MANAGING FRESHWATER INFLOW TO ESTUARIES IN NORTHEASTERN PUERTO RICO: ECOLOGICAL AND INSTITUTIONAL CONSIDERATIONS

by

KATHERINE LECONTE SMITH

(Under the Direction of Catherine M. Pringle)

ABSTRACT

Estuaries in northeastern Puerto Rico provide critical habitat for diadromous, estuarine, and marine species. While freshwater abstraction has been recognized as a threat to riverine species in this region, the issue of decreasing inflow to estuaries has received very little research or management attention. To address this research gap, the ecological importance of freshwater inflows to estuaries in northeastern Puerto Rico and the management framework for this resource are examined in this dissertation. The ecological importance of freshwater inflow was examined in two studies: (1) a comparison of salinity and fish community data collected from the Espiritu Santo estuary in 1977 and 2004, before and after the 1984 construction of an upstream low-head dam and water intake structure and (2) a stable isotope and gut content analysis of the contribution of freshwater organic matter to estuarine fishes in the Espiritu Santo and Mameyes. Results of the first study illustrate the potential importance of freshwater inflow to estuarine fish communities. 2004 sampling yielded lower fish species richness and abundance than 1977 sampling. Freshwater-oriented species demonstrated the greatest decline, with only 25% of freshwater-oriented species redetected in 2004 versus redetection of more than 50% for marine and euryhaline species. Results of the second study illustrate the contribution of riverine organic matter to estuarine fish diet. While riverine organic matter was of limited (<33%) importance to three of four fishes sampled (*Centropomus pectinatus*, *Bairdiella ronchus*, and *Mugil curema*), stable isotope analyses indicated that it potentially contributed as much as 69% of the diet of one species, *Diapterus rhombeus*. Gut content analysis of these four and eleven other common fishes collected from the two estuaries demonstrated the importance of riverine-derived organisms, specifically juvenile diadromous freshwater shrimps, to fish diet. Freshwater shrimps were frequently encountered (in 37% and 39% of guts examined) and composed an average of 18% and 22% of the gut content material of omnivorous fishes sampled in the Espiritu Santo and Mameyes estuaries, respectively. After assessing the ecological importance of freshwater inflow to estuaries, the management framework for this resource was examined via a legal analysis and manager interviews. The primary legal and policy authorities with relevance to inflow management in northeast Puerto Rico are the Clean Water Act, the Rivers and Harbors Act, and the Puerto Rico Water Law. Inflow management actions under these authorities, however, have focused on riverine, rather than estuarine, inflow needs. Results of manager interviews illustrate the role of several key factors in limiting management of inflow to estuaries: low priority of inflow to estuaries, lack of relevant scientific information, lack of a champion pushing the issue, programmatic limitations, as well as issues related to Puerto Rico's wider institutional and political environment that affect natural resource management in general. Based on the results of these three studies, management and future research recommendations are provided.

INDEX WORDS: Tropical island estuaries, estuarine fish communities, long-term change, freshwater inflow, stable isotopes, food-webs, institutional analysis, management

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CHAPTER 1:

GENERAL INTRODUCTION

Water abstraction for municipal uses is one of the primary threats to rivers and aquatic species in the Luquillo Experimental Forest (LEF) in northeastern Puerto Rico (March et al. 2003; Oritz-Zayas and Scatena 2004; Crook et al. 2007). To address this issue, scientists associated with National Science Foundation's Luquillo Long Term Ecological Research Program (LTER) have made considerable advances in the study of instream flows. This research has included: instream flow and habitat requirements of diadromous freshwater shrimps[1] (Scatena and Johnson 2001); migratory patterns/drift of these organisms (March et al. 1998; Benstead et al. 2000); and effects of water diversions on their populations (Benstead et al. 1999). Results of these studies have ultimately led to strategies to minimize the effects of water abstractions on aquatic species (March et al. 2003; Oritz-Zayas and Scatena 2004).

Increased water abstraction may also affect downstream estuaries (Drinkwater and Frank 1994; Alber 2002; Gillanders and Kingsford 2002). Although estuaries in northeastern Puerto Rico provide critical habitat for diadromous freshwater organisms and many important marine species (Center for Energy and Environmental Research 1979), the issue of decreasing inflow to estuaries has received very little research or management attention (Benstead et al. 2000; March et al. 2003). In fact, there are no published studies regarding inflow to estuaries in Puerto Rico. To address this gap, this dissertation examines the ecological importance of freshwater inflows to estuaries in northeastern Puerto Rico and the management framework for this resource.

[1] Diadromous freshwater shrimps are the dominant macroconsumers in Puerto Rican streams.

In the first study (Chapter 2), I compare salinity and fish community data collected from the Espiritu Santo estuary in 1977 and 2004, before and after the 1984 construction of an upstream low-head dam and water intake structure. Specifically, I address the following questions: Are there strong indicators of change in the fish assemblage of one of Puerto Rico's best preserved estuaries, the Espiritu Santo? If so, which species or types of species are most affected? Do changes in the fish community reflect construction of the upstream dam and water intake facility? For example, have freshwater oriented species declined more than marine oriented species?

In the second study (Chapter 3), I examine the contribution of freshwater organic matter to estuarine fishes in the Espiritu Santo and Mameyes via stable isotope and gut content analyses. Specific research questions include: Is riverine derived organic matter, including riverine organisms, important to estuarine fishes and consumers? If so, to what extent and for which species? Are there apparent differences in the contribution of riverine organic matter between the Espiritu Santo and Mameyes, estuaries which differ in upstream water management practices?

Lastly, in Chapter 4, I examined the management framework for inflow to estuaries in northeast Puerto Rico through the use of legal analysis and manager interviews. Specifically, I examined (1) the legal and administrative framework under which inflow to estuaries is managed and (2) factors influencing the management of inflow to estuaries. Specific research questions include what legal authorities do managers use to address inflow to estuaries? To what extent has this issue been addressed under these authorities? What factors influence managers' efforts regarding inflow to estuaries?

The research presented in this dissertation expands on the Luquillo LTER's research relevant to water management. Luquillo LTER researchers began examining the effects of hydrological alterations within the boundaries of the LEF, but have recently made efforts to expand this research to rivers outside the LEF boundaries (e.g., Greathouse et al. 2006a; Greathouse et al. 2006b; Luquillo LTER 2006). This dissertation further expands on the geographic scope of Luquillo LTER research by addressing the ecological importance of freshwater inflow to estuaries. By providing research on the framework for management of inflow to estuaries, this dissertation also contributes to an emerging goal of the LTER program: addressing resource management and governance (LTER 2006). While each chapter of this dissertation is written as a stand alone publication and couched in the broader scientific literature, all are tied together by the broader objective of understanding the ecology and management of inflow to estuaries.

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# CHAPTER 2:

# A COMPARISON OF CURRENT AND HISTORICAL FISH ASSEMBLAGES IN A CARIBBEAN ISLAND ESTUARY: CONSERVATION VALUE OF HISTORICAL DATA[1]

[1] Smith, K.L., Corujo Flores I., and Pringle C.M. In Press with *Aquatic Conservation*. Reprinted here with permission of publisher.

**ABSTRACT**

Historical data are often one of the only resources for documenting and assessing causes of environmental change, particularly in developing regions where funding for ecological studies is limited. In this paper, previously unpublished data from a 1977 year-long study of the fish community of the Espiritu Santo estuary are presented. This dataset is among the oldest and most extensive surveys of a Caribbean island estuarine fish community. A comparison of these historical data with data collected in June and July 2004 using identical sampling methods allowed description of potential long-term changes in the fish community, identification of vulnerable species, and assessment of potential drivers of change. Results strongly suggest a decline in species richness and abundance in the Espiritu Santo estuarine fish community, with greater declines in freshwater-tolerant than marine or euryhaline species. Declines in freshwater inflow to the estuary, due to large-scale upstream water abstractions for municipal use, have increased since the initial 1977 survey. This is the first study to examine long-term change in the fish community of a tropical island estuary. Additional research and conservation efforts are needed to understand mechanisms of change and to protect Caribbean island estuarine fish communities.

*Key Words: estuarine fishes, freshwater fishes, long-term change, watershed change, freshwater diversion.*

## INTRODUCTION

Historical observations, even if limited or qualitative, often provide one of the only resources for documenting and assessing causes of ecosystem change. Use of historical data is particularly important in developing regions with limited funding for ecological studies and few long-term datasets. This approach, however, can be challenging because historical studies are often characterized by missing or unclear records. In addition, the original data collector may be difficult to locate, potentially leading to methodological uncertainties about the original study. Several studies have, nonetheless, effectively documented species declines or extinctions via comparison of current and historical data. For example, Drayton and Primack (1996) found large changes in the plant community of a small Boston woodland over a century; Kattan *et al.,* (1994) identified local extinctions and bird species declines in Columbia over 80 years; and Reinthal and Stiassny (1991) reported losses of freshwater fish species in Madagascar, coinciding with increases in exotic species. These examples illustrate that even when historical data are limited in scope, they are valuable for identifying species declines, characteristics of vulnerable species, and environmental drivers of change (Patton *et al.,* 1998). Early recognition of species declines is crucial for preventing extinctions and reducing long-term costs of conservation actions.

Fish communities of Caribbean island estuaries have received little study due to lack of resources and governmental support (Stoner, 1986; Blaber, 2002; Rivera-Monroy *et al*., 2004). Appropriate conservation and management actions are difficult without basic data describing these communities. Such data are crucial: a study of North American marine and estuarine fish species at risk suggests that Caribbean island fishes may be particularly vulnerable to environmental change (Musick *et al*., 2001). Three of the five geographic localities in North America, noted to have a high number of species at risk, were located in southern Florida, a region that shares many species with Caribbean islands. In addition, migratory anadromous and amphidromous species were identified as particularly vulnerable due to habitat degradation (Musick *et al*., 2001). This finding raises further concern for Caribbean islands such as Puerto Rico, where all native freshwater fishes are amphidromous.

In this paper, previously unpublished historical data from a year-long, 1977 study of the Espiritu Santo fish community (conducted by I. Corujo Flores) are presented and compared to data collected with identical sampling methods in June and July 2004. In 1977, the Espiritu Santo estuary was considered one of the least disturbed estuaries in Puerto Rico; however, in the last 30 years its watershed has been affected by increasing population growth and urbanization (Ramos Gonzalez, 2001; Ortiz-Zayas and Scatena, 2004). The 1977 fish community presented here is among the oldest and most extensive from a Caribbean island estuary. As such, these data provide a rare opportunity to document "baseline" conditions in the Espiritu Santo estuary, examine potential long-term changes in its fish community, and identify vulnerable species and drivers of species declines.

## METHODS

### Study site

The Espiritu Santo estuary is adjacent to the town of Rio Grande in north-eastern Puerto Rico (Figure 2.1). Puerto Rico's north-eastern estuaries, including the Espiritu Santo, are riverine type estuaries that, in comparison to lagoonal or deltaic estuaries, are characterized by a high ratio of freshwater to tidal inflow, a low width to depth ratio, and a high perimeter to area ratio (Morris and Hu, 1995). The estuary is relatively small extending less than 7 km inland, ranging from 12 to 55 m in width and 1 to 6 m in depth, and with a drainage area of approximately 25

$km^2$. Its substrate is composed of sand and gravel, with some areas of cobble in its upper reaches and a thick layer of organic detritus in the mid and lower reaches. The estuary is bordered by pasture lands in the upper reaches and by mangrove wetlands in the lower reaches. Long-term annual flow to the estuary averages 1.68 $m^3$/sec most of which reaches the estuary during large flood events. Due to the high elevational gradient of its drainage basin, flow through the estuary is visible except during periods of very low discharge. The estuary is strongly and permanently stratified (at approximately 0.5 m in depth) with a distinct salt wedge. Flooding may disrupt this stratification, though generally for less than 24 hours. Turbidity ranges from an average of 15 NTU during normal flow to more than 50 NTU after storm events. Tidal amplitude is in the region is low (< 1 m).

The Espiritu Santo is the only estuary in Puerto Rico's north-eastern coast that remains open to the ocean year-round, with no sandbar formation at its mouth. In addition, an extensive reef system lies just outside the mouth of the estuary. As a result of these two characteristics, the Espiritu Santo hosts many marine migrants and has unusually high fish species richness for the region (Negron and Cintron, 1979). The Espiritu Santo is also one of the most protected estuaries in Puerto Rico. The Espiritu Santo river originates in Luquillo Experimental Forest (LEF) at an elevation of approximately 1,000 metres and the estuary is included in the Espiritu Santo Reserve. The National Forest designation has protected much of the Espiritu Santo watershed from development. In addition, because of the protection conferred by its reserve status, the Espiritu Santo estuary, unlike most of Puerto Rico's estuaries, has retained some of its mangrove wetlands. The areas surrounding the reserve, however, are primarily urban and suburban (Ramos Gonzalez, 2001). There is no commercial and only limited recreational fishing in the estuary although a small marina is located on the estuary and commercial fisherman use the estuary for boat access to offshore reefs. The estuary is also used for kayaking and recreation.

### Changes to the Espiritu Santo watershed between 1977 and 2004

Despite its reserve status, the Espiritu Santo estuary is threatened by urbanization, loss of mangroves within the reserve, and upstream water diversions. Water diversions are a threat to estuaries throughout Puerto Rico and particularly so in the densely populated north-east where water demand is high and ground water is limited (March *et al*., 2003; Ortiz-Zayas and Scatena, 2004). The Espiritu Santo river is the most heavily diverted river in the LEF (Crook *et al*., 2007). At least ten water intakes, most of which were built within the past 30 years, are currently located within the Espiritu Santo basin. These intakes extract more than 20% of the Espiritu Santo's annual runoff. Because most of the runoff occurs during large storm events, the day-to-day impact is even greater with 82% of median flow withdrawn from the river (Crook *et al*., 2007).

Upstream water diversions have greatly increased since the Espiritu Santo estuary was designated as a reserve. The largest water intake on the river was constructed in 1984, after the estuary was given reserve status. Withdrawals at this intake account for more than twice the total of all the other intakes combined (Crook *et al*., 2007). During drought periods, all fresh water in the stream is diverted at this intake. On such occasions, marine fish species have been observed directly below the dam, located more than 1 km above the head of the estuary (March *et al.,* 2003). Two changes to the estuary and near shore marine environment may have also influenced the Espiritu Santo salinity patterns. Dredging, from the middle to the mouth of the estuary, has occurred for sand mining and to facilitate boat traffic from the estuary to ocean fishing grounds. In addition, a portion of the reef located near the mouth of the estuary was removed to facilitate boat traffic from the estuary to marine fishing grounds. These changes may have increased the penetration of the salt wedge into the estuary.

Large-scale shifts in landuse have also occurred in north-eastern Puerto Rico since the late 1970s. Ramos Gonzalez (2001) evaluated landuse change in north-eastern Puerto Rico between 1978 and 1995, documenting an almost completed replacement of agricultural lands with forest and shrub cover in the uplands, and urban and suburban development in the coastal plains. Eighty-five percent of the new development between 1978 and 1995 occurred in the lowlands and coastal plains region (Ramos Gonzales, 2001). Urbanization in the basin has likely altered sediment inputs to the estuary (Edgar and Barrett, 2000) and has encroached on mangrove stands surrounding the Espiritu Santo estuary (I. Corujo Flores, personal observation).

Many improvements have been made to the water quality of the Espiritu Santo estuary since the 1970s. Point source pollution has decreased due to improvements in sewage treatment and water quality regulations. In the late 1970s, the estuary received 0.8 million gallons/day of discharge from a secondary sewage treatment plant. Fish sampling near the sewage discharge point was often difficult in 1977 because gill nets frequently became clogged with toilet paper (I. Corujo Flores, personal observation). Sewage is no longer discharged directly into the estuary although failure of the treatment system resulted in sewage overflow to the estuary on several occasions in 2004 (K. Smith, personal observation). The decline of agriculture in the region has likely reduced fertilizer and pesticide runoff to the estuary. Water hyacinth (*Eichhornia crassipes*), which covered large portions of the estuary in 1977, was absent from the estuary in 2004 possibly due to these reduced nutrient inputs.

## Field sampling

*1977 sampling*

Fish were collected monthly by I. Corujo Flores between February 1977 and January 1978 (referred to as 1977 sampling) from eight approximately evenly-spaced sampling stations along the salinity gradient (Figure 2.1). On each sampling event, four experimental 100 x 8 ft nylon sinking gill nets, each of a single mesh size (½, 1, 2, and 3 inches square), were deployed to capture fish at each station. Each net was anchored to the shore and deployed at a 45-degree angle sloped towards the freshwater flow. The 2” and 3” nets were placed on opposite shores at extremes of the sampling station and the ½” and 1” nets were placed on opposite shores between the larger nets. Nets were set for 1.5 hours between 0700 and 1100 hours. Dip nets were used to collect smaller fishes along the shores. All fish were weighed and measured for total and standard lengths.

