Estuaries Vol. 25, No. 6B, p. 1318–1332 December 2002

A Percent-of-flow Approach for Managing Reductions of Freshwater Inflows from Unimpounded Rivers to Southwest Florida Estuaries

MICHAEL S. FLANNERY[1,*], ERNST B. PEEBLES[2], and RALPH T. MONTGOMERY[3]

[1] *Southwest Florida Water Management District, 2379 Broad Street, Brooksville, Florida 34604*
[2] *University of South Florida, College of Marine Science, 140 Seventh Avenue South, St. Petersburg, Florida 33701*
[3] *PBS&J, Inc., 5300 West Cypress Street, Suite 300, Tampa, Florida 33606*

ABSTRACT: The Southwest Florida Water Management District has implemented a management approach for unimpounded rivers that limits withdrawals to a percentage of streamflow at the time of withdrawal. The natural flow regime of the contributing river is considered to be the baseline for assessing the effects of withdrawals. Development of the percent-of-flow approach has emphasized the interaction of freshwater inflow with the overlap of stationary and dynamic habitat components in tidal river zones of larger estuarine systems. Since the responses of key estuarine characteristics (e.g., isohaline locations, residence times) to freshwater inflow are frequently nonlinear, the approach is designed to prevent impacts to estuarine resources during sensitive low-inflow periods and to allow water supplies to become gradually more available as inflow increases. A high sensitivity to variation at low inflow extends to many invertebrates and fishes that move upstream and downstream in synchrony with inflow. Total numbers of estuarine-resident and estuarine-dependent organisms have been found to decrease during low-inflow periods, including mysids, grass shrimp, and juveniles of the bay anchovy and sand seatrout. The interaction of freshwater inflow with seasonal processes, such as phytoplankton production and the recruitment of fishes to the tidal-river nursery, indicates that withdrawal percentages during the springtime should be most restrictive. Ongoing efforts are oriented toward refining percentage withdrawal limits among seasons and flow ranges to account for shifts in the responsiveness of estuarine processes to reductions in freshwater inflow.

Introduction

Stream ecologists have emphasized the importance of natural flow regimes for maintaining the geomorphological and ecological characteristics of rivers (Hill et al. 1991; Poff et al. 1997; Richter et al. 1997). There is also evidence that naturally occurring patterns of freshwater inflow are important for maintaining the structure and productivity of estuarine ecosystems. Suspended sediments transported by periodic pulses of high river discharge are a major factor controlling the geomorphological structure of river deltas and bays (Kennish 1986; Jay and Simenstad 1996; Day et al. 1997). The productivity of coastal fisheries is positively related to freshwater inflow (Browder 1985; Drinkwater 1986; Day et al. 1989), and alterations to inflow regimes have caused dramatic declines and recoveries in fish stocks (Moyle and Leidy 1992; Mann and Lazier 1996; Sinha et al. 1996). Significant relationships have been found between fishery yields of estuarine-dependent species and preceding freshwater inflow terms calculated over 2-mo or 3-mo intervals, indicating that the seasonality of inflow can have a significant effect on fish abundance (Browder 1985; Longley 1994). Wilber and Bass (1998) also found that oyster harvests were negatively correlated with the number of low-flow days that occurred 2 yr prior, indicating that alteration of one component of a flow regime can have an effect on a specific stage of an organism's life history.

As groundwater sources reach their sustainable limits in southwest Florida, there is growing emphasis on using rivers for water supply. Many major rivers in Florida are not impounded and have not been used for water supplies in the past (Jue 1989; Fernald and Purdum 1998). Based on a series of studies of the freshwater inflow relationships of estuaries in the region, the Southwest Florida Water Management District (SWFWMD) has implemented a management approach for unimpounded rivers that limits withdrawals to a percentage of streamflow at the time of withdrawal. This approach considers the natural flow regime of a river to be the baseline for assessing the effects of withdrawals. Trends in various streamflow parameters

---

* Corresponding author; tele: 352/796-7211; fax: 352/797-5806; e-mail: sid.flannery@swfwmd.state.fl.us.

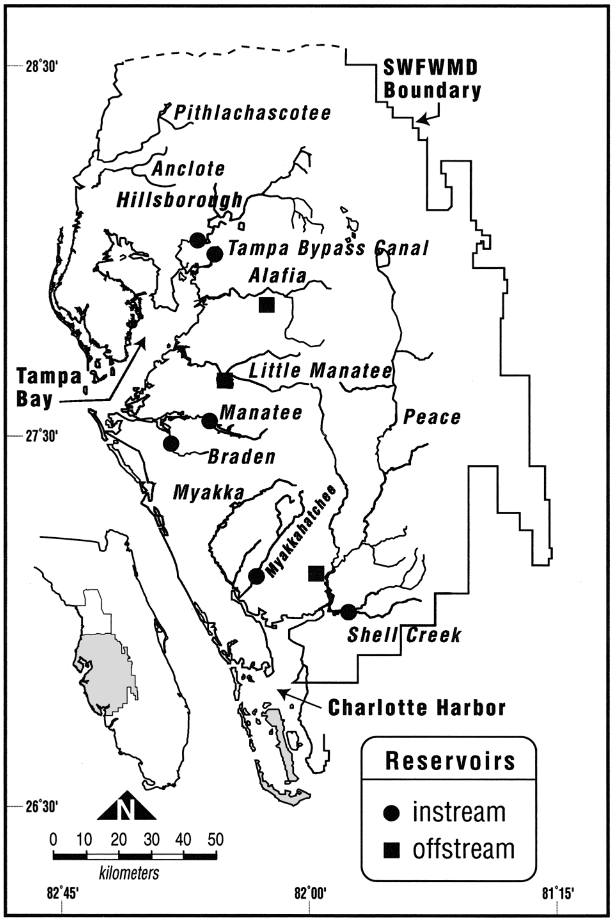

Fig. 1. Location of rivers in the Southwest Florida Water Management District extending from the Tampa Bay area to Charlotte Harbor, including the location of instream and offstream reservoirs used for water supply.

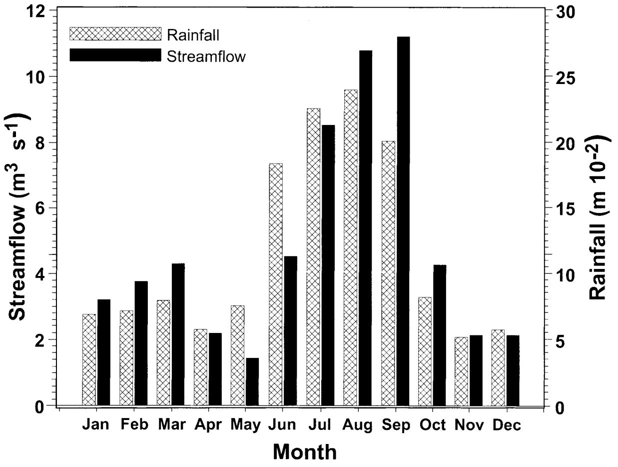

Fig. 2. Mean monthly rainfall at Bradenton, Florida and streamflow (U.S. Geological Survey gauge 02300500) for the Little Manatee River basin for the period 1940–2000.

are evaluated to determine if any components of a river's flow regime have changed. Estuarine relationships with freshwater inflow are then examined within seasons and flow ranges in order to determine percentage withdrawal limits that do not result in adverse environmental impacts. We review the theoretical and empirical framework on which the percent-of-flow approach is based and describe how it is applied in the water management setting. Analyses supporting this approach have emphasized hydrobiological relationships within tidal-river zones of larger estuarine systems in southwest Florida. Representative findings from these tidal rivers are reviewed to illustrate key ecological relationships and applications to the management of freshwater inflow.

Hydrologic Setting of the Region

West-central Florida contains 14 named rivers and numerous small streams that flow to the Gulf of Mexico. The flow regimes of several rivers north of Tampa Bay are dominated by groundwater discharges from large artesian springs, whereas flows in rivers from just north of Tampa Bay southward (Fig. 1) are dominated by surface runoff (Estevez et al. 1991). The region receives an average rainfall of about 1.35 m yr^{-1} with about 60% occurring from June through September. The temporal variability of streamflow in spring-fed rivers is typically more subdued than seasonal variations in rainfall, while average monthly flows in rivers dominated by surface runoff exhibit greater seasonal variability than monthly rainfall (Fig. 2). In rivers dominated by surface runoff, low flows occur in April and May when rainfall is low and potential evapotranspiration rates are increasing (Bidlake and Boetcher 1997; Lee and Swancar 1997); peak flows typically occur in August or September when depressional storage is full and water tables are high. The interaction of this seasonal streamflow pattern with estuarine processes forms the hydrobiological setting for managing freshwater inflows in these systems.

Detecting Changes in Inflow from Unimpounded Rivers

The water supply planning and regulation programs administered by the SWFWMD are designed to maintain the physical structure and ecological characteristics of the region's unimpounded rivers. Municipal water supplies are obtained from five instream impoundments in southwest Florida (Fig. 1), including major reservoirs on the Hillsborough and Manatee Rivers and small, low-head structures that serve as salinity barriers on three smaller streams (Braden River and Shell and Myakkahatchee Creeks). Water supplies are also obtained from the Tampa Bypass Canal, which is a regulated flood control waterway that was constructed in the channel of the Palm River. With the exception of the Tampa Bypass Canal, all of these impoundments were constructed before 1965. Since the mid-1970s, the SWFWMD (1992, 2001b) has emphasized the use of alternative water storage methods for the development of water supplies from unimpounded rivers in order to avoid impacts to riverine systems that can result from impoundment (Petts 1984; Ligon et al. 1995; Collier et al. 1996). Water supply storage from unimpounded rivers has been achieved using offstream reservoirs, which are diked or excavated areas located away from the river channel, and aquifer storage and recovery facilities, in which treated surface waters are pumped into underground aquifers for storage and subsequent retrieval.

