyses in inflow optimization. Martin (1987) developed a linear model for monthly inflow needs but problems with the approach included nonlinear relationships, and uncertainty, which were addressed by Tung et al. (1990). The new model led to the main inflow analytical tool used by Texas, described as a completely new second generation model that expanded on the first through nonlinear equations, consideration of probability functions, and problem analysis through multi-objective analysis. The Texas Estuarine Mathematical (TxEMP) Model requires very large data sets to operate, even when the number of target species is held to a minimum. Several policy decisions are required: what species will be used as indicators, what levels of probability will be used, and what fishery harvest targets will be sought (Longley 1994). Of performance curve models like the TxEMP Model Sklar and Browder (1998) note that success depends on availability of historic data, meaningful links between key species and estuarine sustainability, constancy in species-salinity relationships, absence of extreme events such as red tides or hurricanes, and insignificance of slowly changing directional processes such as sea level rise or climate change.

Recently, TxEMP has been run in a geographic information systems (GIS) environment in conjunction with a two-dimensional hydrodynamic circulation model (TXBLEND). TXBLEND simulates patterns of salinity and bay circulation. In the Trinity-San Jacinto estuary, all three tools were used to compare salinity fields under differing inflows, and maps of wetlands and oyster reefs were spatially queried in monthly intervals to depict potential impacts. Time-series analyses were used to determine how often salinity constraints would be violated for target species such as oysters. GIS spatial analysis of fisheries data was used to depict zones of abundance and salinity preference for several species (Texas Parks and Wildlife Department 1998).

ECOLOGICAL FINDINGS AND TEXAS INDICATOR SPECIES

After decades of basic and applied studies and data analysis, Texas estuary scientists found relationships between inflow or salinity and phytoplankton abundance or production. Because phytoplankton was affected more by light climate, biomass and chlorophyll were not used as objective functions in the optimization model. Marsh plants were more affected by water level and soil moisture than inflow or salinity. Some tidal freshwater emergent plant species were affected adversely by salinity but no empirical relationships using marsh response as an objective function were used in the model. Most Texas SAV is estuarine or marine and prefer higher salinities; except in Laguna Madre (Quammen and Onuf 1993), excess flows and freshwater shocks to Texas SAV are apparently not an issue. Zooplankton abundance was related to freshwater inflow up to the point that zooplankters were physically exported from the estuary. Meiobenthic species and abundance declined with freshwater inflow, and patterns were discovered relating inflows to macrofaunal benthic communities, but neither group was used as an objective function. The abundances of several species of invertebrates and fishes varied with respect to inflow, but the relationship was stronger among juveniles than adults. Empirical relationships between freshwater inflows and select indicator species were developed on the basis of long-term data sets. Black drum, red drum, and seatrout harvests were a function of a 3-yr average antecedent inflow. Two-year antecedent average inflows explained most of the variance in landings of oyster and blue crab, whereas antecedent yearly inflow was used to account for variances in brown, pink, and white shrimp landings. Air temperature was a second independent variable of importance.

Insights from Florida Minimum Flows and Levels Work in Progress

Florida scientists are working to establish minimum flows and levels (MFL) for a variety of surface waters. Guidance documents have not emphasized the importance of establishing quantitative goals for minimum flows, although the 1995 House Select Committee on Water Policy found, ''the establishment of a minimum flow and level is a scientific determination based solely on criteria of the sustainability and viability of the resource. It is a floor number that is based on science. The concept means that if flows and levels are reduced below that number, we do not sustain the resource'' (Worth 1998, p. 53). The significance of this legislative intent is three-fold: it states that resource-based criteria form the basis of minimum flow determinations, the objective of the flow or level must be to sustain the resource, and the intent implies that a minimum flow determination is a bottom-up process, with scientists determining criteria and the definition of sustainability. In estuaries, at least, ''individual water management districts have been given the discretion to determine what measures are appropriate to determine when a specific flow or level may result in significant harm'' (Worth 1998, p. 6). There are five water management districts in Florida, and programs to establish minimum flows in three districts are described elsewhere in this volume by Mattson (2002; Suwannee River District), Flannery et al. (2002; Southwest Florida District), and Doering et al. (2002; South District).