At each station, water samples were taken after each sampling event from the middle of the channel at 0.25 m below the surface and 0.25 m above the estuary floor. Samples were stored in polyethylene bottles and returned to the laboratory where salinity was determined with a Bausch and Lomb temperature compensated refractometer. Standard MohR titration with silver nitrate ($AgNO_3$) was used when salinity levels were under detection limits of the refractometer. Temperature was recorded *in situ* with a Kemmerer water sampling bottle equipped with a calibrated thermometer.

*2004 sampling*

In June and July of 2004, the same eight stations (Figure 2.1) were sampled once per month also between 0700 and 1100 hrs with identical gear and methods as in 1977. To ensure consistency between 1977 and 2004 sampling, I. Corujo Flores re-delineated the 1977 sampling stations and trained K. Smith in sampling methods. To increase the sample size and capture of crepuscular fishes, additional night sampling (between 1900 and 2300 hours) was carried out at least once per month at all sampling stations. Night sampling effectively doubled our 2004 sampling effort over our 1977 sampling effort. During each 2004 sampling event, surface (at 0.25 m) and bottom (at 0.25 m above the substrate) temperature, salinity, dissolved oxygen, and turbidity were recorded from the middle of the channel with a Hydrolab Quanta (Hydrolab Inc.).

**1977 & 2004 Comparisons**

Raw data from the 1977 study were lost when the Center for Energy and Environment, where they were stored, was closed. Detailed summaries of the fish community and environmental conditions were preserved in a Masters thesis by I. Corujo Flores (Corujo Flores, 1980). These data are used here to describe the 1977 fish community and environmental conditions. After summarizing the 1977 data, species richness, diversity, abundance, and community composition were compared between 1977 and 2004 using identical subsets of the 1977 and 2004 data - June and July day sampling (further referred to as base sampling). For some comparisons, additional data such as 2004 night sampling and year long 1977 data are presented alongside base sampling comparisons. It is important to note that many statistical analyses could not be applied because the 1977 data were only preserved in summary form.

The number of species (observed species richness) detected during 1977 and 2004 base sampling was compared. Because observed species richness may not reflect the true number of species present in an area (Colwell and Coddington, 1994), estimated species richness (the

Chao1 estimator) was calculated with EstimateS Version 7.5 (Colwell, 2005). The Chao1 estimator is defined as:

$$\hat{S}_{Chao1} = S_{obs} + [f^2(1)/2f(2)]$$

where $S_{obs}$ is the observed number of species, $f(1)$ is the observed number of singletons (only a single individual is observed), and $f(2)$ is the observed number of duplicates. Because of potential differences between species richness estimators we also examined results of the ACE and Chao2 estimators, also calculated with EstimateS, to ensure that trends did not vary between estimators. Lastly, 1977 (day only) observed and estimated species richness was compared with 2004 day and 2004 day plus night sampling.

A comparison of species diversity (Fisher's Alpha) between 1977 and 2004 base sampling was undertaken. This index, also calculated with EstimateS, was defined as:

$$S = \alpha \ln(1 + N/\alpha)$$

where N is the number of individuals sampled and S is the number of species in the sample. Results from two other diversity indices, the Shannon and Simpson diversity indices, were also calculated to ensure that results did not differ between indices.

Total catch and catch per effort between 1977 and 2004 base sampling was also compared. Because the 1977 data were only available in summary form, catch per effort is presented as the number of fish collected in each month averaged across the eight sampling stations. Catch per effort between 1977 and 2004 base sampling was compared and then put in context of catch per effort for the entire 12 months sampled in 1977. To illustrate differences in catches of individual species, total catch by species in 1977 versus 2004 was also plotted.

To examine changes in species abundance in context of their environmental tolerances, information on the salt tolerance and resilience of each species was collected from the FishBase database (Froese and Pauly, 2000). Species were classified by salt tolerance as either *freshwater-oriented* (reported as occurring in fresh water or freshwater and brackish habitats), *marine-oriented* (occurring in marine and brackish habitats), or *euryhaline* (freshwater, brackish, and marine habitats). The relative abundance of species in each salinity and resilience category was compared between 1977 and 2004 base sampling. It was predicted that given increased freshwater diversions upstream of the estuary, fewer freshwater-oriented than marine or euryhaline species would be redetected in 2004. Minimum, maximum, and average surface and bottom salinity at high and low tide at each sampling station was also calculated and compared between 1977 and 2004. Fish base resilience categorizations were either high, medium, or low based on reproductive capacity and ability to withstand and recover from exploitation or disturbance (Froese and Pauly, 2000). Changes in the relative abundance of species in each resilience category might indicate changes in estuarine conditions or offshore exploitation. Diet and habitat preference descriptions were not available for all species, so analysis of these factors was not possible.

## RESULTS

### Description of historical (1977) fish community

The year-long, 1977 survey yielded 30 families and 60 species of fish (Table 2.1), a high species richness for the region (Negron and Cintron, 1979). The majority of species were represented by only a few individuals. Two-thirds of the species comprised less than 1% of the total number of individuals in 1977. Only six species represented more than 5% of the catch. The most common species, *Eleotris pisonis*, comprised only 12% of the total number of individuals captured in 1977. The two most common families, Eleotridae and Clupeidae, comprised 28% and 10% of the catch respectively (Table 2.1).

Only four species, *E. pisonis*, *Gobiomorus dormitor*, *Mugil curema*, and *Microphis brachyurus*, were captured in all 12 months of the study (Table 2.1). Twenty percent of the species were residents (i.e. collected in at least 7 out of 12 months). The majority of species (42%) were transients (i.e. collected in the estuary in only one or two non-consecutive months). The remaining 37% of the species were cyclical or regular visitors (i.e. those using the estuary 3 to 6 months out of the year or for two consecutive months).

The majority of species were only found in a few of the sampling stations (Table 2.1). Half of the species were found in only one or two of the eight stations and 15 of these species were collected from only one sampling station. Only four species (*Centropomus ensiferus*, *Opisthonema oglinum*, *Eugerres plumieri*, *Bairdiella ronchus*) were found at all stations and only eight species were found in more than six of the eight stations.

**The 2004 fish community**

The June and July 2004 base sampling survey yielded 16 families and 19 species (Table 2.2). As in 1977, most species were represented by only a few individuals. Only four species, *O. oglinum* (9.3%), *Lutjanus jocu* (7.0%), *M. curema* (11.7%), and *M. brachyurus* (18.6%) comprised over 5% of the base sampling catch. Most species were captured at only one or two stations and none were captured at over four stations. An additional eight species were captured during night sampling for a total of 27 species captured in 2004. *Caranx latus* (5.6%), *Centropomus pectinatus* (8.3%), *O. oglinum* (7.0%), *Polydactylus virginicus* (8.3%), and *B. ronchus* (11.1%) were most common in 2004 day and night sampling (Table 2.2).

**1977 and 2004 comparisons**

1977 base sampling yielded 15 more species than 2004 base sampling. Despite identical sampling methods and effort, 34 species were collected in 1977 while only 19 species were detected in 2004. Even the 1977 *observed* species richness was higher than 2004 *estimated* species richness. In addition, the 1977 *day* sampling species richness was greater than the 2004 *day and night* sampling species richness (Figure 2.2). Species diversity in 1977 (Fishers Alpha = 14.2, SD = 1.9), however, was not significantly greater than 2004 diversity (13.0, SD = 3.3). These trends were consistent among different estimators of species richness and diversity.

Fish abundance (catch) was also greater in 1977 (Figure 2.3). Catch per effort was low and highly variable across all sampling months and years; however, catch per effort in June and July of 2004 was lower than in all 12 months sampled in 1977. Because the 1977 data were summed by month and station, it was not possible to apply statistical analyses to these comparisons. It was also not possible to assess changes in biomass because size information collected in 1977 was not retained for all species.

Figure 2.4, comparing species abundances between 1977 and 2004, illustrates that most species were more abundant in 1977. Several species commonly detected in 1977 (e.g. *C. ensiferus*, *Trichiurus lepturus* and *Anchovia clupeoides*) were not redetected or were only detected in low numbers (e.g. *D. rhombeus*) in 2004. Only four species found in 1977 were more abundant in 2004 (*O. oglinum, L. jocu, Selene vomer* and *Archosargus rhomboidalis*) and another five species that were not detected in 1977 were represented by one individual in 2004. Exotic species were rare in the Espiritu Santo both in 1977 and 2004. *Oreochromis mossambicus*, the only known exotic species found in 1977, decreased in relative abundance from 3.5% of total catch in 1977 to 1.4% in 2004.

Freshwater-tolerant species showed greater declines than marine species. Only 25% of freshwater-oriented species collected in 1977 were re-detected in 2004. In comparison, 53% and 54% of marine and euryhaline-oriented species, respectively, were redetected in 2004. Of the 10 new species detected in 2004 (including night sampling), six were marine-oriented and four euryhaline-oriented but none were freshwater-oriented. These changes coincided with apparent increases in estuarine salinity. The mean, minimum, and maximum bottom salinity was higher in 2004 than in 1977 at all sampling stations (Figures 2.5c,d). Surface salinity was similar in 2004 and 1977 (Figures 2.5a,b); however, rainfall in the region was much higher in 2004 than 1977 (Figures 2.5e,f). Because 1977 data were only available in summary form, it was not possible to apply statistical tests to these comparisons.

Habitat classifications were not available for many species and, when available, they were often vague. Although these limitations prevented formal analysis, all four species noted to prefer estuarine creeks and tributaries (*Pseudophallus mindii*, *Agonostomus monticola*, *Dormitator maculates* and *Bathygobius soporator*) were not redetected in 2004. The percentage of species classified as low, medium, and high resilience was similar in 1977 and 2004.

## DISCUSSION

### Interpretation of long-term change from limited data

Often, only limited historical data are available for studies of long term change (Drayton and Primack, 1996). Several methods have been used to improve the strength of conclusions drawn from historical data. For example, using the same collector or training researchers in identical methods serves to minimize sampling biases between surveys (Anderson *et al.,* 1995). Standardizing sampling effort and gears or otherwise accounting for sampling effort will strengthen the ability to draw conclusions about long-term change (Patton *et al*., 1998). Consideration of change at multiple spatial scales (Anderson *et al*., 1995; Patton *et al*., 1998) and over multiple years (Cabral *et al.,* 2001) may further improve ability to draw statistical conclusions.

Although the aforementioned methods can not always be applied due to the nature of historical data collections and records, these data may still reveal important signals of change. For example, Drayton and Primack (1996) identified changes in the plant community of a Boston woodland between 1894 and 1993, despite loss of some historical data and methodological questions about the original study. Reinthal and Stiassny (1991), compared compilations of historical museum records to a six-week preliminary survey conducted in 1989. Even with this limited dataset, they reported dramatic reductions in freshwater fishes in Madagascar which coincided with an increase in exotic species. Several factors increase the robustness of the conclusions drawn from comparisons of current and historical data in this study: (1) the primary investigator of the 1977 survey, I. Corujo Flores, ensured consistency in sampling methods between the 1977 and 2004 surveys; (2) sampling effort was standardized between surveys; and (3) identical gear was used in both surveys.

**Differences in the Espiritu Santo fish community between 1977 and 2004**

This study strongly suggests declines in fish species richness (Figure 2.2) and possibly abundance (Figures 2.3 and 2.4) in the Espiritu Santo estuary. Sstudies from other regions, however, suggest that estuarine fish may be relatively resilient to environmental change. For example, in a comparison of fish communities over a 21-year period, Richardson *et al.,* (2000) found that fish communities in the industrialized estuary of the Fraser River showed no more change than those in the more protected freshwater reaches of the river. Reinthal and Stiassny (1991) reported losses of many freshwater fish species in Madagascar but found little evidence of decline in euryhaline species. Despite large changes in vegetation over a four year period, Whitfield (1986) found little change in the fish community of a South African estuarine lake. Meng *et al.,* (1994), however, reported declines of native estuarine species in the San Francisco bay estuary coinciding with increases in exotic species and declines in freshwater inflow during a 14-year study.

In contrast to other studies of tropical freshwater fish communities (e.g. Reinthal and Stiassny, 1991; Kaufman, 1992), declines in species richness in the Espiritu Santo did not coincide with increases in exotic species. Only one exotic species, *O. mossambicus* was collected from the estuary, and its numbers declined between 1977 and 2004. Exotic species may be relatively uncommon in this estuary because it is distant from major ports. In addition, improvements in water quality of the estuary over the past 27 years may have prevented *O. mossambicus*, which tolerates turbid, nutrient-rich waters, from out-competing native species.

Given the lack of research and monitoring of Caribbean island estuarine fishes, little is known about species that may have been extirpated or are in danger of being extirpated from the Espiritu Santo or other estuaries. In a report of extirpated species in the Caribbean Isles, insufficient data were available to estimate the number of extirpated fishes (Johnson, 1988). One species found in the Espiritu Santo estuary in 1977, *Mugil liza*, is considered to be a species "at risk" in Puerto Rico. Only one specimen of *M. liza* was found in 1977 and none were found in 2004. Given the rarity of this species in 1977, more sampling is needed to determine if this species has been extirpated from the Espiritu Santo estuary. Additional study and monitoring of estuaries and estuarine fishes is needed to determine if other fishes are at risk.

**Influence of environmental change**

*Salinity and freshwater diversion*

Freshwater inflow to the Espiritu Santo estuary has decreased due to upstream water diversions (Crook *et al*., 2007). While the exact change in inflow since 1977 is unknown, the largest water intake on the Espiritu Santo river, constructed in 1984, is estimated to extract approximately 34% of the instream flow on average and as much as 100% of the flow during low flow periods (Benstead *et al*., 1999). These upstream changes, combined with changes to the marine and estuarine environment (i.e. dredging and coral removal at the mouth of the estuary) which may increase the marine influence and penetration of the salt wedge into the estuary are reflected in an increase in bottom salinity at all stations of the Espiritu Santo estuary in 2004 (Figure 2.5). This increase occurred despite the fact that 1977 experienced average rainfall while 2004 was a relatively wet year, with May 2004 experiencing record high rainfall for 1975-2004 (Ramírez *et al*., 2005).

Changes in freshwater inflow and salinity structure have been shown to regulate fish communities in many estuaries (Meng *et al*., 1994; Freyrer and Healey, 2003; Barletta *et al*., 2005). Our results suggest that altered inflow and estuarine salinity has also affected the Espiritu

Santo fish community. In addition to declines in species richness and catch per effort, in 2004 fewer freshwater tolerant species (25%) than marine oriented species (53%) were redetected. This finding suggests that freshwater-oriented species are either more vulnerable to environmental change than marine or euryhaline species or that long-term change in freshwater inflow and estuarine salinity are decreasing adequate habitat for these species. Given these findings, and the ever increasing demand for freshwater in Puerto Rico (Ortiz-Zayas and Scatena, 2004), studies of freshwater requirements for Puerto Rico's estuaries are urgently needed.

*Urbanization*

Increases in urbanization surrounding rivers and estuaries in Puerto Rico's coastal plains may have also contributed to declining species richness in the Espiritu Santo estuary. While a small mangrove fringe remains around the estuary, most of the mangroves surrounding creeks, backwaters, and tributaries to the Espiritu Santo estuary have been removed as these areas were developed for tourism and suburban development. None of the species known to inhabit estuarine creeks and tributaries (*P. mindii*, *A. monticola*, *D. maculates*, and *B. soporator*) were redetected in 2004. These species, however, were detected in riverine areas above the estuary during exploratory sampling (K. Smith, personal observation), indicating that while less common in the estuary, they have not been extirpated from the Espiritu Santo river. Urbanization is a large and increasing threat to Puerto Rico's coastal plains (Thomlinson *et al.*, 1996; Thomlinson and Rivera, 2000; Ramos Gonzalez, 2001) and its effects on estuarine fish communities requires future study.