The initial step for evaluating potential withdrawals (and resulting reductions in freshwater inflow) from an unimpounded river involves the assessment of historical changes in the river's flow regime. Many factors, such as changes in land use or surface water-groundwater relations in a river basin, can affect flow regimes in the absence of impoundment or direct withdrawals (Newson 1994; FISRWG 1998). Richter et al. (1996) developed a series of quantifiable indicators of hydrologic alteration that can be used to evaluate trends in different components of a flow regime over time. Another useful technique for evaluating changes in low or high flows is trend analysis of daily flow percentiles within each year (Lins and Slack 1999). Using one or more of these hydrologic indicators, historical streamflow records are evaluated to identify trends in different components of a flow regime or changes in seasonal flows. If changes have occurred, analytical effort is directed toward distinguishing the relative effects of climatic variability and anthropogenic influences, which can occur either as distinct events or as gradual changes through time. A series of hydrologic studies have been conducted on the three unimpounded rivers in southwest Florida that are currently allocated for water supply (Peace, Alafia, and Little Manatee; see Fig. 1) in order to assess trends in long-term flows (Hammett 1990; Flannery et al. 1991; Flannery and Barcelo 1998; SDI Environmental Services 1998), seasonal flows (Flannery et al. 1991; Coastal Environmental 1996a), low and high flows (Flannery et al. 1991; Stoker et al. 1996; Flannery and Barcelo 1998), and to compare the effects of anthropogenic influences and climatic variability on streamflow (Hammett 1990; Coastal Environmental 1996b; Flannery and Barcelo 1998; SDI Environmental Services 1998). The findings of these studies have been used to help define the baseline flow regime against which projected withdrawals and potential ecological effects are evaluated.

Defining Interactions Between Stationary and Dynamic Features in Tidal Rivers

The SWFWMD's approach to evaluating estuarine responses to freshwater inflow has been based on a series of literature reviews, workshops, and field studies that have been conducted since the mid-1970s. Two years after being delegated the authority to manage consumptive water use, the SWFWMD sponsored a literature review of the role of freshwater inflow in estuarine systems (Snedaker et al. 1977) and a workshop on the relationships of freshwater inflow to the resources of the Florida coast (Seaman and McLean 1977). A few years later, the proceedings of a national symposium on freshwater inflow to estuaries (Cross and Williams 1981) produced many valuable papers, including one by Browder and Moore (1981), who suggested that fishery recruitment is maximized when there is optimal overlap between stationary and dynamic habitats (i.e., salinity). Stationary components of estuarine habitat include features associated with the geomorphological structure of an estuary plus biological features, such as oyster reefs and tidal wetlands, that change relatively slowly over periods of years. Dynamic components of estuarine habitat include characteristics that can change rapidly as a function of freshwater inflow, such as circulation patterns, turbidity maxima, salinity distributions, and dissolved oxygen concentrations. Biological processes that move within the estuary in response to freshwater inflow can also be considered part of the dynamic component of estuarine systems. The management strategies employed by the SWFWMD are oriented to the conceptual model of Browder and Moore (1981), as the withdrawal of freshwater can move dynamic components away from what are structurally the most productive regions of an estuary.

The stationary components of estuarine habitats have been characterized by mapping and quantifying the distribution of important physical features in tidal rivers such as estuarine volume, the area of deep and shallow habitats, shoreline length, and the area of contiguous wetlands. Salinity distributions are then superimposed over these features to derive the area or volume of habitats within various salinity zones (Peebles and Flannery 1992; Estevez and Marshall 1997; PBS&J 2001). The distribution and salinity relations of tidal wetlands have been emphasized due to the important functions these communities have with regard to habitat structure and the abundance of fish and wildlife associated with estuaries (Odum et al.

1984; Lewis et al. 1985; Coultas and Hsieh 1997). The Florida Marine Research Institute (1997, 1999) used aerial imagery to map the distribution of major wetland communities within tidal freshwater, brackish marsh, salt marsh, and mangrove zones in seven rivers for which salinity data were available. Clewell et al. (2002) investigated the relationships of salinity distributions to plant species composition at 462 shoreline sites in these tidal rivers.

Other investigations of relationships between largely stationary ecological features and freshwater inflow have involved the distribution of mollusk populations and macroinvertebrate communities associated with oyster reefs. Mote Marine Laboratory (2001a) compared the distribution of live and dead mollusk shells in the Peace River and found that as a severe drought progressed, living shells aligned with relict shell footprints, reflecting the effect of periodic droughts on mollusk distributions. Sprinkel (1986) sampled oyster reefs extending off the mouths of four spring-fed rivers and found that the largest oysters were at inshore reefs where mean salinity values were in the range of 11 to 16 psu. On these same rivers, Gorzelany (1986) found there was greater similarity (Morisita's index) among macroinvertebrate communities associated with inshore oyster reefs from different rivers than among communities from inshore, middle, and offshore reefs from the same river.

To address the dynamic component of estuarine systems, a series of studies of the salinity characteristics of tidal rivers in west-central Florida was initiated in the late 1970s, including several that developed regression models to predict the locations of various isohalines as a function of freshwater inflow. These studies indicated that isohalines respond to freshwater inflow in a largely linear manner in five spring-dominated rivers north of Tampa Bay (Yobbi and Knochemus 1989a,b), but respond in a curvilinear manner in seven rivers dominated by surface runoff located farther south (Giovannelli 1981; Stoker et al. 1989; Fernandez 1990; Hammett 1992; Peebles and Flannery 1992; Coastal Environmental 1996b; Estevez and Marshall 1997; Janicki Environmental 2001). The shape of the relationship between isohaline location and freshwater inflow for the Peace and Little Manatee Rivers is typical of this southern region, in that relatively small reductions in freshwater inflow during the dry season can result in dramatic upstream movement of isohalines (Fig. 3). This characteristic response is due to the funnel shape of these tidal rivers, in which the cross-sectional area and volume of the estuary increase rapidly with distance downstream.

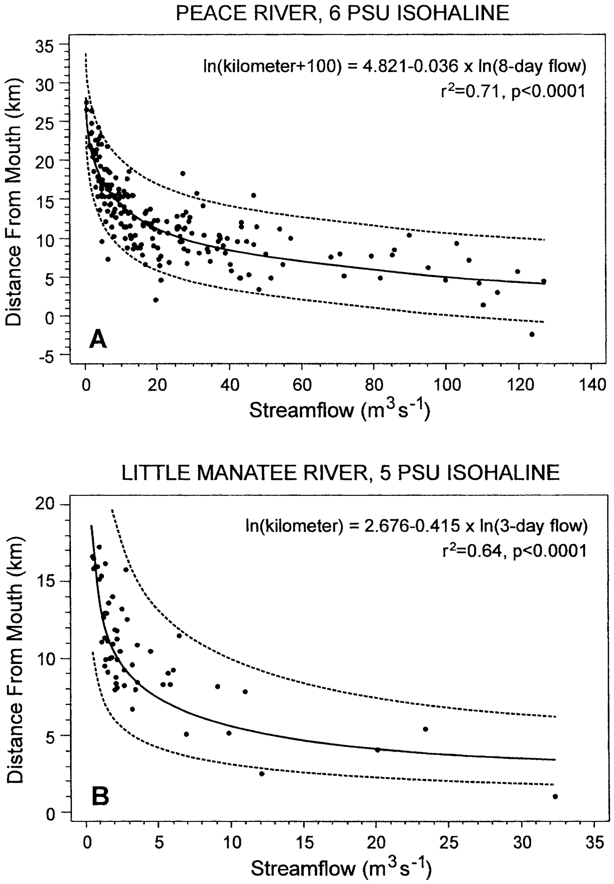

Fig. 3. Regressions of freshwater inflow with (A) the location of the 6 psu surface isohaline in the Peace River (adapted from Janicki Environmental 2001) and (B) the location of the 5 psu surface isohaline in the Little Manatee River (adapted from Peebles and Flannery 1992), with the 95% confidence limits for the predicted values. Regressions are plotted using non-transformed data.

The curvilinear response of isohaline locations to freshwater inflow was a principal finding used by SWFWMD to develop the percent-of-flow approach for managing withdrawals. Limiting withdrawals to a fixed percentage of streamflow results in relatively small isohaline movements (< 0.8 km) at low, medium, and high inflows (Table 1), preventing major changes to salinity distributions throughout the year. Although isohaline movements for a given percentage flow reduction may be slightly greater at low inflows, the reduction in water volume within a given salinity zone (e.g., < 5 psu) may be greater at higher inflows due to the isohalines being located in a broader region of the estuary. Since the percent-of-flow approach was first implemented, the SWFWMD has emphasized the development of hydrodynamic models to simulate salinity distributions in tidal river estuaries, including the Manatee (Camp, Dresser and McKee, Inc. 1995), Hillsborough (Chen et al. 2000),

TABLE 1. The locations and upstream movements of low-salinity surface isohalines in four rivers in response to 10% reductions of streamflow at flows equal to the 10th, 50th, and 90th percentile flows in the long-term streamflow records. Locations were predicted using regressions developed for the Peace (Janicki Environmental 2001), Myakka (Hammett 1992), Little Manatee (Peebles and Flannery 1992), and Anclote Rivers (Fernandez 1990).

River	Isohaline (psu)	Location + Upstream Movement (km from River Mouth)		
		10th Percentile	50th Percentile	90th Percentile
Peace	6	18.39 + 0.45	12.76 + 0.43	5.69 + 0.41
Myakka	0.5	33.95 + 0.55	21.64 + 0.35	16.18 + 0.26
Little Manatee	5	17.67 + 0.79	11.35 + 0.51	5.57 + 0.25
Anclote	5	14.37 + 0.18	12.47 + 0.18	7.54 + 0.18

Alafia (Chen 2001), and Palm (Myers et al. 2002) Rivers.

Primary Production as a Management Criterion

Phytoplankton populations are among a suite of parameters than can be considered to be dynamic habitat components, as their abundance and distribution can respond quickly to changes in freshwater inflow. To investigate the influence of freshwater inflow on abundance and distribution of phytoplankton, a suite of parameters including chlorophyll *a* (chl *a*) and phytoplankton species counts has been collected at four surface isohalines (0.2 or 0.5, 6, 12, and 18 or 20 psu) in the Peace, Little Manatee, and Alafia Rivers (Vargo et al. 1991; PBS&J 1999a; SWFWMD 2002b). With the exception of the Little Manatee, where chl *a* concentrations were highest near the boundary with tidal freshwater (0.5 psu), mean chlorophyll values were greatest and concentrations most variable at the 6 and 12 psu isohalines, whereas lower values typically occurred in higher salinity waters (Table 2).