The Northwest District is working primarily on the Apalachicola River and Bay, with its study program for the Apalachicola-Chattahoochee-Flint (ACF) Tri-State Compact setting research priorities. Detailed study was made of the floodplain forest (Light et al. 1998). Chief among the bay studies were works by Wilber (1992) showing that oyster CPUE was meaningfully related to antecedent inflow, and by Livingston et al. (2000) that river flow regulated oyster mortality. Earlier, Livingston et al. (1997) reported on the trophic effects of a natural drought. The District intends to protect natural patterns of hydrological variation in both the river and bay and measures of hydrological variation have been used to assess future flow scenarios (Army Corps of Engineers 1998).

The St. Johns River District established Florida's first minimum flow for a stream, on the Wekiva River. A minimum flow was established in terms of four hydrologic parameters: minimum flow, minimum level, duration, and recurrence interval. Event-wise parameters were evaluated for each of five goals, criteria, or values: inundation of riparian wetlands for stream biota, saturation of hydric hammocks, maintenance of riparian hydric soils, adequate depths for fish passage and eelgrass beds, and protection of eelgrass beds from boat and canoe traffic (CH2M Hill 1999). The District is attracted by the idea that MFLs in headwaters, low-order streams, and larger tributaries offer promise in protecting the larger St. Johns estuary. In work sponsored by the District, Estevez and Marshall (1993) recommended salinity targets for the Sebastian River and Indian River Lagoon. A canal connects the upper St. Johns River to the coast via Sebastian River and Inlet, and large discharges for flood control have caused ecological harm to coastal resources. A series of salinity targets was developed to protect hard clam and seagrass resources, and included means, standard deviations, coefficients of salinity variation, minima, maxima, and ranges for nine spatial segments. Other salinity targets were defined to protect *Halodule, Syringodium, Mercernaria,* and *Crassostrea* resources.

The Southwest District requires hydrobiological monitoring programs (HBMP) in permits to distinguish estuarine responses attributable to water use from those caused by natural variability. Biological indicators include spatial and temporal analyses of riparian and SAV, benthic macroinvertebrate epifauna and infauna, ichthyoplankton and other macro-zooplankton, juvenile and adult fishes, and water-dependent birds. Target species include red drum, snook, spotted seatrout, striped mullet, hogchoker, bay anchovy, pink shrimp, grass shrimp, and blue crab. Oysters have not figured prominently in HBMP designs.

Insights from River Science and Instream Flow Determinations

To ecologists and resource managers seeking to establish minimum freshwater flows to estuaries, the accomplishments of river science can seem breathtaking. There exists a coherent theory of river ecology, and managers seeking to establish minimum or other regulatory flows work in a tool-rich environment (Hardy 1998). Changes to river flow have been classified as reduced average annual flow, reduced seasonal flow, altered timing of annual extremes, reduced flood magnitudes, and imposition of unnatural pulses. In estuarine settings it is appropriate to add increased flow and altered locations of flow. In an estuarine context, it is apparent that this list may also be used to classify types of changes to salinity fields. The effects of river regulation by instream dams are serial, beginning with the structure's barrier effect. Downstream effects are classified as first order (basic flow and material flux), second order (channel geometry and disequilibrium, water quality), and tertiary (ecological). Impacts are understood to cascade from low to high order (Petts 1984). This understanding raises the question of where significant harm (in minimum flow determinations) is appropriately defined. Do minimum flows based on low order impacts assert that impacts of higher order do not cascade to unacceptable levels?