**Need for Long-term Monitoring**

Comparing historical and current data may provide valuable information on ecological trends and species declines; however, long-term monitoring is critical for detection of changes outside the range of natural variability. Temporal patterns of variability are well-documented in many temperate estuaries with established monitoring programmes. These data allow changes outside the normal range of variability to be detected. However, even with such monitoring programmes, it may only be possible to detect dramatic signals of change. For example, in an intensive multi-year study of temporal variability of physical and biotic characteristics of the Apalachicola estuary, Livingston (1987) found that fish community parameters demonstrated large, weekly variation that could mask interannual trends. No similar long-term datasets are available for Caribbean island estuarine fish communities and therefore differences in the 1977 and 2004 Espiritu Santo estuarine fish community could not be examined within the context of natural population fluctuations. Future studies are clearly needed to monitor and determine patterns of variability in the Espiritu Santo estuary.

This study illustrates the need to ensure that historical data are appropriately archived and made available to the scientific community. In the 1970s, the Center for Energy and Environmental Research (CEER) funded several studies of the environment (sediment and water quality) and biota (plankton, crustacean, molluscs, and fish) of the Espiritu Santo estuary. As a result, more was known about the ecology of the Espiritu Santo, one of the few well described Caribbean island estuaries, in the late 1970s than at the present. The majority of this information, including the raw data for this study, was lost with the closure of the CEER. The loss of these data precludes most statistical analyses as well as an examination of change in fish size structure and biomass in the Espiritu Santo estuary. This example illustrates the importance of preserving both short- and long-term data and the need for programmes such as the National Science Foundation's Long Term Ecological Research (LTER) program to archive data and make it available to future generations.


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Table 2.1. Relative abundance, stations, and month of fishes captured in the Espiritu Santo estuary, Puerto Rico in 1977. Stations refer to the sampling stations where fish were captured. "Transient" refers to species collected in the estuary in only one or two non-consecutive months. "Visitor" refers to species collected in the estuary for three to six months or for two consecutive months. Species collected in seven or more months are classified as "resident".

| Family | Rel abu | Species | Rel abu | Stations | Months | Estuary Use |
|---|---|---|---|---|---|---|
| Achiridae | 0.16 | *Achirus lineatus* | 0.16 | 5 | 4, 5 | visitor |
| Anguillidae | 2.79 | *Anguilla rostrata* | 2.79 | 1, 2, 3, 5, 6 | 1, 11 | transient |
| Belonidae | 0.24 | *Strongylura timucu* | 0.24 | 1, 6 | 5, 8, 11 | visitor |
| Bleniidae | 1.67 | *Lupinoblennius dispar* | 1.67 | 5, 6, 7 | 4, 8, 9, 11, 12 | visitor |
| Carangidae | 2.63 | *Caranx hippos* | 0.24 | 6, 7, 8 | 2, 6, 7 | visitor |
| Carangidae | | *Caranx latus* | 1.19 | 1, 2, 3, 5, 6, 7, 8 | 2, 4, 5, 6, 7, 8, 9, 10, 11 | resident |
| Carangidae | | *Chloroscombrus chrysurus* | 0.88 | 3, 4, 6, 7, 8 | 2, 3, 4, 5, 6, 7 | visitor |
| Carangidae | | *Selene vomer* | 0.16 | 7, 8 | 4, 5 | visitor |
| Carangidae | | *Trachinotus goodei* | 0.16 | 4, 7 | 5, 7 | transient |
| Centropomidae | 4.38 | *Centropomus ensiferus* | 2.31 | 1, 2, 3, 4, 5, 6, 7, 8 | 1, 2, 3, 4, 5, 6, 7, 8, 10, 11 | resident |
| Centropomidae | | *Centropomus pectinatus* | 0.16 | 3, 4 | 8 | transient |
| Centropomidae | | *Centropomus undecimalis* | 1.91 | 1, 2, 3, 4, 5, 6 | 2, 3, 4, 5, 6, 7, 9, 10, 11 | resident |
| Cichlidae | 1.35 | *Oreochromis mossambicus* | 1.35 | 3, 4, 5, 7 | 1, 2, 3, 5, 6, 7, 10, 11, 12 | resident |
| Clupeidae | 10.35 | *Harengula humeralis* | 0.32 | 8 | 12 | transient |
| Clupeidae | | *Opisthonema oglinum* | 10.03 | 1, 2, 3, 4, 5, 6, 7, 8 | 6 | transient |
| Cynoglossidae | 0.08 | *Symphurus plagiusa* | 0.08 | 5 | 2 | transient |
| Eleotridae | 28.03 | *Dormitator maculatus* | 9.16 | 1, 2, 3, 4, 5, 6, 7 | 1, 3, 6, 8, 11, 12 | visitor |
| Eleotridae | | *Eleotris pisonis* | 11.54 | 1, 2, 3, 4, 5, 6 | 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 | resident |
| Eleotridae | | *Gobiomorus dormitor* | 7.32 | 1, 2, 3, 4, 5 | 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 | resident |
| Elopidae | 0.24 | *Elops saurus* | 0.24 | 2, 4, 8 | 2, 4, 12 | visitor |

| | | | | | | |
|---|---|---|---|---|---|---|
| Engraulidae | 6.45 | *Anchoa hepsetus* | 0.40 | 7 | 5 | transient |
| Engraulidae | | *Anchovia clupeoides* | 2.79 | 2, 5, 6, 7 | 2, 4, 5, 6, 7, 9 | visitor |
| Engraulidae | | *Cetengraulis edentulus* | 3.26 | 1, 2, 3, 4, 5, 6, 8 | 6 | transient |
| Ephippidae | 0.08 | *Chaetodipterus faber* | 0.08 | 6 | 3 | transient |
| Gerreidae | 6.21 | *Diapterus rhombeus* | 3.34 | 2, 3, 4, 5, 6, 8 | 1, 2, 3, 4, 5, 6, 7, 9, 11 | resident |
| Gerreidae | | *Diapterus auratus* | 0.24 | 3 | 8, 10 | transient |
| Gerreidae | | *Ulaema lefroyi* | 0.08 | 3 | 7 | transient |
| Gerreidae | | *Eucinostomus melanopterus* | 0.16 | 2, 4 | 7, 10 | transient |
| Gerreidae | | *Eugerres plumieri* | 1.75 | 1, 2, 3, 4, 5, 6, 7, 8 | 2, 3, 4, 5, 6, 8, 9, 11, 12 | resident |
| Gerreidae | | *Gerres cinereus* | 0.64 | 1, 2, 3, 5 | 2, 6, 7, 11 | visitor |
| Gobiidae | 5.41 | *Awaous tajasica* | 0.16 | 1 | 8, 10 | transient |
| Gobiidae | | *Bathygobious soporator* | 2.31 | 5, 6, 7 ,8 | 1, 4, 7, 8, 9, 10, 11, 12 | resident |
| Gobiidae | | *Ctenogobius boleosoma* | 0.72 | 4, 5, 7 | 1, 5, 6, 8, 9, 10 | visitor |
| Gobiidae | | *Gobionellus oceanicus* | 0.08 | 2 | 5 | transient |
| Gobiidae | | *Gobiosoma spes* | 2.15 | 5, 6 | 8, 9, 10, 11, 12 | visitor |
| Haemulidae | 0.24 | *Pomadasys crocro* | 0.24 | 1, 2 | 11, 12 | transient |
| Lutjanidae | 0.64 | *Lutjanus apodus* | 0.24 | 7 | 5 | transient |
| Lutjanidae | | *Lutjanus griseus* | 0.08 | 7 | 5 | transient |
| Lutjanidae | | *Lutjanus jocu* | 0.32 | 5, 6, 8 | 5, 8, 9, 10 | visitor |
| Megalopidae | 0.48 | *Megalops atlanticus* | 0.48 | 2, 4 | 7, 11 | transient |
| Mugilidae | 9.32 | *Agnostomus monticola* | 1.19 | 1, 2 | 1, 6, 8, 9, 11 | visitor |
| Mugilidae | | *Mugil curema* | 7.96 | 1, 2, 3, 4, 5, 7, 8 | 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 | resident |
| Mugilidae | | *Mugil liza* | 0.16 | 5, 6 | 7, 8 | visitor |
| Myliobatidae | 0.32 | *Aetobatus narinari* | 0.32 | 3, 5 | 4, 5 | visitor |
| Paralichthyidae | 0.16 | *Citharichthys spilopterus* | 0.16 | 3, 6 | 3, 7 | transient |
| Poeciliidae | 0.56 | *Poecilia vivipara* | 0.56 | 4, 5 | 11 | transient |
| Polynemidae | 0.64 | *Polydactylus virginicus* | 0.64 | 5, 6, 7, 8 | 4, 5, 6, 12 | visitor |
| Sciaenidae | 5.57 | *Bairdiella ronchus* | 3.03 | 1, 2, 3, 4, 5, 6, 7, 8 | 2, 3, 4, 5, 6, 7, 8, 11, 12 | resident |

| | | | | | | |
|---|---|---|---|---|---|---|
| Sciaenidae | | *Cynoscion jamaicensis* | 0.72 | 5, 7 | 5, 7 | transient |
| Sciaenidae | | *Larimus breviceps* | 0.40 | 5, 7 | 5, 6 | visitor |
| Sciaenidae | | *Micropogonias furnieri* | 1.43 | 4, 5, 6, 7, 8 | 4, 5, 6, 11, 12 | visitor |
| Scombridae | 0.56 | *Scomberomorus regalis* | 0.56 | 5, 6, 8 | 2, 6, 7 | visitor |
| Sphyraenidae | 0.16 | *Sphyraena barracuda* | 0.08 | 2 | 12 | transient |
| Sphyraenidae | | *Sphyraena guachancho* | 0.08 | 7 | 5 | transient |
| Syngnathidae | 9.24 | *Microphis brachyurus* | 9.08 | 1, 2, 3, 4, 5, 6 | 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 | resident |
| Syngnathidae | | *Pseudophallus mindii* | 0.16 | 1 | 7, 9 | transient |
| Tetraodontidae | 1.19 | *Lagocephalus laevigatus* | 0.40 | 5, 6, 8 | 2, 5 | transient |
| Tetraodontidae | | *Sphoeroides testudineus* | 0.80 | 8 | 1, 2, 3, 4, 8, 11 | visitor |
| Trichiuridae | 0.88 | *Trichiurus lepturus* | 0.88 | 6, 7 | 6, 7 | visitor |

Table 2.2. Relative abundance and locations of fishes captured in the Espiritu Santo estuary, Puerto Rico in June and July 2004. Rel. abu. = relative abundance for day sampling (D) and day and night sampling combined (D+N). Stations refer to the sampling stations where fish were captured. Station numbers in italics indicate the species was only captured during night sampling.

| Family | Species | Rel. abu. (D) | Rel. abu. (D+N) | Stations |
|---|---|---|---|---|
| Belonidae | *Strongylura timucu* | - | 3.0 | *5*, *8* |
| Carangidae | *Caranx hippos* | - | 1.5 | *8* |
| Carangidae | *Caranx latus* | 2.3 | 6.0 | 2, *8* |
| Carangidae | *Oligoplites saurus* | 2.3 | 4.5 | 8 |
| Carangidae | *Selene vomer* | 4.7 | 3.0 | 7, 8 |
| Centropomidae | *Centropomus ensiferus* | - | 3.0 | *5* |
| Centropomidae | *Centropomus pectinatus* | - | 9.0 | *2, 8* |
| Centropomidae | *Centropomus undecimalis* | 2.3 | 1.5 | 4 |
| Cichlidade | *Oreochromis mossambicus* | 4.7 | 3.0 | 1, 2 |
| Clupeidae | *Opisthonema oglinum* | 9.3 | 7.5 | 3, 5, 8 |
| Eleotridae | *Eleotris pisonis* | 4.7 | 1.5 | 5 |
| Elopidae | *Elops saurus* | - | 1.5 | *8* |
| Engraulidae | *Anchovia clupeoides* | - | 1.5 | *5* |
| Engraulidae | *Cetengraulis edentulus* | - | 1.5 | *2* |
| Gerreidae | *Diapterus rhombeus* | 2.3 | 3.0 | *2*, 4 |
| Gerreidae | *Diapterus auratus* | 2.3 | 1.5 | 2 |
| Lutjanidae | *Lutjanus jocu* | 7.0 | 4.5 | 5, 7 |
| Haemulidae | *Pomadasys crocro* | 2.3 | 3.0 | 2 |
| Mugilidae | *Mugil curema* | 11.7 | 4.5 | 1, 3, *8* |
| Polynemidae | *Polydactylus virginicus* | 4.7 | 9.0 | *2, 5*, 7, *8* |
| Sciaenidae | *Bairdiella ronchus* | 4.7 | 11.9 | 2, *5*, 6, *8* |
| Sciaenidae | *Cynoscion jamaicensis* | - | 1.5 | *8* |
| Scombridae | *Scomberomorus regalis* | 7.0 | 4.5 | 5, *8* |
| Sphyraenidae | *Sphyraena barracuda* | 2.3 | 1.5 | 5 |
| Sparidae | *Archosargus rhomboidalis* | 4.7 | 1.5 | 8 |
| Syngnathidae | *Microphis brachyurus* | 18.6 | 4.5 | 4, 5 |
| Tetraodontidae | *Sphoeroides testudineus* | 2.3 | 1.5 | 8 |

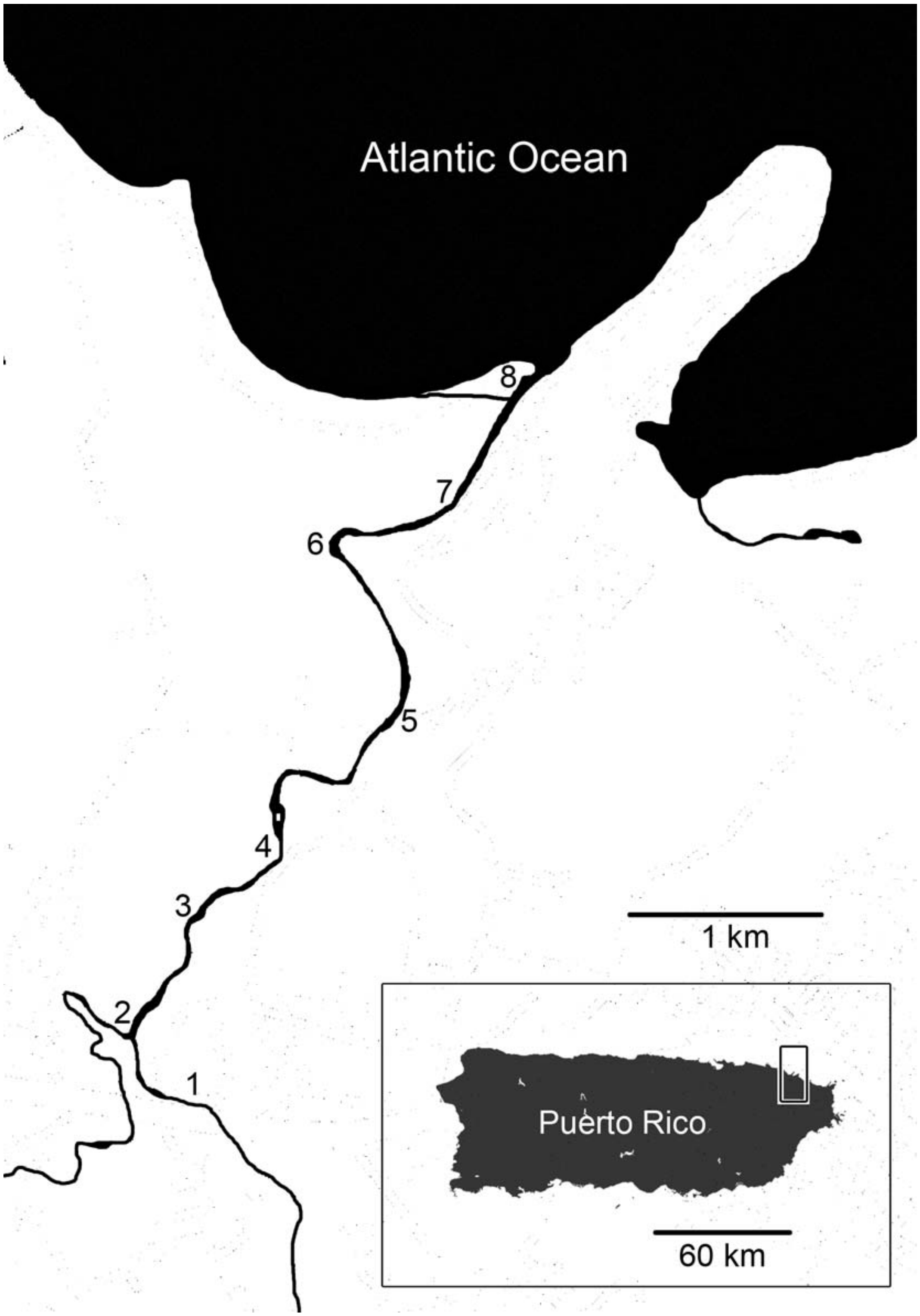



Figure 2.1. Espiritu Santo estuary, Puerto Rico showing locations of sampling stations for 1977 and 2004 fish community surveys.