The most extensive data for examining phytoplankton response to freshwater inflow are from the Peace River, where phytoplankton production (^{14}C uptake) and chl *a* have been monitored monthly since 1984, with taxonomic cell counts conducted since 1988 (PBS&J 1999a). McPherson et al. (1990) concluded that maximum phytoplankton production and biomass in the Peace River and Charlotte Harbor estuarine system occurs in mid-salinity zones, where freshwater inflow increases the availability of nutrients, but organic color of riverine origin is diluted, allowing for increased light penetration. There is also a positive response to water temperature and presumably photoperiod, as the highest monthly mean values for chl *a* tend to occur in warm waters with moderate amounts of color (PBS&J 1999a). Monthly mean chl *a* concentrations generally increase with water temperature from February through April, but decline or are relatively stable during May and June (Fig. 4). Freshwater inflow typically declines from April through mid-June, reducing nutrient delivery from the watershed. As inflow and nutrient loads increase during the summer rainy season, chl *a* values increase at the 6, 12, and 20 psu isohalines.

These data indicate that reductions of inflow and nutrient loading during the spring dry season could act to limit phytoplankton biomass in the tidal river. Because isohaline locations are sensitive to movement during periods of low inflow, reductions in freshwater inflow during the springtime could move areas of maximum phytoplankton abundance farther upstream with implications for secondary production. Depending on dry-season nutrient loads, increased residence times resulting from reductions in freshwater inflow could act to increase phytoplankton biomass in zones of a tidal river (Ingram et al. 1985; Vallino and Hopkinson 1998). Current SWFWMD efforts are directed toward better defining the roles of light penetration, nutrient loading, and residence time in controlling phytoplankton abundance in tidal rivers in the region, including the highly eutrophic Alafia.

Fish Nursery Use as a Management Criterion

An important component of the SWFWMD's management approach to tidal rivers has involved the response of zooplankton, benthic macroinver-

TABLE 2. Mean (± standard deviation) and number of surveys (n) for chlorophyll *a* concentrations (μg L^{-1}) at four surface isohalines in the Peace, Alafia, and Little Manatee Rivers. Values for the 0.2 and 20 psu isohalines in the Peace River are listed with the 0.5 and 18 psu isohalines, respectively (data from Vargo et al. 1991; PBS&J 2001; SWFWMD 2002b).

River	n	Isohaline (psu)			
		0.5	6	12	18
Peace	208	9.6 (11.2)	23.7 (27.4)	23.3 (32.5)	12.7 (18.8)
Alafia	24	13.1 (15.7)	78.7 (135.2)	106.0 (163.6)	47.2 (41.1)
Little Manatee	28	22.1 (14.9)	15.9 (8.6)	10.7 (8.4)	5.6 (2.0)

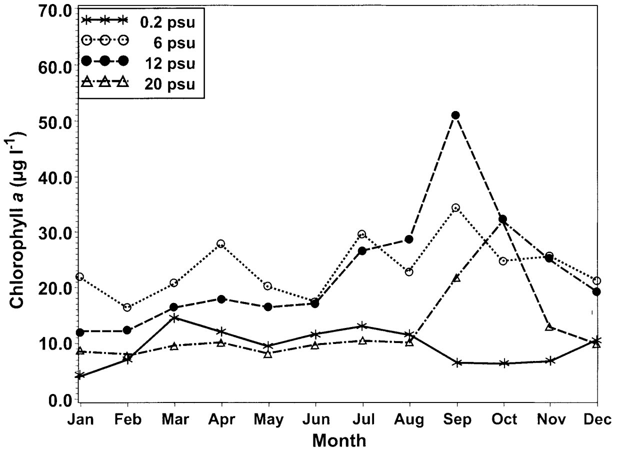

Fig. 4. Monthly mean concentrations of chlorophyll *a* at four surface isohalines in the lower Peace River for the period 1984–2000 (data from PBS&J 2001).

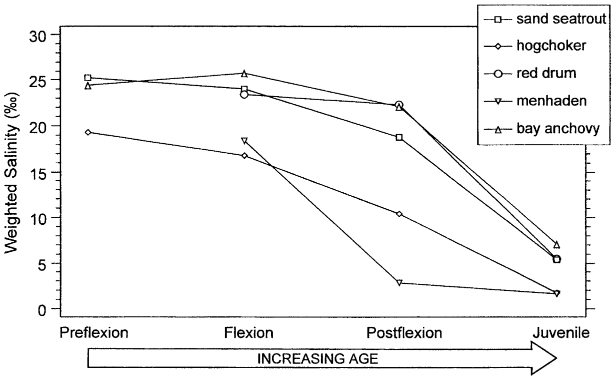

Fig. 5. Decreasing mean salinity at capture during fish development in the Little Manatee River. Preflexion, flexion, and postflexion are successive larval stages (Peebles and Flannery 1992).

tebrates, and fishes to freshwater inflow. These studies have been primarily directed toward young or short-lived organisms, particularly the estuarine-dependent fishes that use tidal rivers as juvenile nursery habitat and the prey organisms that these fishes depend on while occupying such habitats. Because tidal-river habitats are small and are directly affected by watershed runoff, the potential for an inflow-related influence on fish recruitment success would appear to be strong. Juvenile estuarine-dependent fishes are generally described as being seasonal migrants (Merriner et al. 1976; Peters and McMichael 1987; McMichael et al. 1989; Barry et al. 1996; Livingston 1997), which is a status that subjects them to inflow variations at subannual time scales.

Rast et al. (1991) found that most zooplankters have peak densities in the downstream, higher-salinity reaches of the Little Manatee River, making them abundantly available as prey for the early life stages of fishes that are spawned near the mouth of the river or migrate there from more seaward locations. Within the tidal river, larval fishes tend to be most abundant near this downstream zooplankton maximum (Peebles and Flannery 1992). As the larvae develop into juveniles, a number of species move into areas of reduced salinity in the interiors of the tidal rivers (Fig. 5). This estuarine-dependent life history pattern is associated with growth-related diet shifts, such as the shift from copepods and other zooplankton to bottom-dwelling organisms, notably mysids, amphipods, and deposit-feeding invertebrates in general (Peters and McMichael 1987; McMichael and Peters 1989; McMichael et al. 1989; Barry et al. 1996; Peebles 1996). Deposit-feeding invertebrates have been observed to be abundant within organically enriched regions of the upper estuary, both locally (Mote Marine Laboratory 2001a,b; Grabe et al. 2002) and elsewhere (McBee and Brehm 1982; Holland et al. 1987; Gaston and Nasci 1988).

Phytoplankton biomass is often maximal either within or immediately upstream of the organically enriched oligohaline and mesohaline areas that are used as juvenile fish nursery habitat (Table 2; Fig. 4). Some species, such as menhaden, appear to associate directly with the chlorophyll maximum in other estuaries (Hughes and Sherr 1983; Friedland et al. 1996). Although the estuarine-dependent pattern of habitat use would appear to increase food availability in many cases (Barry et al. 1996; Peebles 1996; Livingston 1997), various alternative explanations have also been proposed to explain this phenomenon, including benefits associated with reduced predator diversity, reduced predator access to shallow water, and increased structural complexity (Reis and Dean 1981; Weinstein and Brooks 1983; Miller et al. 1985; Day et al. 1989; Hoss and Thayer 1993). Regardless of the cause, the estuarine-dependent life history places the juvenile fishes and their prey within relatively small, semi-confined areas of tidal rivers that constitute focal points for watershed runoff.

The locations occupied by both the fishes and their prey shift upstream and downstream in apparent response to changes in freshwater inflow (Table 3; Fig. 6). This response has been observed in both planktonic forms and active swimmers. For estuarine-resident and estuarine-dependent organisms, movement upstream during low-inflow periods usually involves movement into river reaches that have reduced volumes (Peebles and Flannery 1992; Peebles 2002a,b), which raises the possibility that carrying capacities could also be reduced by low inflow.

The abundances of many estuarine-resident and

TABLE 3. Organism distribution (mean km weighted by CPUE) responses to same-day freshwater inflow ($\ln m^3 s^{-1}$) into the tidal Alafia River, ranked by linear regression slope (b). Other regression statistics are the number of monthly transects in which each taxon was encountered (n), intercept (a), slope probability (p), and fit (r^2, as %). DW identifies possible serial correlation (x indicates $p < 0.05$ for Durbin-Watson statistic). Gear codes: P = 500-µm mesh, 0.5-m mouth plankton net deployed surface to bottom over about 400 m of channel length during nighttime flood tide, S = 21.3-m center-bag seine with 3.2-mm mesh deployed at shoreline during day under variable tide stage, T = 6.1-m otter trawl, 38-mm stretched mesh and 3.2-mm liner, deployed over about 180 m of channel bottom during day under variable tide stage (adapted from Peebles 2002a).