First principles exist in the ecology of river regulation. The first is that habitat diversity is substantially reduced when natural river flow is altered. Second, native biodiversity decreases and non-native species proliferate. Third, biophysical conditions reset according to the influence of tributaries and as distance downstream from the dam increases. These are provocative principles to consider in an estuarine context. Comparative data on estuaries grouped by the extent of their inflow alterations have not been compiled to allow informed assessments of the principles. Beyond certain levels of alteration the potential exists to reduce habitat diversity. Saline intrusion to tidal freshwater reaches of a river may decimate those habitats. Sudden large discharges of freshwater can extirpate seagrass and mollusk communities. Native biodiversity can decrease in estuaries where stenotopes are displaced by eurytopes, but do inflow and salinity alterations promote non-native species in estuaries? Although parallels have been drawn between diseases and exotic species, no one has compared pathogen levels between impounded and free-flowing streams or their estuaries. The third principle is possibly the most interesting, at least for cases where dams and other flow alterations occur in proximity to the coast. Inflow alterations are manifest more in low-salinity reaches of a system than elsewhere, but the effects of inflow regulation have not been evaluated formally in terms of reset distance through the system.

INSTREAM FLOW METHODS

Instream flow assessment methods fall generally into three categories. Historic flow techniques rely solely on historic data or estimated flows. The seminal Tennant or Montana Method is a historic flow technique generally assuming a linear relationship of flow to resource protection. Hydraulic techniques relate a channel's hydraulic geometry to flow. Hydraulic techniques generate resource curves with non-linear inflections, which singular flows are taken as thresholds for resource protection. The third approach is a habitat method. Habitat suitability curves are related to flows to decide instream flows. Complex relationships often result. A number of variations exist but the most widely known is the physical habitat simulation component (PHABSIM) of the instream flow incremental methodology (Orth and Maughan 1982). Habitat methods often yield higher minimum flows for small streams and lower estimates for large ones, than the other methods (Jowett 1997).

RECENT ADVANCES IN FLOW ANALYSIS

According to the National Research Council (1992) long-term hydrological data and especially measures of their variability have been under-utilized in the vast majority of river management decisions aimed at ecosystem protection or restoration. Because modifications of hydrologic regimes in rivers are known to alter their ecology, river scientists agree that it is better to approximate natural flow regimes and maintain entire ensembles of species, than to optimize water regimes for one or a few species. In reality, the great majority of instream determinations have been based on one or a few species' requirements. It is now understood that native aquatic biodiversity depends on maintaining or creating natural flow variability, and that native species and natural communities will perish if the environment is pushed outside the range of natural variability. Where rivers are concerned, a natural flow paradigm is gaining acceptance. It states ''the full range of natural intra- and inter-annual variation of hydrologic regimes, and associated characteristics of timing, duration, frequency and rate of change, are critical in sustaining the full native biodiversity and integrity of aquatic ecosystems'' (Richter et al. 1997, p. 233). A corollary idea is that ensembles of species and ensembles of habitats should be used to gauge the effect of hydrological alteration.

A new method has developed for determining hydrologic alterations in rivers (Richter et al. 1996). The Range of Variability Approach is based on the calculation of means, and coefficients of variability, of 32 hydrologic variables grouped into five sets: magnitude of monthly water condition, magnitude and duration of annual extreme conditions, timing of annual extreme water conditions, frequency and duration of high and low pulses, and rate and frequency of water condition changes. Comparisons are made between before and after modifications. In the absence of before data, models can be used to estimate water conditions. Some alterations affect only a few indicators, whereas others affect many. Patterns of alteration help managers determine which aspects of flow to modify. This is an appealing method, presaged by simpler efforts in Europe. This technique employs more variables and offers more promise in protecting ecosystem integrity. It is gaining in popularity and has been used by the Northwest Florida Water Management District in its role in the ACF Tri-State Compact (Army Corps of Engineers 1998, Appendix E).