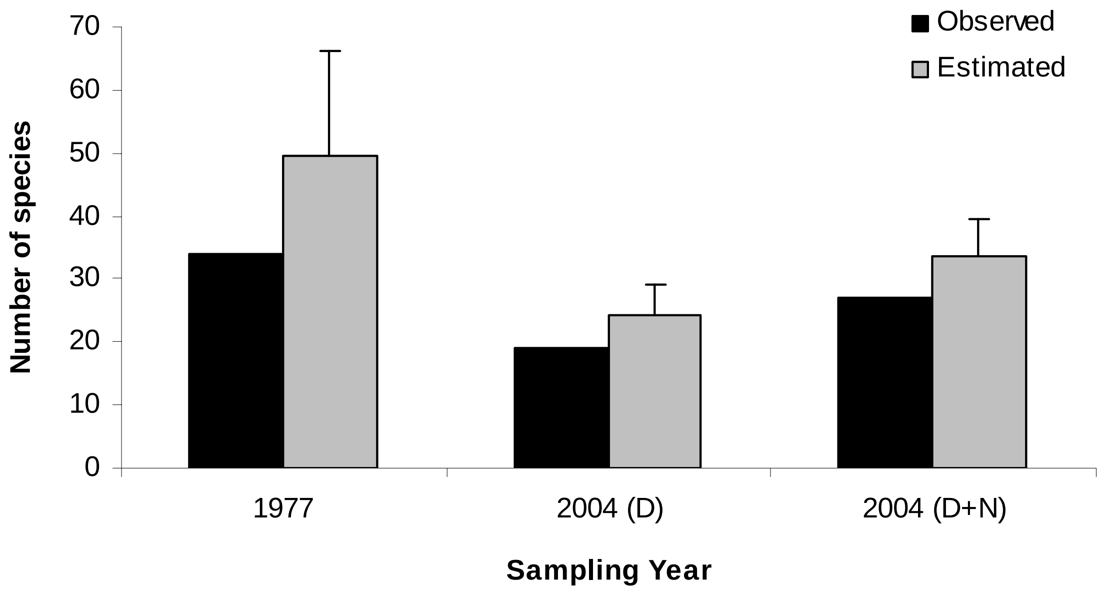
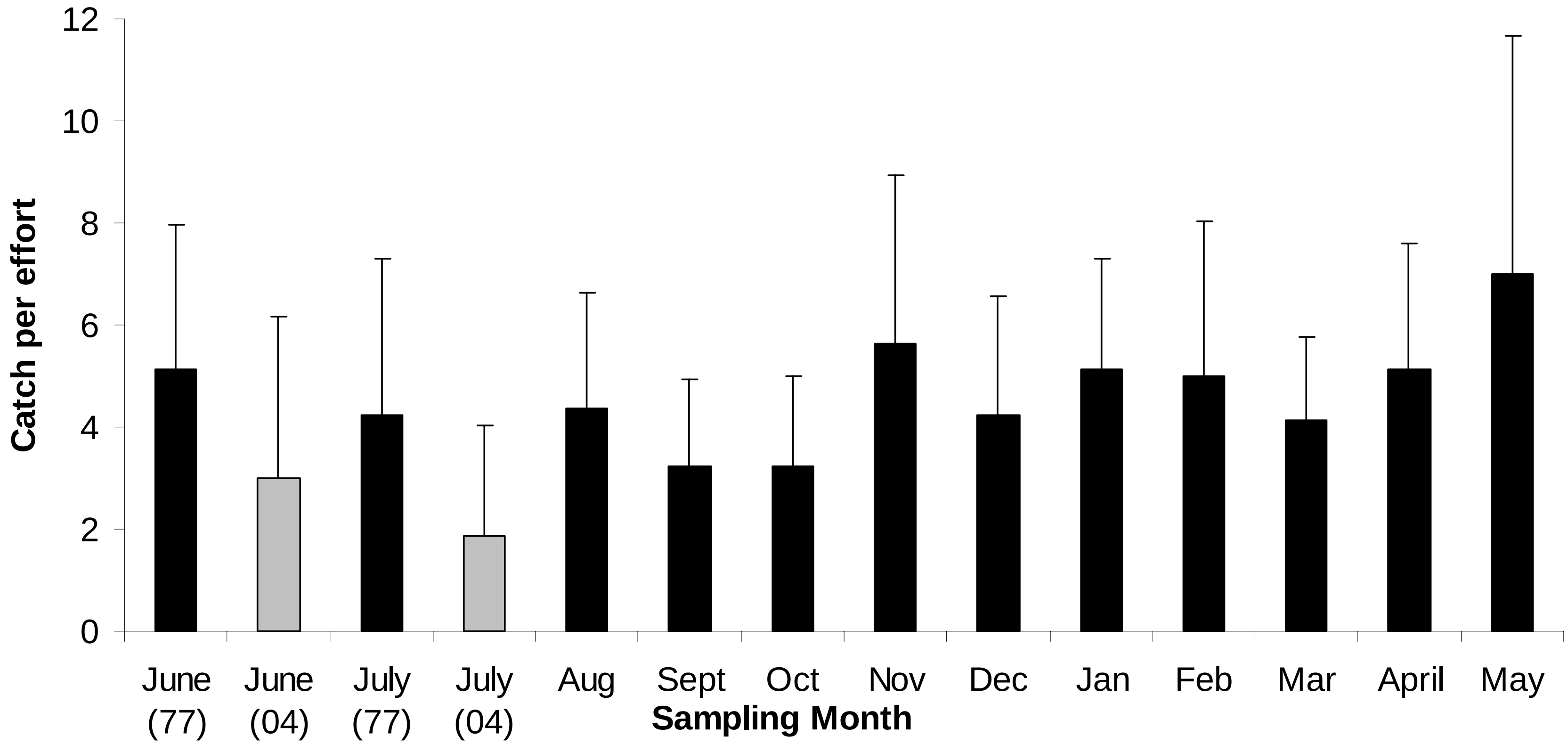



Figure 2.2. Fish species richness of the Espiritu Santo estuary in 1977 and 2004. "Observed" refers to the observed number of species and "Estimated" refers to the estimated species richness (calculated with the Chao1 species estimator). 2004 (D) indicates the number of species found with day sampling only while 2004 (D+N) indicates the number of species found during day and night sampling combined. Night sampling was not conducted in 1977.

Figure 2.3. Catch per effort in the Espiritu Santo estuary by month in 1977 compared to June and July 2004.


12
10
8
6
4
2
0
Catch per effort
June (77)
June (04)
July (77)
July (04)
Aug
Sept
Oct
Nov
Dec
Jan
Feb
Mar
April
May
Sampling Month

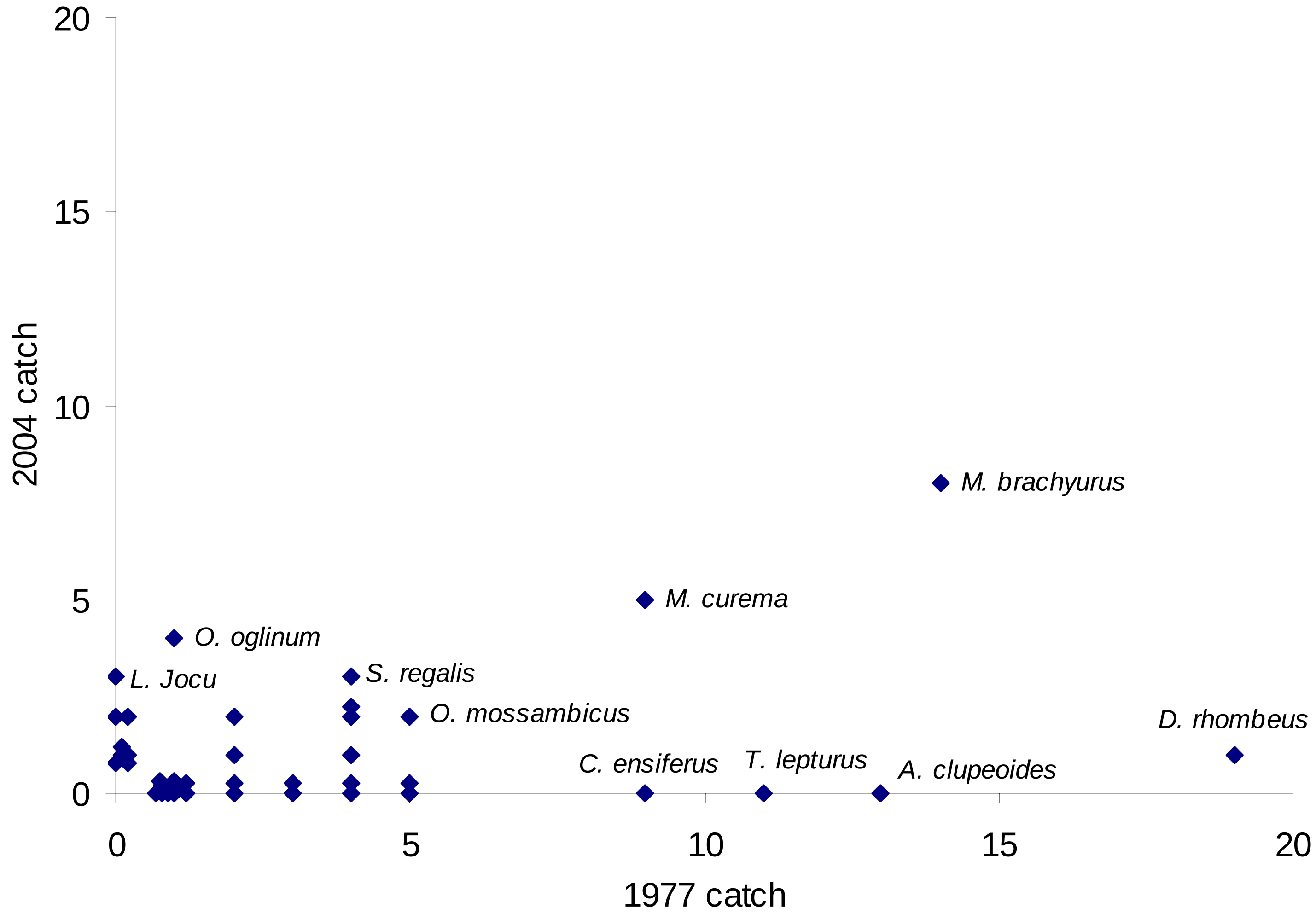
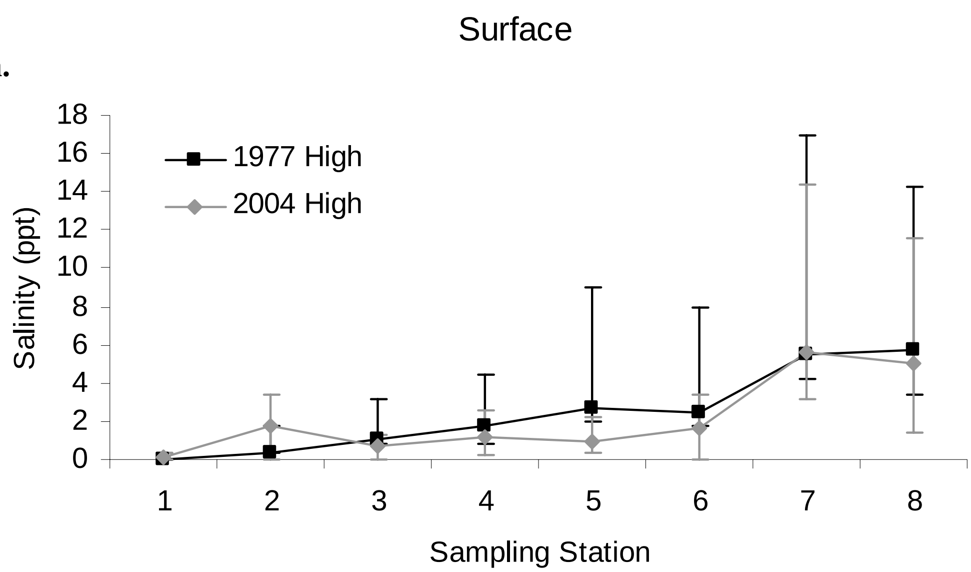


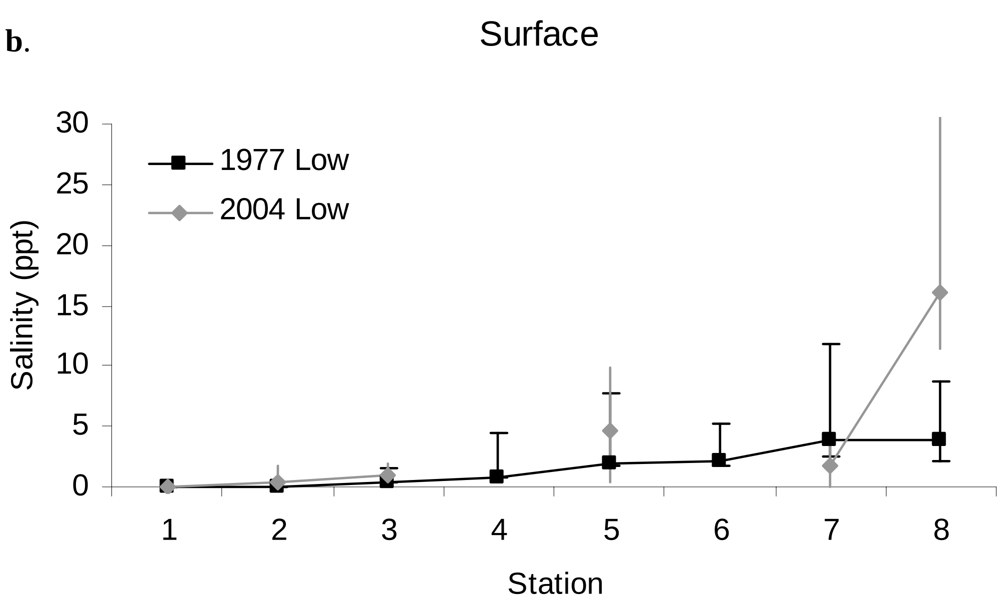

Figure 2.4. Number of fish by species collected in the Espiritu Santo estuary in 1977 versus 2004. Names of the most common species are given.

Figure 2.5 a-f. Average surface (a,b) and bottom (c,d) salinity (ppt) at high (a,c) and low (b,d) tide in the Espiritu Santo Estuary in 1977 and 2004. Error bars represent minimum and maximum salinity (standard errors for 1977 salinity data could not be calculated because only summaries of these data are available). Annual rainfall (1975 to 2004) from wettest to driest year for the Luquillo Experimental Forest is shown in figure 2.5e. Figure 2.5f shows monthly average, minimum, and maximum rainfall for 1975-2003 in comparison to 2004. Monthly values for 2004 are shown as open circles. Figures 2.5e & f are adapted from Ramírez *et al*. (2005).