Gear	Taxon	Common Name	n	a	b	p	r^2	DW
S	*Gobiosoma bosc*	naked goby	18	5.22	1.57	0.0275	27	
P	calanoids	copepods	21	−0.05	−0.31	0.0224	25	x
P	all dipteran larvae	flies, mosquitoes	26	11.33	−0.45	0.0384	17	
P	*Anchoa* spp. flexion larvae	anchovies	20	1.36	−0.62	0.0333	23	
P	dipterans, chironomid larvae	midges	26	11.56	−0.64	0.0060	27	
P	odonates, zygopteran larvae	damselflies	12	13.11	−0.64	0.0438	35	
P	*Anchoa* spp. preflexion larvae	anchovies	19	1.42	−0.65	0.0440	22	
S	*Achirus lineatus*	lined sole	20	2.95	−0.67	0.0333	23	
S	*Fundulus seminolis*	Seminole killifish	21	12.58	−0.68	0.0020	40	
P	trichopteran larvae	caddisflies	17	13.71	−0.69	0.0389	25	
T	*Farfantepenaeus duorarum*	pink shrimp	21	3.97	−0.76	0.0245	24	
P	*Lucifer faxoni*	shrimp	25	1.81	−0.80	0.0121	24	x
T	*Callinectes sapidus*	blue crab	23	4.70	−0.84	0.0146	25	x
S	*Oligoplites saurus*	leather jack	15	4.78	−0.89	0.0501	26	
S	*Eucinostomus gula*	silver jenny	20	2.57	−0.92	0.0104	31	
S	*Cynoscion nebulosus*	spotted seatrout	16	3.34	−0.93	0.0189	33	x
T	*Menticirrhus americanus*	southern kingfish	19	3.64	−0.96	0.0028	42	
P	*Erichsonella attenuata*	isopod	12	2.91	−1.01	0.0092	51	
P	copepods, freshwater cyclopoids	copepods	14	13.65	−1.02	0.0122	42	
P	cumaceans	cumaceans	26	2.94	−1.05	0.0002	44	x
P	*Anchoa mitchilli* adults	bay anchovy	26	5.36	−1.07	0.0050	28	x
P	cladocerans, daphniid	water fleas	11	14.14	−1.09	0.0071	57	
T	*Cynoscion arenarius*	sand seatrout	20	6.07	−1.10	0.0190	27	
P	*Anchoa mitchilli* juveniles	bay anchovy	26	8.00	−1.13	0.0005	40	
S	*Farfantepenaeus duorarum*	pink shrimp	23	4.38	−1.14	0.0091	28	x
P	coleopterans, elmid adults	riffle beetles	18	13.47	−1.18	0.0469	22	x
P	gobiid preflexion larvae	gobies	16	5.44	−1.21	0.0243	31	
P	*Anchoa mitchilli* postflexion larvae	bay anchovy	18	3.78	−1.21	0.0103	35	
P	decapod zoeae	crab larvae	26	3.91	−1.23	0.0261	19	x
P	mysids	opossum shrimp	26	5.85	−1.23	0.0120	24	
P	polychaetes	worms	26	7.93	−1.25	0.0006	39	
P	hydracarina	water mites	20	13.98	−1.26	0.0002	54	
S	*Cynoscion arenarius*	sand seatrout	14	5.45	−1.33	0.0082	45	x
S	*Symphurus plagiusa*	blackcheek tonguefish	14	4.42	−1.34	0.0408	30	
S	*Callinectes sapidus*	blue crab	20	5.29	−1.36	0.0012	45	
P	branchiurans, *Argulus* spp.	fish lice	18	10.55	−1.41	0.0065	38	
S	*Synodus foetens*	inshore lizardfish	12	3.36	−1.52	0.0036	59	
P	*Limulus polyphemus* larvae	horseshoe crab	13	3.93	−1.52	0.0260	38	
P	*Cynoscion arenarius* juveniles	sand seatrout	14	7.04	−1.56	0.0036	52	
S	*Membras martinica*	rough silverside	12	4.75	−1.57	0.0040	58	
P	*Microgobius* spp. postflexion larvae	gobies	18	4.70	−1.60	0.0098	35	
S	*Menidia* spp.	silversides	23	9.36	−1.65	0.0031	35	
S	*Menticirrhus americanus*	southern kingfish	17	5.01	−1.70	0.0025	47	
P	*Edotea triloba*	isopod	25	8.08	−1.75	0.0000	59	
P	isopods (grouped)	isopods	26	7.92	−1.76	0.0000	57	
P	cymothoid sp. a (*Lironeca*)	isopod	26	7.79	−1.80	0.0000	53	
P	*Gobiosoma* spp. postflexion larvae	gobies	20	6.72	−1.87	0.0234	25	
S	*Cyprinodon variegatus*	sheepshead minnow	14	7.26	−1.94	0.0129	41	x
P	*Trinectes maculatus* juveniles	hogchoker	19	9.89	−2.04	0.0024	43	
P	*Trinectes maculatus* postflexion	hogchoker	18	8.66	−2.11	0.0002	60	
P	*Syngnathus louisianae* juveniles	chain pipefish	10	5.76	−2.16	0.0235	49	x
P	*Trinectes maculatus* flexion larvae	hogchoker	12	6.85	−2.36	0.0141	47	
S	*Brevoortia* spp.	menhaden	10	10.42	−3.49	0.0034	68	

young estuarine-dependent species appear to decline during low-inflow periods (Figs. 7 and 8; Table 4). This trend could raise concern over calculation artifacts because river-segment volume is strongly influential in the calculation of total number and organisms typically move downstream into regions with larger volume-weighting factors during high inflow periods. For many taxa in Table 4,

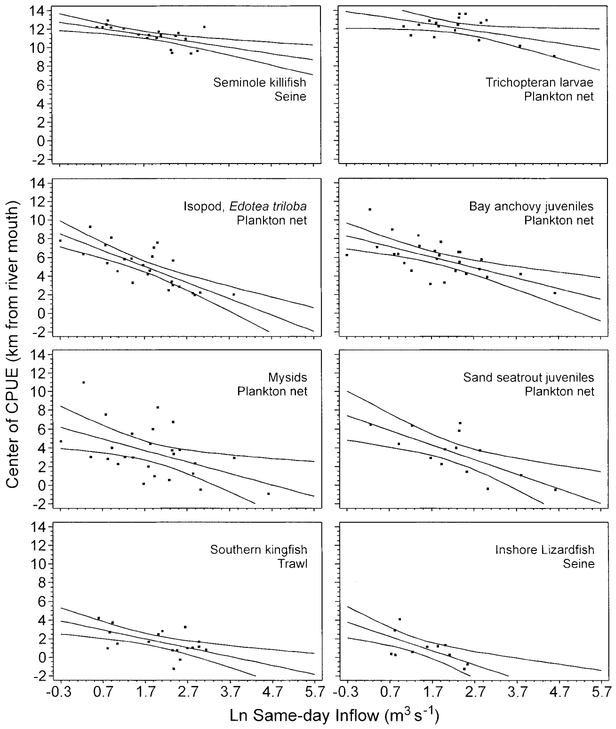

Fig. 6. Regressions of organism distribution against freshwater inflow into the tidal Alafia River, with 95% confidence limits for predicted means. Center of catch per unit effort (CPUE) is the mean location of capture during monthly transects, with the mean being weighted by CPUE. During each transect, the seine and plankton net were deployed at 12 stations and trawls were deployed at four stations. CPUE is either the number per deployment for seines and trawls or the number per volume filtered by the plankton net. Regression statistics are presented in Table 3 (adapted from Peebles 2002a).

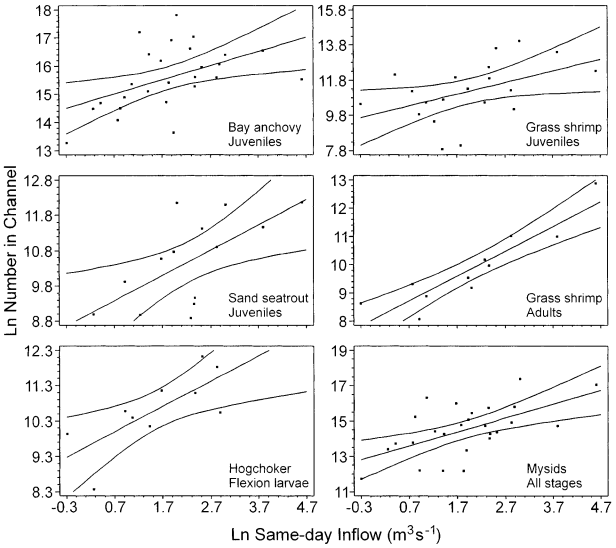

Fig. 7. Regressions of organism number against freshwater inflow into the tidal Alafia River, with 95% confidence limits for predicted means. Number was calculated for each monthly transect by summing the products of mean organism density (ind m^{-3}) and a volume weighting factor (m^3) for six contiguous river segments. All data are from plankton net deployments, which were made at 12 stations per transect. Regression statistics are presented in Table 4 (adapted from Peebles 2002a).

the positive inflow relationship also exists when total catch is used (no volume-weighting factor), suggesting that the response is not merely a calculation artifact. For other taxa, the relationship is also likely to be real, as the approach for estimating total number is conceptually robust. It should be kept in mind that the number estimated is actually the number of individuals that are vulnerable to the collection gear within the channel's water column, and this number may be affected by influx from the shoreline, bottom, or downstream directions. The relationships in Fig. 7 represent the ascending limb of a broader response curve; very high flows could decrease abundance in the tidal river.

Other studies (e.g., Jassby et al. 1995; Kimmerer et al. 2001) have documented abundance responses to inflow-related variables by comparing annual averages, which would tend to eliminate the influence of recruitment seasonality and would strongly reduce the effects of short-term time lags in the response. Figures 7 and 8 indicate that abundance responses can also be identified within sub-annual time intervals for a variety of organisms, and often without any indication of serial correlation (Table 4). Several factors encourage synchrony between the inflow and abundance observations. Because the regressions are based on plankton-net data, most of the animals in the analysis are short-lived species. Longer-lived fish and crustacean species

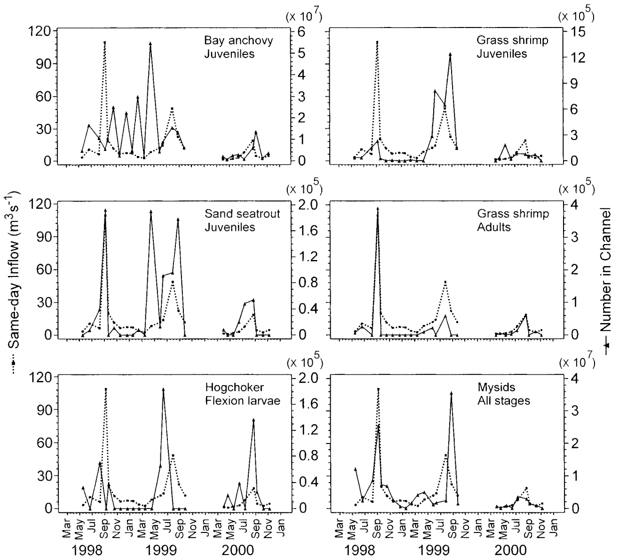

Fig. 8. Time series of the data in Fig. 7.

TABLE 4. Response of total estimated number (ln number of individuals) to same-day freshwater inflow (ln $m^3 s^{-1}$) into the tidal Alafia River, ranked by linear regression slope (b). Other regression statistics are the number of monthly transects in which each taxon was encountered (n), intercept (a), slope probability (p), and fit (r^2, as %). DW identifies possible serial correlation (x indicates $p < 0.05$ for Durbin-Watson statistic). Total number was estimated by summing the products of mean plankton-net density (individuals m^{-3}) and water-level-corrected volume across 6 contiguous river segments (adapted from Peebles 2002a).