SEVERELY ALTERED STREAMS

Are some estuaries too modified to restore? Are principles and methods of river or estuarine science and management relevant if constraints are overwhelming? These ideas open the possibility that flow alterations may be too extreme and unchangeable to justify other management efforts, and open the possibility that improvements to altered flows may accomplish little if other constraints unrelated to flow cannot be relieved. Can a tidal stream in an urban setting, for example, ever become an unimpaired estuary? Can it become some other tidal ecosystem of value? A common problem in instream science is that a river is so drastically altered, or altered before records were made of its virgin condition, that goal-setting is next to impossible with information in hand. An approach proposed for use in Europe is to create an Ökologisches Leitbild (German for ecological guiding view) to serve as a standard against which watershed, stream-bank, and instream flow alternatives can be evaluated. Although based on historical research and transfers of data from reference sites, the Leitbild functions not to reestablish unmodified river systems but to show where managers are on an ecological scale (Muhar et al. 1995). The Leitbild represents a process of ecological visioning that has been employed for terrestrial habitat networks, greenways, and refuges, but not as a tool for estuary management. In the case of a highly-altered tidal river, a Leitbild implies the creation of an overall spatially-referenced vision for the estuary, informed by historical and proxy records but constrained by ecological principles and permanent changes wrought by humans. Flow management would be part of a larger program of physical, geological, and chemical rehabilitation.

Discussion

A trend-line in science related to freshwater inflows to estuaries has five overlapping phases with the first being a rich history of research documenting the structure and function of estuaries, and how estuarine biota are adapted from molecular to ecosystem levels to the changing conditions found there. A second phase developed when obvious harm caused by the most extreme of inflow disruptions was documented. A third phase was defined by early efforts to define single-species performance curves relative to single factors such as inflow or salinity. A fourth phase involved multi-objective models that sought to combine multiple performance curves, and a fifth phase added consideration of habitat and community-level attributes. All phases continue to the present.

Much valuable basic research is ongoing, as is new documentation of harm caused by inflow alteration. Accounts of harm have tended to be opportunistic; new accounts would contribute more to inflow science by addressing issues of recruitment (Peebles 2002), trophic organization, and the questions of reset distance, pathogens, and exotic species. It will also be helpful for such studies to determine whether observed impacts resulted from direct or indirect consequences of flow change. Past efforts to define performance curves have succeeded where long-term CPUE data or fishery-independent stock estimates were available, especially for shellfish and fin-fish of recreational or commercial value. Weaknesses of this approach include dependence on large data sets, lack of transferability, and limited usefulness when an estuary is supplied by several rivers but management decisions are needed for only one.

At present, a variety of approaches are in use for estuarine inflow studies. From least to most complex these include instream flow methods, hydrological variability techniques, habitat approaches (sensu Browder and Moore 1981), indicator species, valued ecosystems component approaches, food web methods (Jassby et al. 1995), community-index approaches, and landscape and adaptive management approaches.

Synthesizing past with contemporary works, a future trajectory of inflow science can also be outlined. More than ever, non-linear relationships of biological and ecological attributes to flow and salinity need to be sought and exploited to identify possible break-points and thresholds in estuarine responses to inflow change. At the species level, this means that new work with performance curves must look harder at the role of recruitment times. Lags between flow or salinity and the number, biomass, or catch of target species need to be sought after careful consideration of life history patterns and estuary dynamics. At the community level, two techniques offer promise in defining non-linear break-points. Benthic community species richness and abundance often fail as objective functions, but available data suggest that benthic biomass, appropriately lagged, can succeed. Of greater promise is the further application of overlap analyses (Browder and Moore 1981). Because the surface area and volume of estuaries are strongly non-linear, changes to flow affect most the salinities where area and volume also change the most. Catch, productivity, stock, and other objective functions should be normalized by areas of available habitat falling within particular salinity ranges before and after flow alteration. Ensembles of data must be sought from multiple levels of biological organization below and above the species level. Much new work should evaluate habitat, community, and landscape scales of estuary structure and function, and such data from estuaries with greatly altered inflows should be compared with data from relatively unaltered estuaries nearby.