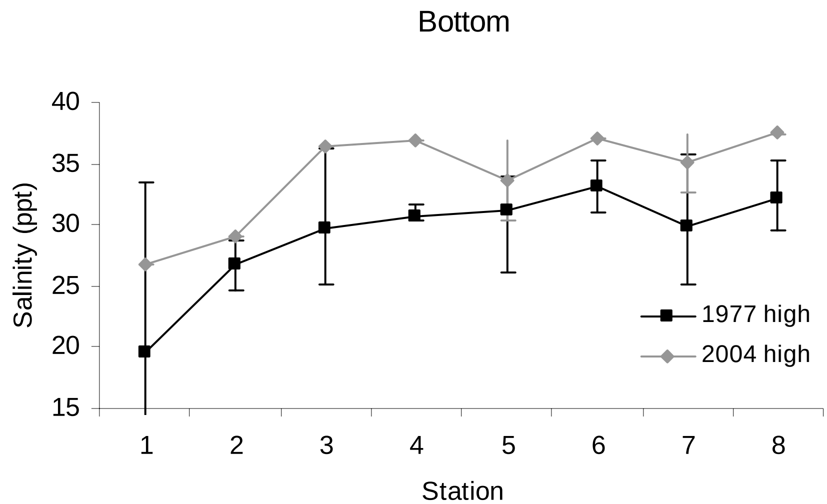
**a.**


Surface
18
16
14
12
10
8
6
4
2
0
Salinity (ppt)
1977 High
2004 High
1
2
3
4
5
6
7
8
Sampling Station

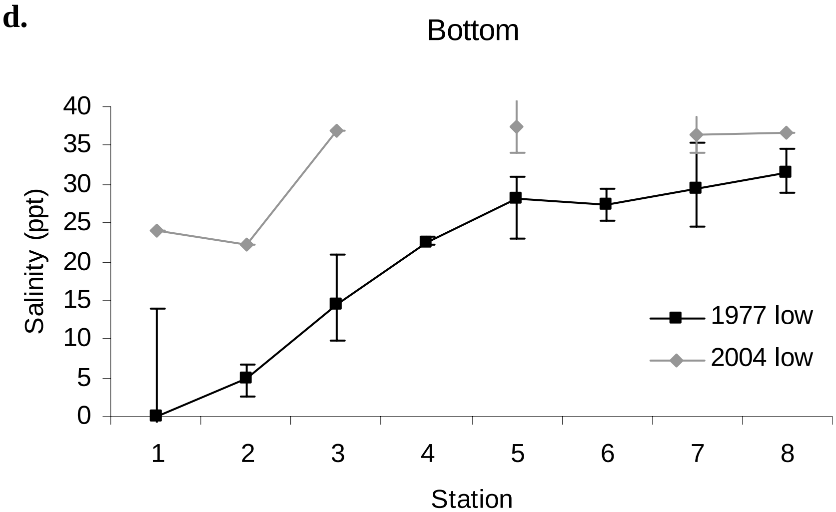
**b.**


Surface
30
25
20
15
10
5
0
Salinity (ppt)
1977 Low
2004 Low
1
2
3
4
5
6
7
8
Station

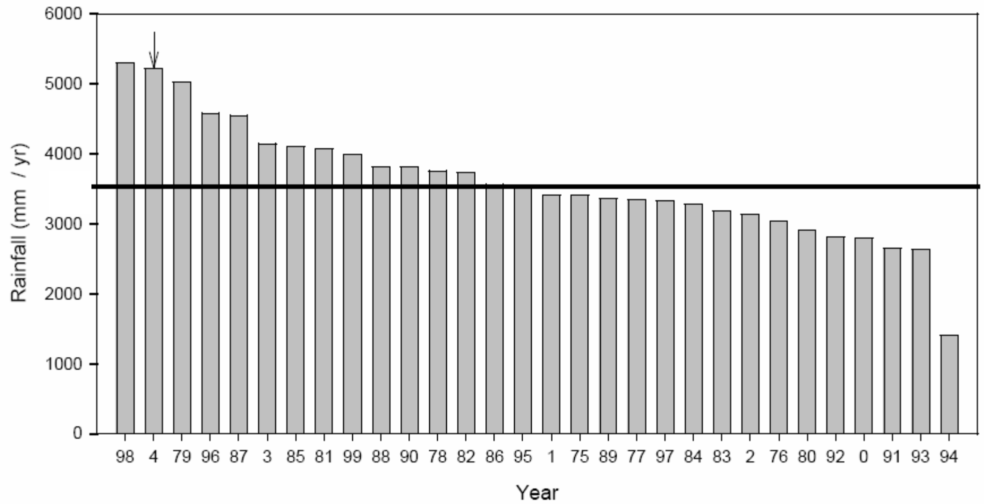
**c.**


Bottom
40
35
30
25
20
15
Salinity (ppt)
1
2
3
4
5
6
7
8
Station
1977 high
2004 high

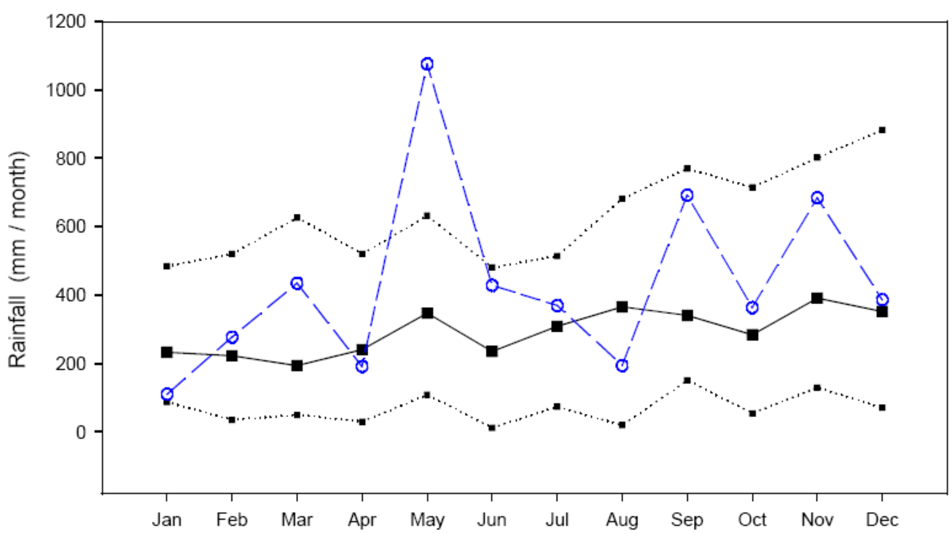
**d.**


Bottom
40
35
30
25
20
15
10
5
0
Salinity (ppt)
1
2
3
4
5
6
7
8
Station
1977 low
2004 low

**e.**


6000
5000
4000
3000
2000
1000
0
Rainfall (mm / yr)
98 4 79 96 87 3 85 81 99 88 90 78 82 86 95 1 75 89 77 97 84 83 2 76 80 92 0 91 93 94
Year

**f.**


1200
1000
800
600
400
200
0
Rainfall (mm / month)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

# CHAPTER 3:

# STABLE ISOTOPES AND GUT CONTENT ANALYSES REVEAL CONTRIBUTIONS OF RIVERINE ORGANISMS AND OTHER ORGANIC MATTER INPUTS IN TWO CARIBBEAN ISLAND ESTUARIES[1]

[1] Smith, K.L., Rodriguez del Rey, Z., Alber, M., and Pringle, C.M. To be submitted to *Canadian Journal of Fisheries and Aquatic Sciences*.

**ABSTRACT**

The contribution of riverine-derived organisms and organic matter to fishes in the Espiritu Santo and Mameyes estuaries, Puerto Rico, was examined via stable isotope and gut content analyses. Stable isotope analyses indicated that riverine organic matter potentially contributed as much as 69% of the diet of one of four fish species sampled (*Diapterus rhombeus*). In contrast, riverine organic matter was of little direct importance to the three other fishes (*Centropomus pectinatus*, *Bairdiella ronchus*, and *Mugil curema)*, contributing less than 33% of their assimilated material, even in upper reaches of the estuaries. Gut content analysis of these four and eleven other common fishes collected from the Espiritu Santo and Mameyes estuaries demonstrated the importance of riverine-derived organisms, specifically juvenile diadromous freshwater shrimps migrating through the estuary. Freshwater shrimps were frequently encountered (in 37% and 39% of guts examined) and composed an average of 18% and 22% of the gut content material of omnivorous fishes sampled in the Espiritu Santo and Mameyes estuaries, respectively. This study adds new information regarding the contribution of riverine subsidies in Caribbean island estuaries. Given increasing demand for water resources on tropical islands and the importance of diadromy in these systems, we recommend additional research to better inform water management decisions.

Key Words: *Food webs, freshwater inflow, estuarine fishes, freshwater shrimps, stable isotope analysis, gut contents, Caribbean island estuaries.*

## INTRODUCTION

The contribution of riverine organic matter to estuarine consumers has received considerable attention, particularly in temperate estuaries. These studies, which often rely on stable isotope analysis, have generally concluded that local primary producers are the predominant source of organic matter for estuarine organisms (Peterson & Howarth 1987, Deegan & Garritt 1997, Chanton & Lewis 2002). However, a few studies have found riverine organic matter to be an important energy source (Riera & Richard 1996), particularly in high-flow systems (Incze et al. 1982) or in the upper reaches of estuaries (Ruesink et al. 2003). Export of invertebrates may also provide a subsidy from rivers to estuaries. Only a handful of studies have examined this topic, finding high levels of invertebrate export (Williams 1980, Hudon 1994, Wipfli & Gregovich 2002) that may contribute to the diet of downstream fishes (Williams & Williams 1998). Yet another potentially important trophic linkage between rivers and estuaries is the migration of diadromous organisms; larvae and juveniles of diadromous organisms that are exported from rivers to estuaries may provide a food source to estuarine fishes.

The importance of both riverine organic matter inputs (Rivera-Monroy et al. 2004) and freshwater organisms (Freeman et al. 2003) to estuarine fishes is a critical research area for Caribbean island estuaries (March et al. 2003). Within the Caribbean, the small riverine estuaries that drain from mountainous regions, such as northeastern Puerto Rico, may be particularly dependent on freshwater subsidies because of their geomorphology, which results in relatively high riverine but low marine organic matter inputs (Rivera-Monroy et al. 2004). The prevalence of diadromy in freshwater organisms, in Puerto Rico and many other Caribbean Islands, may also serve to increase the importance of marine-freshwater linkages. With the exception of freshwater crabs, almost all of Puerto Rico's native freshwater macroconsumers (e.g. fishes, shrimps, and snails) migrate between streams and salt water (March et al. 1998). Larvae of these diadromous organisms are flushed to the estuary, where they have the potential to contribute to the diet of estuarine fishes (Corujo Flores 1980, Benstead et al. 2000).

Assessing the importance of riverine organic matter and organismal exports to estuarine fishes is important in Puerto Rico, given increasing stream water diversions to meet demand for potable water supplies (March et al. 2003, Ortiz-Zayas and Scatena, 2004). Increased water demand has resulted in construction of dams on all but one of Puerto Rico's rivers and increased water diversions for municipal uses. These alterations may reduce the export of freshwater organisms to estuaries via disruption of migratory routes and mortality of larvae drifting to the estuary at water intakes. In a study of freshwater shrimp, the dominant macroconsumers in Puerto Rican streams, Benstead et al. (1999) estimated that an average of 42% of larval shrimps were entrained at the main water intake dam on a northeast Puerto Rico river. Reductions in freshwater inflow due to water diversions may also reduce export of riverine-derived organic matter and organisms, and ultimately limit their contribution to estuarine fishes.

We examined the importance of riverine energy sources to fishes in two estuaries in northeast Puerto Rico via: (1) stable isotope analysis, to assess the importance of riverine organic matter, and (2) gut content analyses, to assess if estuarine fishes are feeding on larval and/or juvenile freshwater shrimps. Because this study was conducted in two adjacent estuaries with different upstream water management practices, we looked for systematic differences in the contribution of these riverine-derived resources that might indicate an influence of upstream water management. This study adds new information regarding freshwater subsidies to fishes in a Caribbean Island estuary and provides a basis for future research on the effects of water management on riverine subsidies to estuarine fishes.

## METHODS

### Study site description

This study was conducted in the Espiritu Santo and the Mameyes estuaries, both of which drain the Luquillo Experimental Forest (LEF) in northeastern Puerto Rico (Figure 3.1). The LEF is a tropical mountain rainforest receiving an average of over 3000 mm of rainfall per year. There is little to no seasonality in rainfall in the region and temperature is relatively constant. High temperatures average approximately 27°C in the winter and 29°C in the summer at the El Verde Field Station (elevation 350 m) in the LEF (Ramirez et al. 2005). Both the Espiritu Santo and Mameyes rivers originate at over 1000 m above sea level and drain small (8,547 and 4,120 $ha^2$, respectively), fourth-order watersheds. Both estuaries are short and narrow: approximately 7 and 2 km in length, respectively, and less than 60 m at their widest points. Long-term annual flow to the estuaries averages 1.68 and 1.53 $m^3$/sec, respectively. Given the region's topography, most of the stream flow reaches the estuaries during large flood events. Both estuaries are permanently stratified, with a fresh 'surface' layer approximately one meter in depth overlying a 'bottom' saline layer approximately 1 to 4 m in depth.

Although the estuaries have similar geomorphology, there are some physical differences between them. Because of the presence of a near-shore reef system that buffers sand-depositing waves, the Espiritu Santo is the only estuary in Northeastern Puerto Rico that remains open to the ocean year-round, without sandbar formation at its mouth (Morris & Hu 1995). In contrast, drought events and prolonged low flows can result in complete sandbar formation and closure of the Mameyes estuary from the ocean. Complete or partial closure from the ocean has been shown to result in anoxic conditions in the non-mixing (bottom) zone of the water column throughout the mid and lower estuary (Negron & Cintron 1979, Morris & Hu 1995). Although large floods may completely flush out the sandbar and fully open the estuary to the ocean for short periods, under normal flow conditions the Mameyes generally has only a small (< 5 m in width) connection to the ocean.

The two estuaries also differ in upstream water management practices. In 1984, a low-head dam and water intake structure were constructed on the Espiritu Santo River approximately 4 km from the coast. An estimated 34% of the average instream flow is extracted at this intake (Benstead et al. 1999). During low-flow events as much as 100% of the flow can be extracted. Water extraction at this intake has been shown to cause mortality of a large portion of diadromous larval shrimps during their downstream migrations (Benstead et al. 1999). In the Mameyes, a French drain structure that pumps stream water to an off-channel storage system was constructed in 2001. The Mameyes has a minimum environmental flow requirement and the intake does not appear to entrain or block shrimp migration (March et al. 2003).

To describe differences in physical characteristics between the estuaries, physical data were collected at least twice per month between May and August 2004 at three sampling stations distributed along the salinity gradient in each estuary. Stations were located at the upper reach of the salt wedge, in the middle estuary, and near the mouth of each estuary, referred to as stations 1, 2, and 3, respectively (Figure 3.1). Surface (at 0.25 meters) and bottom (at 0.25 meters above the substrate) salinity (PSU), dissolved oxygen (mg/L), and turbidity (ntu) were recorded from the mid-channel with a Hydrolab Quanta (Hydrolab Inc.).

**Fish and shrimp collection**

Fish were collected monthly between May and August 2004 at each of the three sampling stations in each estuary for stable isotope and gut content analyses. Samples were collected with 100 x 8 ft nylon sinking gill nets of differing mesh size (½, 1, 2, and 3 inches square) anchored to the shore and deployed at 45-degree angles from the shore, sloped upstream. Nets were set for no more than 1.5 hours at a time to limit digestion of gut content material in captured fishes. All samples were immediately placed on ice and returned to the laboratory where they were weighed, identified, and measured for total and standard lengths. Stomachs were immediately extracted and the contents were squeezed directly into vials and preserved in 70% ethanol. A white muscle sample was collected from each fish for isotope analysis. These samples were rinsed with distilled water, placed in a sealed glass vial, and immediately frozen. Prior to isotope analysis, each tissue sample was freeze-dried (Virtis Freezemobile 35ES) for at least 36 hours before being ground to a fine power (Spex Certiprep 8000D Mixer Mill). All isotope samples were treated with 0.01% HCl solution to remove carbonates.

A subset of fish were selected for stable isotope analysis. Since there is a high diversity of fishes and limited distribution of most species in the estuaries (Smith et al. In Press), we focused our isotope analysis on four common species found throughout both estuaries to allow for a consistent examination between estuaries and sampling stations. We chose two pelagic species (*Centropomus pectinatus and Bairdiella ronchus*) and two benthic species (*Diapterus rhombeus* and *Mugil curema*). Focusing our isotope analysis on these four species allowed us to compare relative contributions of freshwater organic matter sources among fishes in the upper, middle and lower estuary. We aimed to collect at least three individuals of each species from each station; however, we were not able to reach this target at all stations. For example, no *M.*

*curema* were collected at Station 2 of the Espiritu Santo despite extensive sampling effort (Table 3.1).

Where possible, diadromous freshwater shrimps, a focus of fish gut content analysis, were also collected to assess if these organisms were dependent on (and thus a source of) riverine- or estuarine-derived organic matter. Previous studies have reported difficultly in capturing diadromous shrimps during their larval estuarine stage (Benstead et al. 2000) and we also were unable to collect larval samples in this study. However, juvenile freshwater shrimps (*Atya lanipes*, *Xiphocaris elongata*, and *Macrobrachuim spp*.) that were observed in dense congregations beginning their upstream migration were collected with dip nets from littoral areas of both estuaries. Samples were immediately placed on ice and returned to the laboratory where their exoskeletons were removed and a tissue samples collected from their tail muscle for isotope analysis. Shrimp samples were processed as described above for fish tissue samples.