Taxon	Common Name	n	a	b	p	r^2	DW
dipteran, *Chaoborus punctipennis*	phantom midge	16	7.47	1.43	0.0058	43	
pinnotherid juveniles	pea crabs	18	11.50	1.40	0.0035	42	
crabs (grouped)	crabs	24	10.90	1.32	0.0049	31	
freshwater cyclopoids	copepods	14	7.50	1.31	0.0000	78	
ephemeropterans	mayflies	22	7.94	1.10	0.0001	56	
Palaemonetes pugio adults	daggerblade grass shrimp	11	8.06	0.88	0.0001	83	
coleopterans, dytiscid adults	predaceous diving beetles	13	7.30	0.88	0.0064	51	
mysids	opossum shrimps	26	13.01	0.79	0.0016	35	
Cynoscion arenarius juveniles	sand seatrout	14	8.85	0.72	0.0131	41	
Trinectes maculatus flexion	hogchoker	10	9.46	0.72	0.0139	55	
Palaemonetes pugio juveniles	daggerblade grass shrimp	20	9.84	0.66	0.0375	22	x
dipterans, pupae	flies, mosquitoes	25	10.07	0.63	0.0092	26	x
coleopterans (grouped)	beetles	21	8.72	0.57	0.0053	34	
Anchoa mitchilli juveniles	bay anchovy	26	14.63	0.51	0.0114	24	
dipterans (grouped)	flies, mosquitoes	26	10.98	0.42	0.0064	27	x
alphaeid postlarvae	snapping shrimps	14	13.35	−0.41	0.0386	31	x
Lolliguncula brevis juveniles	bay squid	13	11.49	−0.49	0.0458	32	
cymothoid sp. a (*Lironeca*)	isopods	26	16.03	−0.53	0.0079	26	x
isopods (grouped)	isopods	26	15.73	−0.58	0.0069	27	x
gobiid preflexion larvae	gobies	15	13.00	−0.66	0.0051	46	
gobiid flexion larvae	gobies	17	11.90	−0.91	0.0129	35	
calanoids	copepods	21	19.47	−1.15	0.0219	25	

were partitioned into shorter developmental stages before analysis and abundance was assessed independently for each stage. For such species, the rate of passage though various larval stages is fast relative to the monthly sampling frequency. Even for the potentially long-lived juvenile stages of larger species (e.g., *Cynoscion arenarius*), a combination of gear avoidance and natural mortality (larger individuals becoming rare) dramatically abbreviated the age range observed in the plankton-net data.

Most of the abundance regressions remained significant when inflows from the previous month's collection dates were used, indicating that the response is not as spontaneous as Figs. 7 and 8 might imply. In the relationships illustrated by these figures, significance was generally lost when a 2-mo lag was used, which suggests that the relationships with inflow had durations of less than 2 mo. Explanations for the decreased abundance include reductions in reproductive effort (Peebles 2002c) and survival rates during low-inflow periods.

From a management perspective, the shape of the abundance response curves can be used to identify inflow ranges that have proportionately large influences on abundance. The non-transformed data represented by the regression statistics in Table 4 are described by the power function $y = ax^b$, which is differentiated as $dy/dx = abx^{(b-1)}$. The value of the slope determines the shape of the non-transformed abundance response to variations in inflow. Organisms with slopes < 0 undergo proportionately large decreases in number as low-end inflows increase. This is characteristic of animals that often occupy the higher salinities near the river mouth. Members of the second group, which includes freshwater, estuarine-resident, and estuarine-dependent taxa, have slopes between 0 and 1 and undergo proportionately large increases in number as low-end inflows increase, although the abundance increase becomes more constant for organisms with slopes near 1. Members of the third group, which is primarily composed of freshwater organisms, are characterized by slopes > 1. Freshwater taxa may either wash into the tidal river at a fairly constant rate (e.g., ephemeropteran larvae in Table 4) or, at even larger slopes, increase dramatically in number during floods (freshwater cyclopoids and *Chaoborus punctipennis*). Floods may also cause burrowing marine-derived animals (e.g., the pinnotherid crab *Pinnixa sayana*) to emerge from their burrows in large numbers, producing a very similar pattern.

Because most estuarine-resident and estuarine-dependent taxa tend to have a group-2 response (proportionately large increases in number at the low end of the inflow range), protection of low inflows becomes important. By scaling withdrawals to the concurrent rate of streamflow, the percent-of-flow approach provides a general safeguard against dramatic changes in organism abundance that could result from large withdrawals during periods of low freshwater inflow.

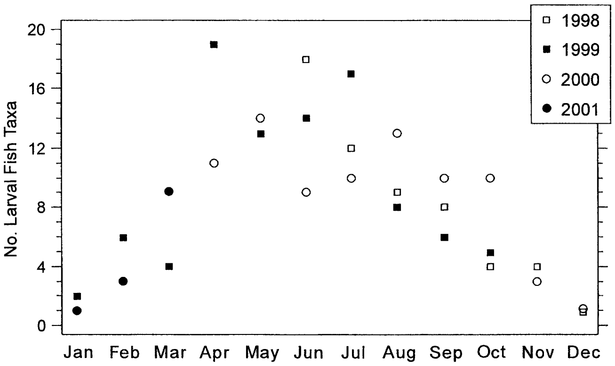

Fig. 9. The seasonal distribution of approximate larval richness in the tidal Alafia River (data from Peebles 2002a).

Most estuarine-dependent fishes have been found to exhibit very regular seasonality in their use of low-salinity habitats, further emphasizing the importance of a seasonal component to inflow management. The spawning-season durations of individual species range from a few months to year-round. Those with shorter seasons generally demonstrate regular seasonality in their spawning. It is interesting that spawning seasons and overall trends in larval taxonomic richness do not conform to the local seasonal rainfall pattern, which can be very different from the pattern in other parts of these species' ranges. Richness is very high during April and May (Fig. 9), which are among the driest months of the year (Fig. 2), and does not change appreciably during the transition to the summer wet season. Richness starts to decline in August and gradually reaches its minimum during December and January. This pattern has been observed repeatedly at various locations since 1988.

The potential for a strong influx of juvenile estuarine-dependent fishes into low-salinity nursery habitats is very high during the spring dry season, making management of freshwater inflow particularly sensitive during that time of year. Although the seasonal pattern of larval richness in Fig. 9 suggests that this sensitivity may diminish during winter, many of the spring and summer larval migrants are still present during winter as older juveniles. There is no season when inflow management becomes less relevant to low-salinity nursery use, although spring appears to be a particularly sensitive season. Any limiting effects associated with the naturally low springtime inflows could be amplified by relatively small freshwater withdrawals.

Applications to the Management of Freshwater Withdrawals

In the late 1980s, the SWFWMD first began to implement a management approach of limiting withdrawals from rivers to a percentage of streamflow at the time of withdrawal. The goals of this approach were to make withdrawals mimic the temporal characteristics of the flow regimes of the streams used for water supply and to protect the estuaries from the effects of large freshwater withdrawals during the ecologically vulnerable dry season. Findings initially used to support the approach included the curvilinear response of isohaline locations to freshwater inflow (Flannery 1989) and the influence of inflow on the location of the center of catch per unit effort (CPUE) for a number of key organisms, a relationship that was first documented in the Little Manatee River (Peebles and Flannery 1992). Studies of the Lower Peace River and Charlotte Harbor estuarine system also demonstrated that the response of residence time to freshwater inflow in that system is strongly curvilinear (Stoker et al. 1989; Miller and McPherson 1991). Reduction of freshwater inflow of a fixed quantity would result in a much greater increase in residence time during periods of low inflow, with possible negative effects on water quality.

The percent-of-flow approach was first applied to the Peace River, where withdrawals for public water supplies began in 1980. The Peace River is not impounded and withdrawals from the river are either pumped directly to the customers after treatment or are stored in an offstream reservoir or the groundwater system using aquifer storage and recovery facilities. Prior to 1989, withdrawals from the Peace River were regulated by the SWFWMD in a manner similar to a groundwater withdrawal, with limitations on maximum-daily and yearly average withdrawal rates. Maximum-daily withdrawals could be taken when flows in the river were above minimum flow rates that were specified for each month. Given this regulatory schedule, withdrawals could take up to 25% of streamflow on low-flow days during the dry season. Based on recommendations of ecologists from both the water supply utility and SWFWMD, the withdrawal schedule was changed in 1989 so that withdrawals could not exceed 10% of the average streamflow from the preceding day as measured at an upstream gauge.

The percent-of-flow approach was also recently applied to allocated withdrawals from the Alafia River, from which withdrawals are scheduled to begin in 2003. These withdrawals by the water supply utility cannot exceed 10% of the streamflow from the preceding day as measured at the intake site, and withdrawals in excess of immediate customer needs will be stored in an offstream reservoir. Withdrawals for cooling water for an electrical power plant have been diverted to an offstream reservoir from the Little Manatee River since 1975. These withdrawals have been regulated as a percentage of streamflow at the time of withdrawal, but at higher percentage rates than allowed for the

Peace or Alafia Rivers (up to 47% on some days during high flows). This power plant has been operating at approximately one-third of capacity since its construction and withdrawals from the Little Manatee River have been relatively infrequent (28% of days) and well below the allocated percentage quantities. In a recent application to convert the power plant from fuel oil to natural gas and increase power production, the utility has requested that the diversion limit be reduced to 10% of the daily flow at the intake site in anticipation of more frequent, but smaller, withdrawals (Florida Power and Light 2002). Findings to support this change in the diversion limit included simulations of changes in salinity distributions and movements of the locations of the center of CPUE for key organisms in the Little Manatee River.

Application of the percent-of-flow approach to these unimpounded rivers has included the use of low-flow cutoffs, or rates of streamflow below which no withdrawals are allowed. These low-flow cutoffs correspond to the long-term 13th percentile flow on the Peace, the 21st percentile flow on the Alafia, and the 36th percentile flow on the Little Manatee. Criteria for determining these low-flow cutoffs have varied, but are generally based on inflections in the response of key variables to freshwater inflow. Data for the Peace River indicate that salinity distributions in the upper estuary are especially sensitive to reductions in freshwater inflow below the low-flow cutoff of 3.7 $m^3 s^{-1}$. During droughts, streamflow in these rivers can be below their low-flow cutoffs for several consecutive months, during which time water supplies must come entirely from storage.

During high flows, the capacities of the diversion structures on these rivers do not allow the utilities to take their full percentage quantities. The effect of regulated percentage withdrawals, including the range of flows over which a full 10% of flow can be diverted, is shown for the Peace River during a typical year (Fig. 10). Due to these regulatory and physical constraints, seasonal and annual reductions in streamflow that result from the percent-of-flow approach are often considerably less than the percent daily limit. Since the streamflow gauges used to calculate the percentage withdrawals do not account for freshwater inflow below the gauging sites, percent reductions of total inflows to the tidal rivers are even less. The drainage areas for the gauges used to calculate percent daily withdrawal limits on the three rivers range from 58% of the total river basin for the Peace River to 91% of the total river basin for the Alafia. Current efforts are directed to modeling the ungauged streamflow in these river basins, so that the actual percentage flow reductions to the tidal rivers can be more closely quantified (Tara et al. 2001).