LESSONS FROM RIVERS

There are two values of river science and flow management for estuarine science and management. First, many principles and techniques used in rivers may be directly applicable to estuaries, especially tidal rivers. Such applications may be through extension (direct transfer) or through addition (of salinity, for example, to lotic habitat criteria). By this way of thinking, estuaries are regarded as fundamentally different ecosystems than rivers, but scientific analogies may be found between them. A second more speculative value comes from the idea that estuaries, and riverine estuaries in particular, are extensions of lotic systems, or at least are dominated by their characteristics. In this way of thinking, river tools could be employed in riverine estuaries for the same causal reasons rather than by analogy. In either case, this review raises a new and fundamental issue for estuarine managers, as to whether an estuary's minimum flows could be established without reference whatsoever to estuarine resources or values. The scientific hypothesis to test is that a set of minimum instream flows established by tested scientific methods, and demonstrated through follow-up monitoring, will necessarily protect the estuary formed by that river. The hypothesis implies that an estuary formed by several rivers can be protected by instream flows set in each of its tributaries.

Conclusions

The question of freshwater inflows to riverine estuaries is a good scientific question, as well as an important one for coastal resource management. Freshwater is an integral part of the definition of an estuary and so deserves primacy in all aspects of estuarine ecology. Changes to inflows have harmed many estuaries in the world and have the potential to harm more. We seek to learn enough about estuaries to restore damaged ones and protect natural ones, but to do so will require the development of insights and tools not presently available.

Lotic studies are informative. Instream techniques have evolved through time and some have been found to work better than others. Instream methods may be useful in riverine estuaries, and instream flows set for rivers may also protect their downstream estuaries. Studies of natural and altered estuaries, and previous attempts to establish their minimum freshwater needs, have often made use of particular species, species groups, and habitats. Some of the more important species have included oysters, shrimps, and crabs. Spotted seatrout and striped bass have been used in several venues, and striped bass work has been extended to include its food web in at least one estuary. SAV has also been used, and is likely to be used more for at least some kinds of estuaries and inflow alterations. Tidal freshwater and oligohaline habitats are likely to be used more in the future although much new study will be needed to document the functional necessity of tidal freshwaters as part of a complete gradient of estuarine salinities and habitats.

Three lessons emerge from this review. First, minimum flow studies, and flow-optimization in general, will be improved if objective functions are defined at multiple levels of biological organization. Evaluating estuarine structure and function at multiple levels promotes cross-checking of conclusions at multiple spatial and temporal scales, so inflow solutions will tend to be convergent and protective. Second, the non-linear geometry of estuaries needs to be exploited to greater advantage than it has in the past. Strong gradients in surface area and volume along the length of an estuary have powerful effects on the total abundance and productivity of its biological elements. Intrinsic non-linearity of flow and salinity and the estuary's geometric asymmetry are multiplicative and can amplify small inflow changes into measurably large ecological responses. Third, instream flow analysis needs to be scrutinized further to determine the extent to which protective riverine flows also protect estuaries.

As Texas work has shown, methods can be developed to inform water management decisions as to the ecological consequences of alternative policies, but the path is long and expensive. Though far from being methods in the formal sense of the term, several possible approaches present themselves from reviews of instream science, estuarine ecology, and case studies of estuaries affected by inflow changes. Estuary scientists and managers will continue to tailor methods to the situation of each tidal stream or estuary, but a convergence of opinions seems to be developing with respect to the role of goals, definitions of significant harm, successful tools, and follow-through by methods of adaptive management. The most successful estuarine inflow tools will most likely be those traceable to flow and salinity, workable at several spatial and temporal scales, operated at different levels of biological and ecosystem organization, advantaged by the discovery of non-linear functions, and transferable to other systems.

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