**Basal resources collection**

We collected samples of potential organic matter sources from each river and estuary for isotope analysis. Replicate samples of upstream riparian leaves and instream leaf litter were collected at the lowest elevation water intake site in the Espiritu Santo and Mameyes rivers (located approximately 0.5 km upstream of the fresh/salt water interface in each case) to characterize riverine organic matter. In the estuaries, fresh mangrove leaves were collected from all stations where mangroves were present (the middle and lower Espiritu Santo and a small area in the lower Mameyes). Macroalgae was collected from woody debris and buoys where present; however, it was not observed at all stations. Neither submerged nor emergent seagrasses were observed in or near either estuary. Samples of estuarine biofilm were also collected at each station by deploying anchored flotation devices that suspended three 12” square tiles in the water column. After one week, the tiles were collected and immediately scraped for biofilm. Biofilm samples were used in the interpretation and discussion of our results. Samples of leaves, macroalgae and biofilm were all dried at 40°C for at least three days before being ground to a fine power.

Collection of pure samples of phytoplankton and/or benthic microalgae for isotope analysis are difficult to obtain. As was the case in several previous studies, (e.g., Peterson & Howarth 1987, Benstead et al. 2006), we rely here on published values (Currin et al. 1995, Deegan & Garrit 1997) rather than exclude these organic matter sources from our analysis.

**Stable isotope analysis**

$\delta^{13}C$ analysis was conducted in the Analytical Chemistry Laboratory of the University of Georgia. Samples were run on a Carlo Erba NA 1500 CHN analyzer (Carlo Erba Instrumentazione, Milan, Italy) coupled to a Finnigan Delta C isotope ratio mass spectrometer (Thermo Electron Corp., Waltham, USA) operating as a continuous flow system. Reproducibility was monitored using a bovine liver standard. Precision was better than ± 0.2‰ (1 SD). Animal tissue $\delta^{34}S$ analysis was run at the Colorado Plateau Stable Isotope Laboratory on a Carlo Erba Model NC2100 elemental analyzer coupled to a Finnigan Delta Plus Advantage isotopic ratio mass spectrometer. Range in measurement error was ± 0.7-1.0‰. Plant and biofilm $\delta^{34}S$ samples were analyzed at the Coastal Sciences Laboratory (Austin, Texas) on a VG (Micromass) isotope ratio mass spectrometer. Isotope values are expressed as $\delta^{13}C$ or $\delta^{34}S$ (with units of ‰) according to the following equation: $\delta^{13}C$ or $\delta^{34}S = [(Rsample/Rstandard) - 1] \times 1000$ where R =

$^{13}C/^{12}C$ or $^{34}S/^{32}S$. Reference standards were PeeDee Belemnite carbonate and Canyon Diablo Troilite for $\delta^{13}C$ and $\delta^{34}S$, respectively.

**Isosource analysis**

Isosource (Version 1.3.1), a mixing model software designed for calculations with *n* isotopes and *n* + 1 sources (Phillips & Gregg 2003), was used to assess the upper and lower feasible contribution of riverine organic matter to fishes and freshwater shrimps at each station in each estuary. Because a definite source cannot be calculated when there are *n* + 1 sources and *n* isotopes, we present results as a range (1-99 percentile) to avoid overemphasizing a single value such as the mean, which has limited meaning (Benstead et al. 2006, Winemiller et al. 2007). Use of the 1-99 percentile (rather than 0-100) also avoids long tails that can obscure the meaningful range of values (Phillips & Gregg 2003). Isosource is most useful for illustrating which sources are of limited importance rather than assigning exact contributions of a source (Benstead et al. 2006). Given our study objectives, we focused our analysis on the contribution of riverine organic matter rather than the feasible contribution of all potential organic matter sources.

Isosource tolerance and increment parameters were set at 0.05 and 1%, respectively. The tolerance parameter was increased where necessary to allow calculation of feasible contributions of riverine organic matter to fishes whose $\delta^{13}C$ or $\delta^{34}S$ values fell just outside the mixing polygon. These outside values could represent an uncollected data source; however, because they fell within the range of primary producer values, they most likely represent natural variation in primary producer values or small measurement error (Phillips & Greg 2003).

Before running Isosource models, average $\delta^{13}C$ values were adjusted to account for trophic enrichment. Pelagic fishes (*C. pectinatus, B. ronchus*), benthic fishes (*M. curema, D.*

*rhombeus*), and freshwater shrimps were adjusted 2.5, 2.0, and 1.5 trophic steps, respectively, above primary producers. Trophic enrichment was calculated at 1.4‰ per trophic step based on estimates of $\delta^{13}C$ enrichment in the tropics (Kilham et al. 2008). Because variations in trophic enrichment values may influence Isosource estimates, we compared the estimated contribution of riverine organic matter calculated with a trophic enrichment of 1.4‰ per step to estimates calculated with a trophic enrichment of 1‰ per step (McCutchan et al. 2003). Use of the lower enrichment value (1‰) decreased estimated contribution of riverine organic matter by only a small fraction (average <10%) of the maximum estimated contribution.

Phytoplankton and benthic microalgae are primary organic matter sources in estuaries and thus were included in mixing models. However, the use of average published values in our analyses could influence Isosource estimates if they are different than the actual values in these systems. To assess this possibility, we conducted a sensitivity analysis by varying values of phytoplankton and benthic microalgae used in Isosource models by ± 2‰ from their average published values. These variations had a relatively small effect (average <5%) on the maximum estimated contribution of riverine organic matter.

**Gut content analysis**

Gut content analysis was conducted to asses the contribution of riverine organisms to estuarine fishes. In addition to the four species targeted for isotope analysis, we also examined the guts from other common omnivorous fishes (*Caranx hippos, Caranx latus, Diapterus auratus, Lutjanus jocu, Micropogonias furnieri, Opisthonema oglinum, Pomadasys crocro, Scomberomorus regalis, Selene vomer, Sphyraena barracuda, Strongylura timucu*). This allowed us to examine the contribution of freshwater shrimps to a wider section of the fish community.

Because guts of some fishes were very small, the percent contribution of each food item could not be calculated volumetrically.  Instead, we placed a petri dish over a grid (2x2 mm) and, using a dissecting scope, calculated the portion of the petri dish covered by each distinct food item (as described in Ley et al. 1994).

## RESULTS

The Espiritu Santo and Mameyes estuaries were both distinctly stratified, with a nearly freshwater surface layer overlaying higher salinity water (Table 3.2).  Surface salinity averaged less than 3 PSU at all stations, with the exception of the Espiritu Santo station 3, where it averaged 10.6 $\pm$ 5.7 (s.d.).  In the Mameyes, average bottom salinity ranged from 17.9 to 29.2 whereas that in the Espiritu Santo was 5-8 PSU higher, ranging from 23.7 to 37.2.  Surface dissolved oxygen was similar between the two estuaries.  Bottom dissolved oxygen, however, was on average 4 and 2 mg/L higher in the middle and lower Espiritu Santo than in the same stations of the Mameyes, where low dissolved oxygen levels indicated hypoxic conditions. Surface turbidity was greater at Stations 2 and 3 of the Espiritu Santo than at the same stations of the Mameyes, whereas bottom turbidity showed no trend between the two estuaries (Table 3.2).

### Basal resources

Riverine organic matter was distinguishable from most other basal resources based on its $\delta^{13}C$ and $\delta^{34}S$ values.  Riverine organic matter $\delta^{13}C$ and $\delta^{34}S$ values averaged -28.2 $\pm$ 0.4‰ (se) and 10.8 $\pm$ 1.2, respectively, in the Espiritu Santo and -29.0 $\pm$ 0.13 and 5.7 $\pm$ 0.7 in the Mameyes.  Macroalgae $\delta^{13}C$ in both estuaries was similar to riverine organic matter; however, it was distinguishable based on its enriched $\delta^{34}S$ (18.1 ± 0.6 in the Espiritu Santo and 14.4 ± 2.5 in the Mameyes). Biofilm (a mixture of microalgae and detritus) was more enriched in both $\delta^{13}C$ and $\delta^{34}S$ than riverine organic matter (with $\delta^{13}C$ and $\delta^{34}S$ values of -23.0 ± 0.40 and12.6 ± 1.4, respectively in the Espiritu Santo and -21.9 ± 1.0 and 15.1 ± 0.5, respectively in the Mameyes). Average published $\delta^{13}C$ and $\delta^{34}S$ values of phytoplankton (-21.2 and 18.6, respectively) and benthic microalgae (-14.9 and 9.9, respectively), were more enriched than both biofilm and riverine organic matter.

Both $\delta^{13}C$ and $\delta^{34}S$ values of mangroves overlapped with riverine organic matter and thus could not be uniquely identified with stable isotopes (Table 3.1). Mangroves were found along less than 30 m of shore at the mouth of the Mameyes and only a small (< 3m wide) fringe of mangroves border the lower half of the Espiritu Santo estuary. Because mangroves were found in such limited areas and overlapped with riverine organic matter, they were excluded from Isosource models. A sensitivity analysis revealed that excluding mangroves had a limited (average of <10%) effect on the maximum estimated contribution of riverine organic matter.

**Fishes**

There was considerable overlap in the isotope values of three of the four fishes evaluated in this study (Figure 3.2). $\delta^{13}C$ and $\delta^{34}S$ values of the two pelagic species, *C. pectinatus* and *B. ronchus*, and one benthic species, *M. curema* were similar, with average $\delta^{13}C$ ranging from -18.6 $\pm$ 0.3‰ (se) (*B. ronchus*) to -17.8 $\pm$ 0.4 (*C. pectinatus*) and average $\delta^{34}S$ ranging from 12.3 $\pm$ 0.8 (*M. curema*) to 17.6 $\pm$ 0.8 (*C. pectinatus*). Average $\delta^{13}C$ and $\delta^{34}S$ of these three species were 18.2 $\pm$ 0.3 and 14.8 $\pm$ 0.5, respectively. In comparison, isotope values of the other benthic feeder, *D. rhombeus,* were depleted with an overall average $\delta^{13}C$ of -20.7 $\pm$ 0.6 (se) and $\delta^{34}S$ of 9.3 $\pm$ 0.9.

Isotope values of *D. rhombeus*, *B. ronchus*, and *C. pectinatus* were similar between the two estuaries, despite the fact that the Mameyes has a minimum flow requirement whereas the Espiritu Santo does not (Figure 3.3). The only notable difference in isotope values between estuaries was observed for *M. curema*, whose $\delta^{13}C$ and $\delta^{34}S$ values were more than 3‰ more enriched and depleted, respectively, in the Espiritu Santo station 3 than in the Mameyes station 3 (Figure 3.3c).

When isotope values of each species were evaluated along the salinity gradient in each estuary, differences among stations were relatively small (Figure 3.3). More depleted $\delta^{13}C$ and $\delta^{34}S$ values in the upper estuary (Stations 1), which would suggest a greater dependence on riverine organic matter, was only observed for *B. ronchus* (Figure 3.3b), whereas *M. curema* $\delta^{34}S$ were more enriched and $\delta^{13}C$ more depleted in the upper estuary (Figure 3.3c). Isotope values of *D. rhombeus* or *C. pectinatus* were similar between the upper and lower estuary (Figure 3.3a,d).

**Contribution of riverine organic matter: Stable isotope analysis**

The $\delta^{13}C$ and/or $\delta^{34}S$ values of *D. rhombeus* generally fell between that of riverine organic matter and benthic microalgae in both the Espiritu Santo and Mameyes estuaries (Figure 3.4a,b), suggesting that riverine organic matter was potentially important to this species. This was supported by Isosource estimates that the feasible contribution of riverine organic matter to *D. rhombeus* diet ranged from 34-69% in the Espiritu Santo and from 33-58% in the Mameyes, depending on station (Table 3.3).

In contrast, $\delta^{13}C$ and/or $\delta^{34}S$ values of *C. pectinatus*, *B. ronchus,* and *M. curema* were more enriched than riverine organic matter in both estuaries (Figure 3.4a,b). Isosource estimated a low feasible contribution of riverine organic matter to these three species, even in the estuaries' upper stations (Table 3.3). Feasible contribution of riverine organic matter was lowest for *C. pectinatus* – with a maximum feasible contribution of 10% in stations 1 and 2 of the Espiritu Santo and no feasible contribution (i.e., both the 1$^{st}$ and 99$^{th}$ percentile = 0) at the other stations. Estimated contribution of riverine organic matter to *B. ronchus* was always a minimum of 0 but ranged as high as 36% in stations 1 and 2 and as high as 12% in stations 3 of both estuaries. Estimated contributions of riverine organic matter to *M. curema* ranged from 0 to less than 28% across all stations except in station 3 of the Espiritu Santo, where it ranged from 11-13% (Table 3.3).

**Contribution of riverine organisms: Gut content analysis**

Freshwater diadromous shrimp were an important food item in the guts of *C. pectinatus, B. ronchus* and many common omnivorous fishes sampled from the Mameyes and Espiritu Santo estuaries (Table 3.4). While other items such as mud, organic detritus, unidentified material, and fish (Figure 3.5) comprised the greatest proportion of guts contents, freshwater shrimp composed an average of 22% and 18% of the gut volume of omnivorous fish collected from the Mameyes and Espiritu Santo estuaries, respectively (Figure 3.5). Freshwater shrimp were not detected in the guts of all omnivorous species sampled (Table 3.4), however, they were frequently encountered (in 37% and 39%) of guts of fish collected from the Mameyes and Espiritu Santo estuaries, respectively.

Freshwater shrimps were not found in the guts of the benthic species (*D. rhombeus* and *M. curema*). Rather, guts of these two species were composed almost exclusively of detritus (32.7.9%), and mud (60.9%). Small amounts of algae, vascular plant material, nematodes, amphipods, fish eggs, and insect larvae (sum of these = 0.32%) and unidentified material accounted for the reminder of their gut contents.

The vast majority of freshwater shrimps that were observed in the gut contents were juveniles, with only one larval shrimp recorded. Juvenile shrimps swim in dense congregations along the shores of the estuary during their upstream migration where they may be more vulnerable to predation than during their larval stage when they are planktonic and widely dispersed (Benstead et al. 2000). The enriched isotope values observed in these juvenile freshwater shrimps indicates they were comprised of estuarine rather than riverine organic matter (Figure 3.4). Estimated contributions of riverine organic matter to juvenile shrimps ranged from 0-32% in the Mameyes and 0-26% in the Espiritu Santo (Table 3.3).

While freshwater shrimp were the most important riverine derived organisms in fish diet, insects and their larvae were also encountered in the guts of fish in the Espiritu Santo and Mameyes Estuaries. However, their frequency was low (20%) compared to more common food items and they represented a very small percentage (<1%) of the gut volume of omnivorous fish. In addition, these insects could not be definitively attributed to riverine sources because they were types that could have come from the perimeter of the estuary.

## DISCUSSION

### Contribution of riverine organic matter: Stable isotope analysis

Several previous studies that have relied on $\delta^{13}C$ to trace organic matter sources have concluded that riverine organic matter is important to estuarine consumers, particularly in upper reaches of estuaries and during high flow periods (Incze et al. 1982, Rierra & Richards 1996, Ruesink et al. 2003, Hoffman et al. 2007). The use of both $\delta^{13}C$ and $\delta^{34}S$, however, is increasingly recommended for tracing riverine organic matter in estuaries, given the relationship between salinity, $\delta^{13}C$ values of dissolved inorganic carbon, and $\delta^{13}C$ values of autochthonous producers (Chanton & Lewis 2002). Studies that have utilized both $\delta^{13}C$ and $\delta^{34}S$, or additional techniques, such as lipid biomarkers, have generally found that riverine organic matter provides little direct contribution to estuarine consumers (Peterson & Howarth 1987, Canuel et al. 1995, Deegan & Garritt 1997, Kwak & Zedler 1997, Hughes et al. 2000, Chanton & Lewis 2002). In fact, low importance of riverine organic matter has been found even in high flow (average 926 $m^3/s$) riverine estuaries (Chanton & Lewis 2002) and after monsoon flushing of estuarine systems (Bouillon et al. 2004). As such, the majority of these studies support the growing consensus that, although riverine export may provide a substantial portion of the organic matter in estuaries (Goni et al. 2003), it is poorly incorporated by consumers because it is older and more recalcitrant than autochthonous algae (Sobczak et al. 2002).