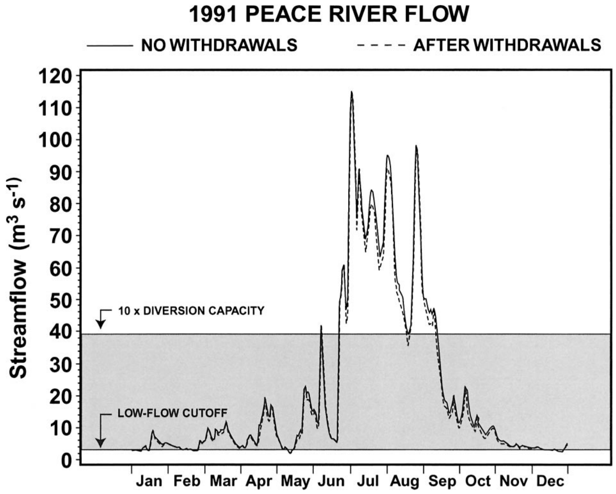

Fig. 10. Daily streamflow values for the Peace River during 1991 (U.S. Geological Survey gauge 02296750), with and without maximum possible withdrawals calculated using the 10% of flow daily limit, combined with a low-flow cutoff of 3.7 $m^3 s^{-1}$ and a diversion capacity of 3.9 $m^3 s^{-1}$. The shaded area represents the range of flows over which a full 10% of streamflow can be diverted.

Ongoing Refinements to the Percent-of-flow Approach

The natural flow regimes of unimpounded rivers and their documented ecological responses provide important information on when estuarine resources are most vulnerable to the effects of reductions in freshwater inflow. Withdrawal quantities that can result in ecological impacts may be markedly smaller during some seasons than others. The findings from southwest Florida estuaries indicate that reductions of freshwater inflow should be most limited during the spring. Historically, the withdrawal of water from rivers has not accounted for the seasonal needs of downstream ecosystems. Rozengurt and Hedgpeth (1989) reported a 12% reduction in the estimated mean annual runoff to the Lower Volga-Caspian Sea ecosystem, but reductions in springtime flows had decreased by as much as 37%. Similarly, water use in southwest Florida also typically peaks during the spring dry season due to increased domestic and agricultural irrigation (SWFWMD 2001a), and percent flow reductions in the region's impounded rivers are greatest during that time of year. The adoption of minimum flow releases that can account for seasonal variations have been scheduled for these impounded rivers (SWFWMD 2002a). It is expected that all new surface water withdrawals in the region will come from unimpounded rivers, for which the

SWFWMD has endorsed the percent-of-flow approach (SWFWMD 1992, 2001b). With the exception of the Little Manatee River, applications of the percent-of-flow approach have used the same percentage rate throughout the year. Current SWFWMD efforts are directed toward evaluating percentage withdrawal limits on a seasonal basis to better account for seasonality in the life histories of various organisms.

The evaluation of potential freshwater withdrawals should also account for the frequent nonlinear response of key estuarine characteristics to freshwater inflow. Changes in residence times, isohaline locations, and salinity at different locations in an estuary can be much greater for a given volume of freshwater withdrawal if it occurs during periods of low freshwater inflow (Miller and McPherson 1991; Uncles and Stephens 1993; Sklar and Browder 1998; Vallino and Hopkinson 1998). The relationships presented herein indicate there can often be a larger decrease in organism numbers if withdrawals of a given quantity are made during low freshwater inflows. A goal of the percent-of-flow approach is to adjust for such nonlinear relationships by scaling withdrawals to the rate of freshwater inflow. The SWFWMD is investigating sliding withdrawal percentages that differ among flow ranges based on changes in the responsiveness of the estuarine variables of concern. In cases where increasing freshwater inflows exacerbate a problem condition such as hypoxia (e.g., Breitburg 2002), percentage withdrawal limits can be adjusted to account for such processes. If high flows cause dispersion of estuarine-dependent organisms away from productive zones of an estuary (e.g., Peebles et al. 1996; Peebles 2002c), this can be factored into the withdrawal management strategy.

Although the percent-of-flow approach uses the flow regime of the contributing river as the basis for determining withdrawals, it is the inflow relationships of the living resources in the estuary that are the final determinant of percentage withdrawal limits. The ambient flow record (without any withdrawals) is used to assess the spatial and seasonal variation of physico-chemical and biological variables within the estuary that are related to freshwater inflow. Percentage withdrawals can then be applied to evaluate responses in the estuary under a range of inflow conditions. For those variables in the estuary that can be modeled, values can be simulated in order to compare the effects of different withdrawal scenarios to the ambient flow record (PBS&J 1998, 2001; Janicki Environmental 2001).

Development of the percent-of flow approach has largely emphasized tidal rivers because most oligohaline and mesohaline zones and nursery habitats in southwest Florida estuaries are located upstream of the tributary mouths. The withdrawal quantities that have been evaluated for unimpounded rivers using the percent-of-flow approach have been relatively small. We have assumed that the physico-chemical effects of these withdrawals and their related biological responses are most strongly manifest within the tidal rivers, due to their small water volumes relative to the open bays. This assumption is periodically reviewed and as the pressure for larger withdrawals increases, the strategy of examining more far-field effects will be increasingly employed.

The percent-of-flow approach lends itself to the process of adaptive management, in which continued data collection can be used to refine management strategies as the body of information expands over time. The SWFWMD requires the monitoring of hydrologic and ecological variables for permits for large surface-water or groundwater withdrawals. At present, extensive monitoring programs are required for withdrawals from both the Peace and Alafia Rivers (PBS&J 1999b, 2001). The findings of these programs can be used to modify percentage withdrawal schedules to better manage the resource, as the findings from the Peace River monitoring program were used to develop the percent-of-flow concept in 1989.

In addition to issuing individual water use permits, the SWFWMD must also establish minimum flow and level rules for flowing water courses which are defined in Florida Statutes (Chapter 373.042) as ''the limit at which further withdrawals would be significantly harmful to the water resources or ecology of the area.'' Minimum flows and levels address not only existing withdrawals, but also the potential effects of future withdrawals and are important for water supply planning. The adoption of minimum flows and levels for the Peace and Alafia rivers could develop percentage withdrawal limits that differ from the 10% regulations currently in effect. The determination of significant harm in the minimum flow and level process rests with Governing Board of the SWFWMD, who are appointed by the Governor of the State of Florida. The role of ecologists is to identify those ecological features, processes, and organisms that can be affected by reductions in freshwater inflow and to develop quantifiable relationships among these variables so that policy makers can determine how much ecological change is to be allowed. The SWFWMD is applying the percent-of-flow approach to evaluate alterations of natural streamflow regimes and to determine how much water may be available for supply without causing adverse impacts to estuarine resources.

Literature Cited

Barry, J. P., M. M. Yoklavich, G. M. Caillet, D. A. Ambrose, and B. S. Antrim. 1996. Trophic ecology of the dominant fishes in Elkhorn Slough, California, 1974–1980. *Estuaries* 19: 115–138.

Bidlake, W. R. and P. F. Boetcher. 1997. Near-surface water balance of an undeveloped upland site in west-central Florida. Water Supply Paper No. 2452. U.S. Geological Survey, Denver, Colorado.

Breitburg, D. 2002. Effects of hypoxia, and the balance between hypoxia and enrichment, on coastal fishes and fisheries. *Estuaries* 25:767–781.

Browder, J. A. 1985. Relationship between pink shrimp production on the Tortugas grounds and water flow patterns in the Florida Everglades. *Bulletin of Marine Science* 37:839–856.

Browder, J. A. and D. Moore. 1981. A new approach to determining the quantitative relationship between fishery production and the flow of fresh water to estuaries, p. 403–430. *In* R. Cross and D. Williams (eds.). Proceedings of a National Symposium on Freshwater Inflow to Estuaries. Report FWS/OBS-81/04. U.S. Fish and Wildlife Service, Office of Biological Services, Washington, D.C.

Camp, Dresser, and McKee, Inc. 1995. Freshwater releases from Lake Manatee—Effects on Manatee River salinity and future water supply. Report prepared for the Manatee County Public Service Department, Bradenton, Florida.

Chen, X. C., M. S. Flannery, and D. L. Moore. 2000. Response times of salinity in relation to changes in freshwater inflows in the Lower Hillsborough River, Florida. *Estuaries* 23:735–742.

Clewell, A. F., M. S. Flannery, S. S. Janicki, R. D. Eisenwerth, and R. T. Montgomery. 2002. An analysis of vegetation-salinity relationships in seven tidal rivers on the coast of west-central Florida. Technical Report. Southwest Florida Water Management District, Brooksville, Florida.

Coastal Environmental, Inc. 1996a. Review and analyses of meteorological, tributary flow, and water quality data from the Charlotte Harbor estuarine system. Report prepared for the Southwest Florida Water Management District, Brooksville, Florida.

Coastal Environmental, Inc. 1996b. Living resource-based freshwater inflow and salinity targets for the tidal Peace River. Report prepared for the Southwest Florida Water Management District, Brooksville, Florida.

Collier, M. C., R. H. Webb, and J. C. Schmidt. 1996. Dams and rivers: A primer on the downstream effects of dams. Circular 1126. U.S. Geological Survey, Tucson, Arizona.

Coultas, C. L. and Y. P. Hsieh (eds.). 1997. Ecology and Management of Tidal Marshes: A Model for the Gulf of Mexico. St. Lucie Press, Delray Beach, Florida.

Cross, R. and D. Williams (eds.). 1981. Proceedings of the National Symposium on Freshwater Inflow to Estuaries. Report FWS/OBS-81/04. U.S. Fish and Wildlife Service, Office of Biological Services, Washington, D.C.

Day, Jr., J. W., C. A. S. Hall, W. M. Kemp, and A. Yáñez-Arancibia. 1989. Estuarine Ecology. John Wiley and Sons, New York.

Day, Jr., J. W., J. F. Martin, L. Cardoch, and P. H. Templet. 1997. System functioning as a basis for sustainable management of deltaic ecosystems. *Coastal Management* 25:115–153.

Drinkwater, K. F. 1986. On the role of freshwater outflow on coastal marine ecosystems—A workshop summary, p. 429–438. *In* S. Skreslet (ed.). The Role of Freshwater Outflow in Coastal Marine Ecosystems. Springer-Verlag, Berlin, Germany.

Estevez, E. D., L. K. Dixon, and M. S. Flannery. 1991. West-coastal rivers of peninsular Florida, p. 187–221. *In* R. J. Livingston (ed.). Rivers of Florida. Ecological Studies No. 83. Springer-Verlag, New York.

Estevez, E. D. and M. J. Marshall. 1997. A landscape-level method to assess estuarine impacts of freshwater inflow alterations, p. 217–236. *In* S. F. Treat (ed.). Proceedings: Tampa Bay Scientific Information Symposium 3. Tampa Bay Regional Planning Council, Clearwater, Florida.

Fernald, E. A. and E. D. Purdum (eds.). 1998. Water Resources Atlas of Florida. Institute of Science and Public Affairs, Florida State University, Tallahassee, Florida.

Fernandez, Jr., M. 1990. Surface-water hydrology and salinity of the Anclote River estuary, Florida. Water Resources Investigations Report 84-4301. U.S. Geological Survey, Tallahassee, Florida.

FISRWG. 1998. Stream corridor restoration: Principles, processes, and practices. Report of the Federal Interagency Stream Restoration Working Group (FISRWG), Item No. 0120-A; SuDocs No. A 57.6/2:EN 3/PT.653. ISBN-0-934213-59-3, U.S. General Printing Office, Washington D.C.

Flannery, M. S. 1989. Part II rule revision: Potential impacts to streams and estuaries. Technical memorandum. Southwest Florida Water Management District, Brooksville, Florida.

Flannery, M. S. and M. D. Barcelo. 1998. Spatial and temporal patterns of streamflow trends in the Upper Charlotte Harbor watershed, p. 63–71. *In* S. F. Treat (ed.). Proceedings of the Charlotte Harbor Public Conference and Technical Symposium. Technical Report 98-02. Charlotte Harbor National Estuary Program, Ft. Myers, Florida.

Flannery, M. S., H. D. Downing, G. A. McGarry, and M. O. Walters. 1991. Increased nutrient loading and baseflow supplementation in the Little Manatee River watershed, p. 369–395. *In* S. A. Treat and P. A. Clark (eds.). Tampa Bay Area Scientific Information Symposium 2. Tampa Bay Regional Planning Council, Clearwater, Florida.

Florida Marine Research Institute. 1997. Development of GIS-based vegetation maps for the tidal reaches of five gulf coast rivers. Report prepared by the Florida Department of Environmental Protection for the Southwest Florida Water Management District, Brooksville, Florida.

Florida Marine Research Institute. 1999. Development of GIS-based maps to determine the status and trends of oligohaline vegetation in the tidal Peace and Myakka Rivers. Report prepared by the Florida Department of Environmental Protection for the Southwest Florida Water Management District, Brooksville, Florida.

Florida Power and Light. 2002. Site certification application for the Manatee expansion project. Report submitted to the Florida Department of Environmental Protection. Florida Power and Light Company, Juno Beach, Florida.

Friedland, K. D., D. W. Ahrenholz, and J. F. Guthrie. 1996. Formation and seasonal evolution of Atlantic menhaden juvenile nurseries in coastal estuaries. *Estuaries* 19:105–114.

Gaston, G. R. and J. C. Nasci. 1988. Trophic structure of macrobenthic communities in the Calcasieu estuary, Louisiana. *Estuaries* 11:201–211.

Giovannelli, R. F. 1981. Relations between freshwater flow and salinity distributions in the Alafia River, Bullfrog Creek, and Hillsborough Bay, Florida. Water Resources Investigation Report 80-102. U.S. Geological Survey, Tallahassee, Florida.

Gorzelany, J. 1986. Oyster associated fauna, Volume IV: A data collection program for selected coastal estuaries in Hernando, Citrus, and Levy counties, Florida. Report prepared by Mote Marine Laboratory for the Southwest Florida Water Management District. Brooksville, Florida.

Grabe S. A., D. J. Karlen, L. Guitierrez-Antrim, C. M. Holden, and B. Goetting. 2002. Benthic habitat status of the lower Hillsborough, Palm, Alafia, and Little Manatee Rivers: 1995–2000. Report prepared by the Environmental Protection Commission of Hillsborough County for the Southwest Florida Water Management District, Brooksville, Florida.

Hammett, K. M. 1990. Land use, water use, and streamflow characteristics of the Charlotte Harbor inflow area, Florida.

Water Supply Paper No. 2359. U.S. Geological Survey, Tallahassee, Florida.

HAMMETT, K. M. 1992. Physical processes, salinity characteristics, and potential salinity changes due to freshwater withdrawals in the tidal Myakka River, Florida. Water Resources Investigations Report 90-4054. U.S. Geological Survey, Tallahassee, Florida.

HILL, M. T., W. S. PLATTS, AND R. L. BESCHTA. 1991. Ecological and geomorphological concepts for instream and out-of-channel flow requirements. *Rivers* 2:198–210.

HOLLAND, A. F., A. T. SHAUGHNESSY, AND M. H. HIEGEL. 1987. Long-term variation in mesohaline Chesapeake Bay macrobenthos: Spatial and temporal patterns. *Estuaries* 10:227–245.

HOSS, D. E. AND G. W. THAYER. 1993. The importance of habitat to the early life history of estuarine dependent fishes. *American Fisheries Society Symposium* 14:147–158.

HUGHES, E. H. AND E. B. SHERR. 1983. Subtidal food webs in a Georgia estuary: δ^{13}C analysis. *Journal of Experimental Marine Biology and Ecology* 67:227–242.

INGRAM, R. G., L. L. LEGENDRE, Y. SIMARD, AND S. LEPAGE. 1985. Phytoplankton response to freshwater runoff: The diversion of the Eastmain River, James Bay. *Canadian Journal of Fisheries and Aquatic Sciences* 42:1216–1221.

JANICKI ENVIRONMENTAL, INC. 2001. Regression analyses of salinity-streamflow relationships in the Lower Peace River/Upper Charlotte Harbor estuary. Report prepared for the Peace River Manasota Regional Water Supply Authority, Sarasota, Florida.

JASSBY, A. D., W. J. KIMMERER, S. G. MONISMITH, C. ARMOR, J. E. CLOERN, T. M. POWELL, J. R. SCHUBEL, AND T. J. VENDLINSKI. 1995. Isohaline position as a habitat indicator for estuarine populations. *Ecological Applications* 5:272–289.

JAY, D. A. AND C. A. SIMENSTAD. 1996. Downstream effects of water withdrawal in a small, high-gradient basin: Erosion and deposition of the Skokomish River delta. *Estuaries* 19:501–517.

JUE, D. K. 1989. Florida rivers assessment. Publication of the Florida Department of Natural Resources, Division of Recreation and Parks, Tallahassee, Florida.

KENNISH, M. J. 1986. Ecology of Estuaries, Volume 1. Physical and Chemical Aspects. CRC Press, Boca Raton, Florida.

KIMMERER, W. J., J. H. COWAN, JR., L. W. MILLER, AND K. A. ROSE. 2001. Analysis of an estuarine striped bass population: Effects of environmental conditions during early life. *Estuaries* 24: 557–575.

LEE, T. M. AND A. SWANCAR. 1997. The influence of evaporation, ground water, and uncertainty in the hydrologic budget of lake Lucerne, a seepage lake in Polk County, Florida. U.S. Water-Supply Paper 2439. U.S. Geological Survey, Denver, Colorado.

LEWIS, III, R. R., R. G. GILMORE, D. W. CREWZ, AND W. E. ODUM. 1985. Mangroves, p. 281–336. *In* W. Seaman (ed.). Florida Aquatic Habitat and Fishery Resources. Florida Chapter of the American Fishery Society, Kissimmee, Florida.

LIGON, K. L., W. M. DIETRICH, AND W. M. TRUSH. 1995. Downstream ecological effects of dams: A geomorphic perspective. *BioScience* 45:183–192.

LINS, L. F. AND J. R. SLACK. 1999. Streamflow trends in the United States. *Geophysical Research Letters* 26:227–230.

LIVINGSTON, R. J. 1997. Trophic response of estuarine fishes to long-term changes of river runoff. *Bulletin of Marine Science* 60: 894–1004.

LONGLEY, W. L. (ED.). 1994. Freshwater inflows to Texas Bays and estuaries: Ecological relationships and methods for determination of needs. Texas Water Development Board and Texas Parks and Wildlife Department, Austin, Texas.

MANN, K. H. AND J. R. N. LAZIER. 1996. Dynamics of Marine Ecosystems. Biological-Physical Interactions in the Ocean. Blackwell Science, Cambridge, Massachusetts.

MCBEE, J. T. AND W. T. BREHM. 1982. Spatial and temporal patterns in the macrobenthos of St. Louis Bay, Mississippi. *Gulf Research Reports* 7:115–124.

MCMICHAEL, JR., R. H. AND K. M. PETERS. 1989. Early life history of spotted seatrout, *Cynoscion nebulosus* (Pisces: Sciaenidae) in Tampa Bay, Florida. *Estuaries* 12:98–110.

MCMICHAEL, JR., R. H., K. M. PETERS, AND G. R. PARSONS. 1989. Early life history of the snook, *Centropomus undecimalis,* in Tampa Bay, Florida. *Northeast Gulf Science* 10:113–125.

MCPHERSON, B. F., R. T. MONTGOMERY, AND E. E. EMMONS. 1990. Phytoplankton productivity and biomass in the Charlotte Harbor estuarine system, Florida. *Water Resources Bulletin* 26:787–800.

MERRINER, J. V., W. H. KRIETE, AND G. C. GRANT. 1976. Seasonality, abundance, and diversity of fishes in the Piankatank River, Virginia (1970–1971). *Chesapeake Science* 17:238–245.

MILLER, J. M., L. B. CROWDER, AND M. L. MOSER. 1985. Migration and utilization of estuarine nurseries by juvenile fishes: An evolutionary perspective. *Contributions in Marine Science* 68: 338–352.

MILLER, R. L. AND B. F. MCPHERSON. 1991. Estimating estuarine flushing and residence times in Charlotte Harbor, Florida, via salt balance and a box model. *Limnology and Oceanography* 36: 602–612.