Our isotope analyses suggest that riverine organic matter is not an important source of material to *C. pectinatus*, *B. ronchus*, and *M. curema*, even in the upper reaches the Espiritu Santo and Mameyes estuaries. Enriched $\delta^{13}C$ and $\delta^{34}S$ values of *C. pectinatus* suggest a dependence on phytoplankton. Enriched $\delta^{13}C$ and intermediate $\delta^{34}S$ values indicate dependence on a mixture of organic matter sources for *B. ronchus* and *M. curema*, with less than a third of their diet provided by riverine organic matter. In contrast, intermediate $\delta^{13}C$ and depleted $\delta^{34}S$ values of *D. rhombeus* indicate a potential dependence on riverine organic matter and benthic microalgae. This may be due to the fact that these fish are benthic feeders. Chanton and Lewis (2002) found that a few species of polycheates and amphipods derived more than 50% of their diet from riverine organic matter in the Apalachicola Bay Estuary. Although a thick layer of terrestrial detritus (i.e., decomposing leaf litter) was observed in grab samples taken from the

Espiritu Santo and Mameyes estuaries, the associated organisms were preserved in ethanol and could not be used for stable isotope analysis.  Thus, the extent to which benthic invertebrates rely on riverine organic matter could not be assessed in this study. Future studies of these and other tropical, riverine estuaries should examine a larger number of species, including benthic invertebrates, to determine the extent to which the wider benthic community assimilates riverine organic matter.

**Contribution of riverine organisms: Gut content analysis**

Isotope values of *M. curema*, *C. pectinatus,* and *B. ronchus* indicated little assimilation of riverine organic matter.  However, gut contents of *C. pectinatus, B. ronchus,* and many other omnivorous fishes revealed the importance of riverine-derived juvenile freshwater shrimps in the Espiritu Santo and Mameyes estuaries.  It is important to note that freshwater shrimps found in guts were almost exclusively juveniles, which had been feeding in the estuary for approximately eight weeks before metamorphosis.  Their isotopic signatures therefore reflected primarily estuarine-derived rather than riverine-derived organic matter (Table 3.3).  Although juvenile freshwater shrimps represent a source of estuarine organic matter to fish, their availability as a food source is dependent on connectivity between rivers and estuaries (Holmquist et al. 1998). Freshwater shrimps were not found in the guts of the two benthic species (*M. curema* and *D. rhombeus*) examined, which is not surprising given that freshwater shrimps are not benthic but rather planktonic (larval stage) or pelagic (juvenile stage) when they are in the estuary.

The few studies that have examined invertebrate export suggest that it may represent a potentially large, organic matter subsidy to estuarine fishes (Hudon 1994, Wipfli & Gregovich 2002).  In the only comprehensive study of freshwater invertebrate export to an estuary, Williams & Williams (1998) estimated an annual export of 30.9 * $10^6$ freshwater invertebrates to the Aber Estuary (North Wales). These invertebrates comprised a substantial portion of goby diets in the upper reaches of the estuary. Freeman et al. (2003) estimated that 11 billion freshwater diadromous shrimp larvae per year are exported from streams in the LEF. Export and downstream contribution of freshwater organisms from these rivers (and likely other Puerto Rican and Caribbean Island rivers) may be particularly high because of the predominance of freshwater diadromous species in the region. These studies, taken together with our results, illustrate the need to consider the contribution of freshwater diadromous species to estuarine fishes.

## CONCLUSIONS

Our isotope results indicate a potentially large contribution of riverine organic matter to *D. rhombeus* throughout the Espiritu Santo and Mameyes estuaries. Although riverine organic matter was of little direct importance to three other fishes (*M. curema*, *C. pectinatus,* and *B. ronchus*), our gut contents results illustrate that *C. pectinatus, B. ronchus,* and many other omnivorous fishes feed on freshwater-derived organisms, primarily juvenile freshwater shrimp. Thus, both riverine derived organic matter and organisms appear to play a role in the diets of estuarine fishes. These findings are particularly important in light of increasing water abstraction from rivers in northeastern Puerto Rico, where on an average day over 50% of instream flow is diverted for municipal uses (Crook et al. 2007).

Despite minimum flow requirements in the Mameyes River versus the Espiritu Santo River, which is characterized by a dam and large-scale water abstraction (March et al. 2003), we did not observe a systematic difference in the contribution of riverine organic matter to fishes between the two estuaries. We also did not observe a marked, systematic difference in the occurrence of freshwater shrimps in fish guts examined. This study, however, was conducted during a relatively high flow period (Ramirez et al. 2005). Potential effects of water management might be evident during low flow or drought periods when a relatively high proportion of stream flow and drifting shrimp are abstracted from the Espiritu Santo River (Benstead et al. 1999, Crook et al. 2007).

To our knowledge, the contribution of riverine-derived organic matter and organisms to estuarine fishes has not previously been assessed in Puerto Rico or other Caribbean Island estuaries. In addition to sampling during low flow periods when effects of water abstraction may be more pronounced, future studies should examine the contribution of freshwater shrimps to a wider range of the fish community and over a longer sampling period (e.g., to assess important periods of shrimp migration or fish feeding). The contribution of riverine organic matter to a wider section of the benthic community also merits additional study. The majority of stable isotope studies have focused on the contribution of riverine organic matter to large temperate areas where the link between inflow and valued fisheries is well established. Although the majority of Puerto Rico's commercially important fishes spend at least a portion of their life in Puerto Rico's estuaries (Center for Energy and Environmental Research 1979), the linkage between freshwater inflow and estuarine fishes continues to receive little study. Results of this study illustrate the importance of considering the effects of water management on tropical island estuaries, particularly given increased pressure on freshwater resources.

## ACKNOWLEDGEMENTS

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Table 3.1. Stable isotope ($\delta^{13}C$ and $\delta^{34}S$) values of basal organic matter sources, fishes, and juvenile freshwater shrimps in the Espiritu Santo (E) and Mameyes (M) estuaries, Puerto Rico. Stations 1 are furthest upstream and stations 3 are furthest downstream. Values represent average ± standard error, with the number of samples in parentheses. Where n=1, sample size is not presented. Riverine OM refers to leaves and leaf litter collected from the Espiritu Santo and Mameyes rivers.

| Type | Estuary | Station | $\delta^{13}C$ | $\delta^{34}S$ |
|---|---|---|---|---|
| Riverine OM | E | | -28.18 ± 0.49 (2) | 10.80 ± 1.2 (2) |
| Riverine OM | M | | -29.01 ± 0.18 (2) | 5.70 ± 0.7 (2) |
| Macroalgae | E | 2 | -30.38 ± 0.49 (2) | 17.45 ± 0.1 (2) |
| Macroalgae | E | 3 | -32.23 ± 0.30 (2) | 19.45 |
| Macroalgae | M | 1 | -31.25 | 18.15 |
| Macroalgae | M | 2 | -32.83 | 15.40 |
| Macroalgae | M | 3 | -30.25 | 19.70 |
| Mangrove | E | 1 | -30.43 | 6.25 |
| Mangrove | E | 3 | -27.86 | 6.15 |
| Mangrove | M | 3 | -31.12 | 14.65 |
| Biofilm | E | 1 | -22.90 ± 0.34 (2) | 15.30 |
| Biofilm | E | 2 | -24.10 ± 0.60 (2) | 11.80 |
| Biofilm | E | 3 | -22.07 ± 0.53 (3) | 10.60 |
| Biofilm | M | 1 | -21.68 ± 1.86 (3) | 14.65 |
| Biofilm | M | 2 | -21.43 ± 2.54 (3) | 16.05 |
| Biofilm | M | 3 | -24.11 | 14.70 |
| *B. ronchus* | E | 1 | -19.48 ± 0.51 (2) | 14.90 ± 0.07 (2) |
| *B. ronchus* | E | 2 | -19.29 ± 0.11 (2) | 14.79 ± 0.39 (2) |
| *B. ronchus* | E | 3 | -17.53 ± 0.95 (3) | 16.71 ± 1.18 (3) |
| *B. ronchus* | M | 1 | -19.58 ± 0.18 (3) | 13.71 ± 0.26 (3) |
| *B. ronchus* | M | 2 | -18.89 ± 0.53 (3) | 14.57 ± 1.05 (3) |
| *B. ronchus* | M | 3 | -17.37 ± 0.74 (3) | 15.33 ± 1.18 (3) |
| *D. rhombeus* | E | 1 | -19.30 ± 0.63 (2) | 8.36 ± 0.25 (2) |
| *D. rhombeus* | E | 2 | -22.29 | 7.39 |
| *D. rhombeus* | M | 1 | -21.97 | 12.11 |
| *D. rhombeus* | M | 2 | -21.40 ± 0.54 (2) | 8.88 ± 2.88 (2) |
| *D. rhombeus* | M | 3 | -20.40 ± 1.45 (2) | 9.37 ± 1.39 (2) |
| *M. curema* | E | 1 | -18.76 ± 1.74 (3) | 14.18 ± 1.45 (3) |
| *M. curema* | E | 3 | -13.90 ± 0.92 (3) | 8.56 ± 1.31 (3) |
| *M. curema* | M | 1 | -19.77 ± 1.15 (3) | 14.71 ± 0.53 (3) |
| *M. curema* | M | 2 | -19.04 ± 0.98 (3) | 12.83 ± 0.88 (3) |
| *M. curema* | M | 3 | -18.04 ± 1.14 (3) | 11.43 ± 1.72 (3) |
| *C. pectinatus* | E | 1 | -18.69 | 18.40 |
| *C. pectinatus* | E | 2 | -18.29 ± 0.34 (3) | 16.17 ± 0.29 (3) |
| *C. pectinatus* | E | 3 | -15.96 ± 0.63 (3) | 17.18 ± 0.61 (3) |
| *C. pectinatus* | M | 1 | -18.68 ± 0.89 (3) | 17.76 ± 3.14 (3) |
| *C. pectinatus* | M | 2 | -17.75 ± 0.41 (3) | 19.57 ± 1.39 (3) |
| Juvenile freshwater shrimps | E | 1 | -22.23 | 22.15 |
| Juvenile freshwater shrimps | E | 2 | -26.87 | 16.27 |
| Juvenile freshwater shrimps | M | 2 | -22.73 | 13.78 |
| Juvenile freshwater shrimps | M | 3 | -19.30 ± 1.22 (2) | 14.27 |

**Tables:**

Table 3.2. Average ± standard error of salinity (psu), dissolved oxygen (DO) (mg/L), and turbidity (ntu) at sampling stations in the Espiritu Santo and Mameyes estuaries, Puerto Rico. Measurements were taken at least twice per month between May and August 2004 at stations 1 (upper estuary), 2 (middle estuary), and 3 (lower estuary).

| | Espiritu Santo | | | | | |
|---|---|---|---|---|---|---|
| | 1 | | 2 | | 3 | |
| | surface | bottom | surface | bottom | surface | bottom |
| Salinity | 0.7 ± 0.4 | 23.7 ± 6.3 | 2.8 ± 1.1 | 35.5± 1.7 | 10.6 ± 5.7 | 37.2 ± 0.4 |
| DO | 7.7 ± 0.6 | 3.5 ± 1.3 | 6.9 ± 0.7 | 6.3 ± 1.4 | 5.5 ± 0.4 | 7.0 ± 0.9 |
| Turbidity | 9.2 ± 2.3 | 22.7 ± 12.3 | 20.2 ± 8.5 | 5.8 ± 2.5 | 23.6 ± 7.6 | 7.9 ± 0.9 |
| | Mameyes | | | | | |
| | 1 | | 2 | | 3 | |
| | surface | bottom | surface | bottom | surface | bottom |
| Salinity | 0.1 ± 0.0 | 17.9 ± 6.1 | 0.2 ± 0.0 | 27.7 ± 1.0 | 0.4 ± 0.1 | 29.2 ± 0.9 |
| DO | 7.7 ± 0.2 | 5.5 ± 1.9 | 7.4 ± 0.4 | 2.0 ± 0.8 | 7.0 ± 0.1 | 4.8 ± 0.5 |
| Turbidity | 9.1 ± 4.5 | 13.4 ± 3.0 | 7.1 ± 1.5 | 20.0 ± 10.8 | 6.7 ± 1.1 | 16.6 ± 4.1 |

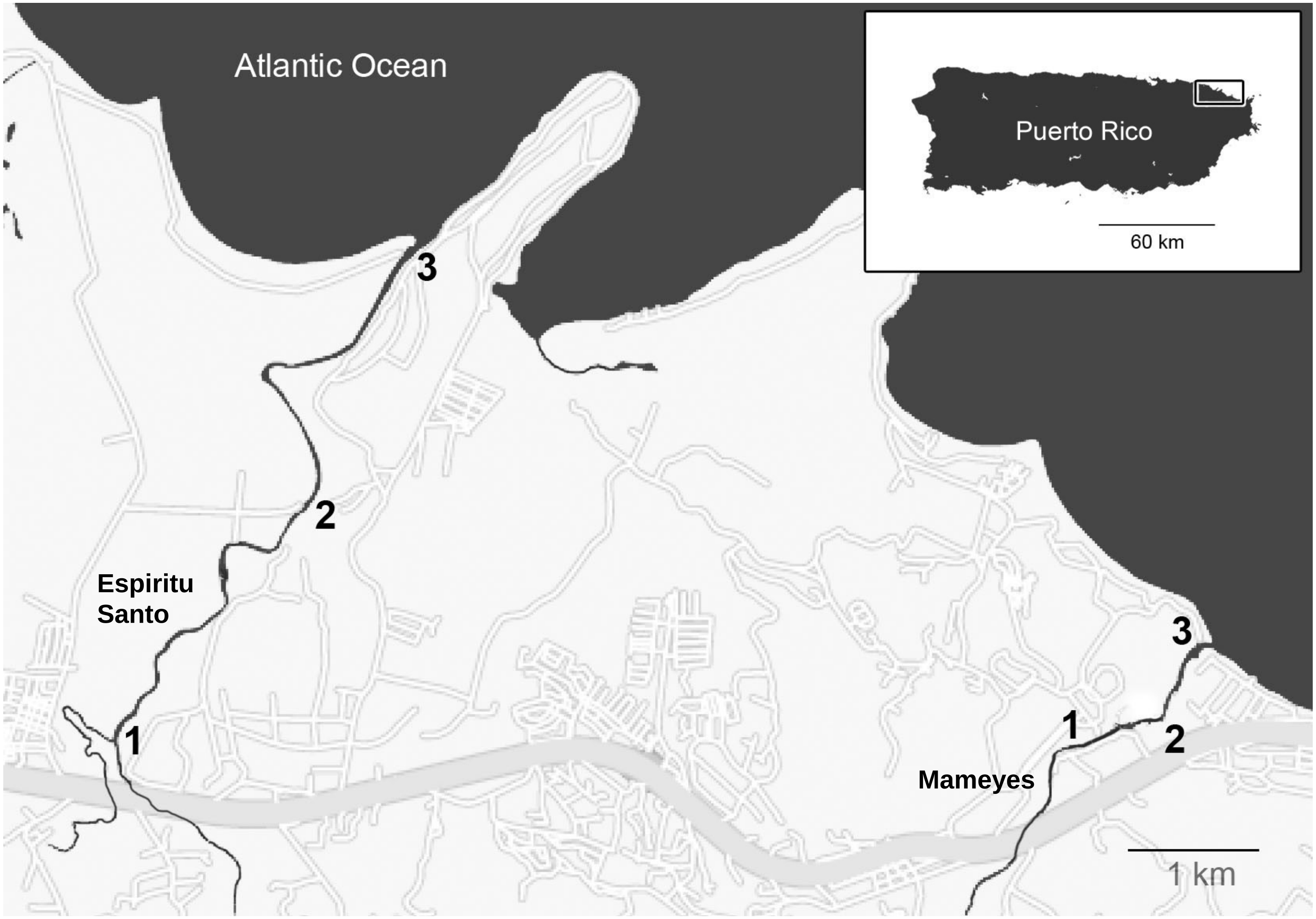
Table 3.3. Isosource estimated contributions (1-99 percentile) of riverine organic matter to fishes and shrimps in stations 1, 2, and 3 of the Espiritu Santo (E) and Mameyes (M) estuaries, Puerto Rico. An asterisk indicates that Isosource tolerance was adjusted to capture values falling just outside the mixing polygon.

| | Contribution of ROM (%) | | | | | |
|---|---|---|---|---|---|---|
| | Espiritu Santo | | | Mameyes | | |
| | 1 | 2 | 3 | 1 | 2 | 3 |
| *C. pectinatus* | 0-10 | 0-10 | 0-0 | 0-0 | 0-0 | 0-0 |
| *B. ronchus* | 0-35 | 0-34 | 0-9 | 0-32 | 0-24 | 0-12 |
| *M. curema* | 0-26 | | 11-13 | 0-24 | 0-27 | 0-24 |
| *D. rhombeus* | 38-51* | 34-69* | | 33-48 | 46-58 | 37-51 |
| Freshwater Shrimp | 0-5* | 0-26 | | | 0-32 | 0-26 |

Table 3.4. Percent volume (% v) and frequency of occurrence (% f) of freshwater shrimp in guts of fish in the Espiritu Santo and Mameyes estuaries, Puerto Rico. n= number of guts examined, excluding empty guts. *M. curema* and *D. rhombeus* are benthic species while the remaining species are pelagic or omnivorous feeders. Isotope analysis focal species are in bold.

| | Mameyes | | | Espiritu Santo | | |
|---|---|---|---|---|---|---|
| | % v | % f | n=32 | % v | % f | n=34 |
| ***Mugil curema*** | **0** | **0** | **9** | **0** | **0** | **2** |
| ***Diapterus rhombeus*** | **0** | **0** | **4** | **0** | **0** | **1** |
| ***Centropomus pectinatus*** | **4.5** | **66.6** | **3** | **46.6** | **60** | **7** |
| ***Bairdiella ronchus*** | **2.9** | **12.5** | **8** | **7.6** | **30** | **10** |
| *Caranx latus* | 70.8 | 100 | 2 | 19.6 | 50 | 4 |
| *Caranx hippos* | 0 | 0 | 1 | 0 | 0 | 1 |
| *Diapterus auratus* | | | | 0 | 0 | 1 |
| *Lutjanus jocu* | 57.1 | 100 | 1 | 0 | 0 | 1 |
| *Micropogonias furnieri* | 24.7 | 50 | 4 | | | |
| *Opisthonema oglinum* | | | | 0 | 0 | 1 |
| *Pomadasys crocro* | | | | 0 | 0 | 1 |
| *Scomberomorus regalis* | 0 | 0 | 1 | 0 | 0 | 1 |
| *Selene vomer* | | | | 0 | 0 | 1 |
| *Sphyraena barracuda* | | | | 0 | 0 | 1 |
| *Strongylura timucu* | 100 | 100 | 1 | | | |

Figure 3.1. Map of the Espiritu Santo and Mameyes estuaries, Puerto Rico. Sampling stations 1, 2, and 3 are indicated for each estuary.