MOTE MARINE LABORATORY. 2001a. Peace River, benthic macroinvertebrate and mollusk indicators. Report prepared by Mote Marine Laboratory for the Peace River Manasota Regional Water Supply Authority, Sarasota, Florida.

MOTE MARINE LABORATORY. 2001b. An investigation of relationships between freshwater inflows and benthic macroinvertebrates in the Alafia River estuary. Report prepared by Mote Marine Laboratory for the Southwest Florida Water Management District, Brooksville, Florida.

MOYLE, P. B. AND R. A. LEIDY. 1992. Loss of biodiversity in aquatic ecosystems: Evidence from fish faunas, p. 127–169. *In* P. L. Fiedler and S. K. Jain (eds.). Conservation Biology: The Theory and Practice of Nature Conservation, Preservation, and Management. Chapman and Hall, New York.

MYERS, S. B., Y. JUNG, AND M. E. LUTHER. 2002. Simulations of salinity distributions and residence times in the Palm River and McKay Bay. Report prepared by the University of South Florida College of Marine Science for the Southwest Florida Water Management District, Brooksville, Florida.

NEWSON, M. 1994. Hydrology and the River Environment. Clarendon Press, Oxford, U.K.

ODUM, W. E., T. J. SMITH, III, J. K. HOOVER, AND C. C. MCIVOR. 1984. The ecology of tidal freshwater marshes of the United States east coast: A community profile. Report FSW/OBS-83/17. U.S. Fish and Wildlife Service, Office of Biological Services, Washington, D.C.

PBS&J, INC. 1998. Assessment of potential impacts of the Tampa Bay Water Surface Water Projects on Tampa Bay. Report prepared for the Tampa Bay Water, Clearwater, Florida.

PBS&J, INC. 1999a. Summary of historical information relevant to the hydrobiological monitoring of the lower Peace River and upper Charlotte Harbor estuarine system. Report prepared for the Peace River Manasota Regional Water Supply Authority, Sarasota, Florida.

PBS&J, INC. 1999b. Tampa Bypass Canal/Alafia River water supply projects: Hydrobiological monitoring program. Report prepared for the Tampa Bay Water, Clearwater, Florida.

PBS&J, INC. 2001. Peace River hydrobiological monitoring program year three interpretive report. Report prepared for the Peace River Manasota Regional Water Supply Authority, Sarasota, Florida.

PEEBLES, E. B. 1996. Ontogenetic habitat and diet selection in estuarine-dependent fishes: Comparisons of observed patterns with model predictions. Ph.D. Dissertation, University of South Florida, Tampa, Florida.

PEEBLES, E. B. 2002a. An assessment of the effects of freshwater inflows on fish and invertebrate habitat use in the Alafia River estuary. Report prepared by the University of South Florida College of Marine Science for the Southwest Florida Water Mangement District, Brooksville, Florida.

Peebles, E. B. 2002b. An assessment of the effects of freshwater inflows on fish and invertebrate habitat use in the Peace River and Shell Creek estuaries. Report prepared by the University of South Florida College of Marine Science for the Southwest Florida Water Mangement District, Brooksville, Florida.

Peebles, E. B. 2002c. Temporal resolution of biological and physical influences on bay anchovy *Anchoa mitchilli* egg abundance near a river-plume frontal zone. *Marine Ecology Progress Series* 237:257–269.

Peebles, E. B. and M. S. Flannery. 1992. Fish nursery use of the Little Manatee River estuary (Florida): Relationships with freshwater discharge. Southwest Florida Water Management District, Brooksville, Florida.

Peebles, E. B., J. R. Hall, and S. G. Tolley. 1996. Egg production by the bay anchovy *Anchoa mitchilli* in relation to adult and larval prey fields. *Marine Ecology Progress Series* 131:61–73.

Peters, K. M. and R. H. McMichael, Jr. 1987. Early life history of the red drum, *Sciaenops ocellatus* (Pisces: Sciaenidae), in Tampa Bay, Florida. *Estuaries* 10:92–107.

Petts, G. E. 1984. Impounded Rivers: Perspectives for Ecological Management. John Wiley and Sons, Chichester, U.K.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. The natural flow regime: A paradigm for river conservation and restoration. *Bioscience* 47:769–784.

Rast, J. P., M. E. Flock, T. T. Sutton, and T. L. Hopkins. 1991. The zooplankton of the Little Manatee River estuary: Combined report for years 1988 and 1989. Report prepared by University of South Florida Department of Marine Science for the Southwest Florida Water Management District, Brooksville, Florida.

Reis, R. R. and J. M. Dean. 1981. Temporal variation in the utilization of an intertidal creek complex by the bay anchovy (*Anchoa mitchilli*). *Estuaries* 4:16–23.

Richter, B. D., J. V. Baumgartner, J. Powell, and D. P. Braun. 1996. A method for assessing hydrologic alteration within ecosystems. *Conservation Biology* 10:1163–1174.

Richter, B. D., J. V. Baumgartner, R. Wigington, and D. P. Braun. 1997. How much water does a river need? *Freshwater Biology* 37:231–249.

Rozengurt, M. A. and J. W. Hedgpeth. 1989. The impact of altered river flow on the ecosystem of the Caspian Sea. *CRC Critical Reviews in Aquatic Sciences* 1:337–362.

Seaman, W. L. and R. McLean (eds.). 1977. Seminar proceedings: Fresh water and the Florida Coast, Southwest Florida. Southwest Florida Water Management District, Brooksville, Florida.

SDI Environmental Services, Inc. 1998. Analysis of streamflow and rainfall at selected sites in west-central Florida. Report prepared for Tampa Bay Water, Clearwater, Florida.

Sinha, M., M. K. Mukhopadhyay, P. M. Mitra, M. M. Bagchi, and H. C. Karamkar. 1996. Impact of Farakka barrage on the hydrology and fishery of Hooghly estuary. *Estuaries* 19:710–722.

Sklar, F. H. and J. A. Browder. 1998. Coastal environmental impacts brought about by alterations to freshwater flow in the Gulf of Mexico. *Environmental Management* 22:547–562.

Snedaker, S., D. de Sylva, and D. Cotrell. 1977. A review of the role of freshwater in estuarine ecosystems. Report prepared by the University of Miami Rosenstiel School of Marine Science for the Southwest Florida Water Management District, Brooksville, Florida.

Southwest Florida Water Management District. 1992. Water supply needs and sources 1990–2020. Southwest Florida Water Management District, Brooksville, Florida.

Southwest Florida Water Management District. 2001a. Estimated water use in the Southwest Florida Water Management District for 1999. Southwest Florida Water Management District, Brooksville, Florida.

Southwest Florida Water Management District. 2001b. Regional water supply plan. Southwest Florida Water Management District, Brooksville, Florida.

Southwest Florida Water Management District. 2002a. Priority list and schedule for the adoption of minimum flows and levels. *Florida Administrative Weekly* 28:243–244.

Southwest Florida Water Management District. 2002b. The occurrence of high nutrient and chlorophyll *a* concentrations in the Alafia River estuary. Technical memorandum. Southwest Florida Water Management District, Brooksville, Florida.

Sprinkel, J. 1986. Oyster Reefs, Volume IV: A data collection program for selected coastal estuaries in Hernando, Citrus, and Levy counties, Florida. Report prepared by Mote Marine Laboratory for the Southwest Florida Water Management District, Brooksville, Florida.

Stoker, Y. E., S. E. Henderson, and B. F. McPhereson. 1989. Hydraulic and salinity characteristics of the tidal reach of the Peace River, southwestern Florida. Water Resources Investigations Report 88-4162. U.S. Geological Survey, Tallahassee, Florida.

Stoker, Y. E., V. A. Levesque, and W. M. Woodham. 1996. The effect of discharge and water quality of the Alafia River, Hillsborough River, and the Tampa Bypass Canal on nutrient loading to Hillsborough Bay, Florida. Water Resources Investigation Report 95-4107. U.S. Geological Survey, Tallahassee, Florida.

Tara, P. E., R. Rokicki, and M. A. Ross. 2001. Estimation of ungaged flows in the Alafia River. Report prepared by the University of South Florida Center for Modeling Hydrologic and Aquatic Systems for the Southwest Florida Water Management District, Brooksville, Florida.

Uncles, R. J. and J. A. Stephens. 1993. The freshwater-saltwater interface and its relationship to the turbidity maximum in the Tamar estuary, United Kingdom. *Estuaries* 16:126–141.

Vallino, J. J. and C. S. Hopkinson. 1998. Estimation of dispersion and mixing times in Plum Island Sound estuary. *Estuarine, Coastal and Shelf Science* 46:333–350.

Vargo, G. A., W. R. Richardson, D. Howard, and J. Paul. 1991. Phytoplankton production in two tidal rivers, the Alafia and Little Manatee, p. 317–340. *In* S. A. Treat and P. A. Clark (eds.). Tampa Bay Area Scientific Information Symposium 2. Tampa Bay Regional Planning Council, Clearwater, Florida.

Weinstein, M. P. and H. A. Brooks. 1983. Comparative ecology of nekton residing in a tidal creek and adjacent seagrass meadow: Community composition and structure. *Marine Ecology Progress Series* 12:15–27.

Wilber, D. A. and R. Bass. 1998. Effect of Colorado River diversion on Matagorda Bay epifauna. *Estuarine, Coastal and Shelf Science* 47:309–318.

Yobbi, D. D. and L. A. Knochemus. 1989a. Salinity and flow relations in the Chassahowitzka and Homosassa Rivers and adjacent areas of the Gulf of Mexico, Florida. Water Resources Investigation 88-4044. U.S. Geological Survey, Tallahassee, Florida.

Yobbi, D. D. and L. A. Knochemus. 1989b. Effects of river discharge and high-tide stage on salinity intrusion in the Weeki Wachee, Crystal River, and Withlacoochee River estuaries, Southwest Florida. Water Resources Investigation 88-4116. U.S. Geological Survey, Tallahassee, Florida.

Source of Unpublished Materials

Chen, X. C. 2001. Studying hydrodynamics in a riverine estuary by a combination of 2-D and 3-D simulations (abstract). Poster presented at the 16th biennial conference of the Estuarine Research Federation, November 4–8, 2001. St. Petersburg Beach, Florida.

Received for consideration, December 13, 2001
Accepted for publication, September 17, 2002