Atlantic Ocean
Puerto Rico
60 km
3
2
Espiritu
Santo
1
3
1
2
Mameyes
1 km

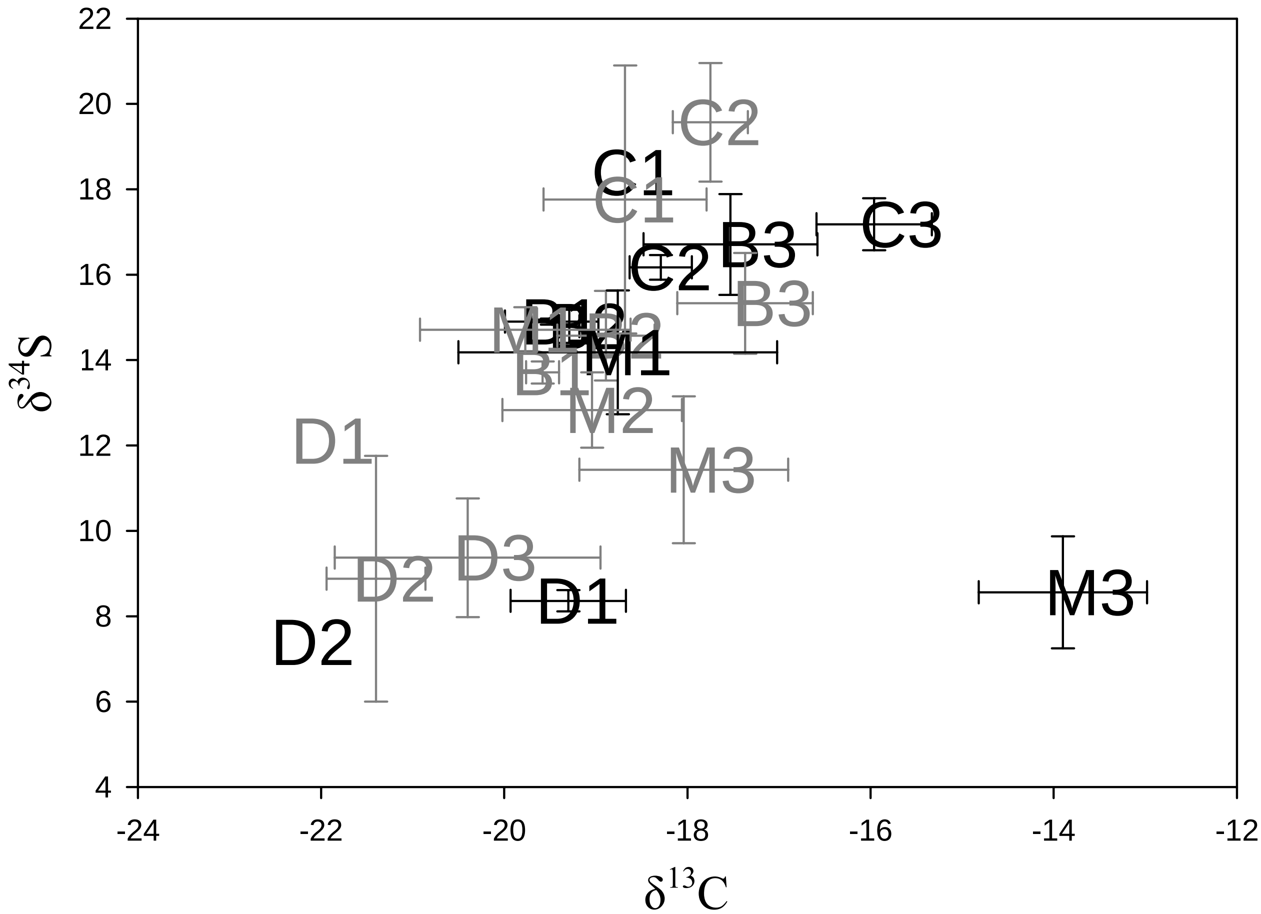



Figure 3.2. Dual isotopes plot of $\delta^{13}C$ and $\delta^{34}S$ for fishes in the Mameyes (grey) and Espiritu Santo (black) estuaries along a salinity gradient. D refers to *D. rhombeus*, C = *C. pectinatus*, B = *B. ronchus* and M = *M. curema*. Numbers indicate sampling station: Station 1 is furthest upstream and station 3 is furthest downstream.

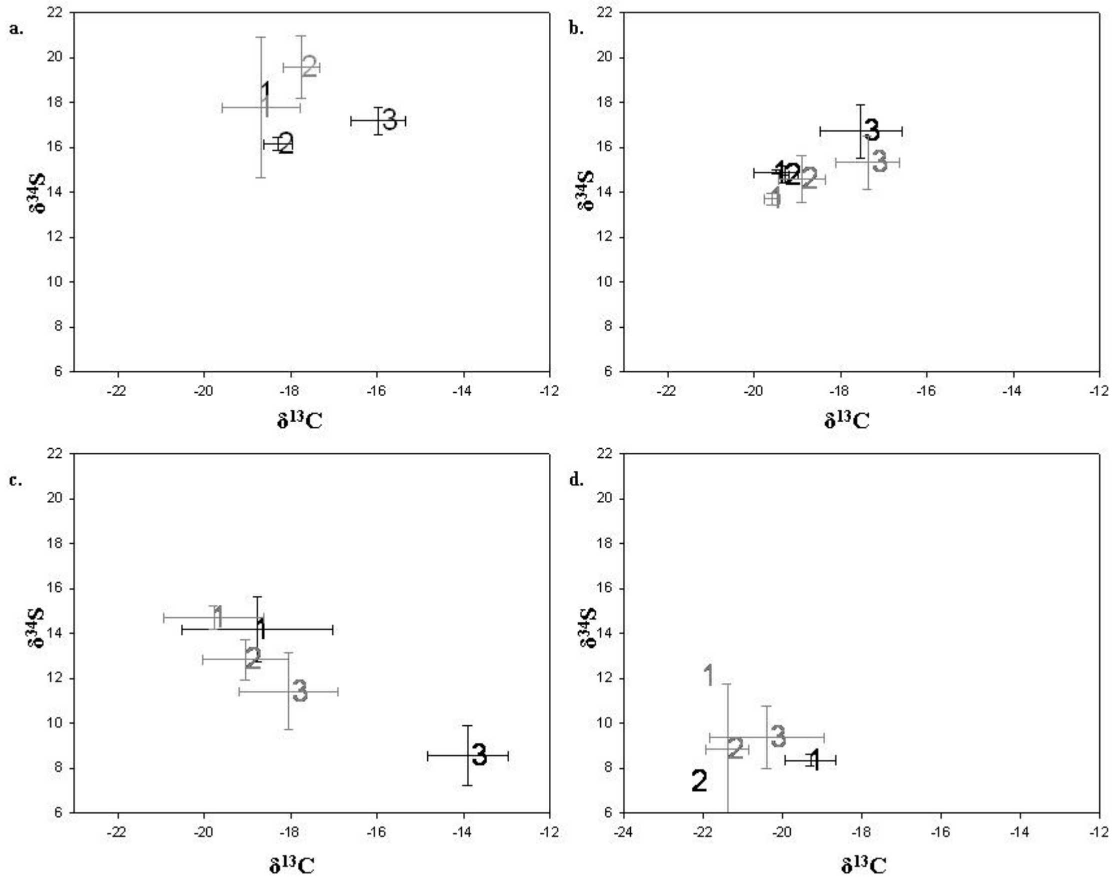
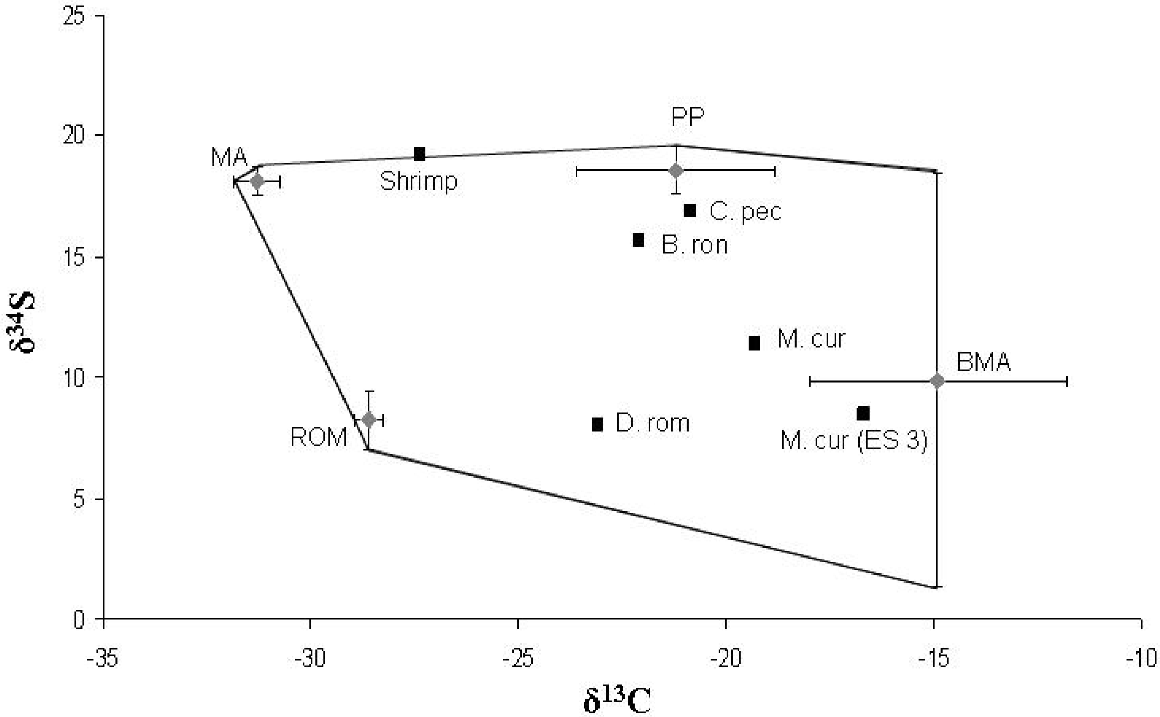



Figure 3.3 a-d. Dual isotopes plots of $\delta^{13}C$ and $\delta^{34}S$ for (a) *C. pectinatus*, (b) *B. ronchus*, (c) *M. curema* and (d) *D. rhombeus* in the Mameyes (grey) and Espiritu Santo (black) estuaries. Numbers represent sampling stations: Station 1 is furthest upstream and station 3 is furthest downstream.

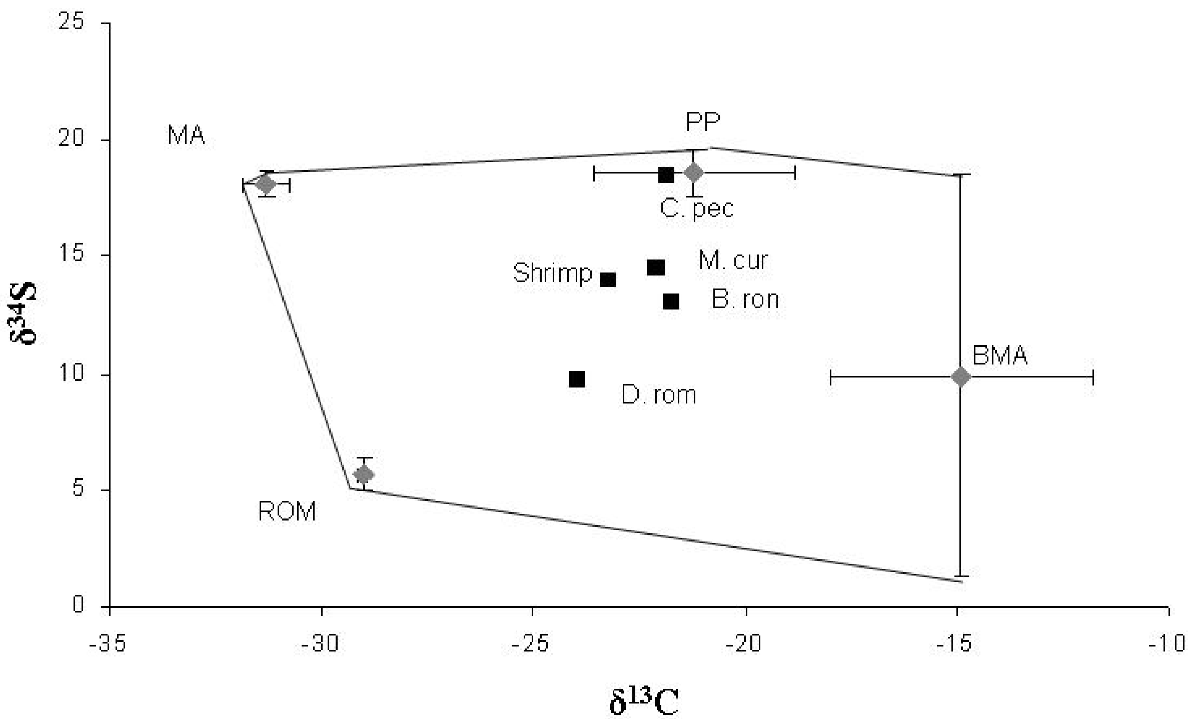
Figure 3.4 a,b. Average isotope ($\delta^{13}C$ and $\delta^{34}S$) values of basal organic matter sources, fishes, and freshwater shrimps in (a) the Espiritu Santo and (b) the Mameyes estuaries, Puerto Rico. *C. pectinatus* = C. pec; *D. rhombeus* = D. rom; *M. curema* = M. cur; *B. ronchus* = B. ron; freshwater juvenile shrimp = shrimp. Organic matter sources = riverine organic matter (ROM), phytoplankton (PP), benthic microalgae (BMA), and macroalgae (MA). Error bars for MA and ROM are ± 1 standard error and error bars for PP and BMA represent the range of published values. *M. curema* from Station 3 (ES 3) are presented separately in figure a because their values were distinct from other stations.

a.



25
20
15
10
5
0
-35
-30
-25
-20
-15
-10
δ34S
δ13C
MA
Shrimp
PP
C. pec
B. ron
M. cur
BMA
ROM
D. rom
M. cur (ES 3)


b.



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D. rom
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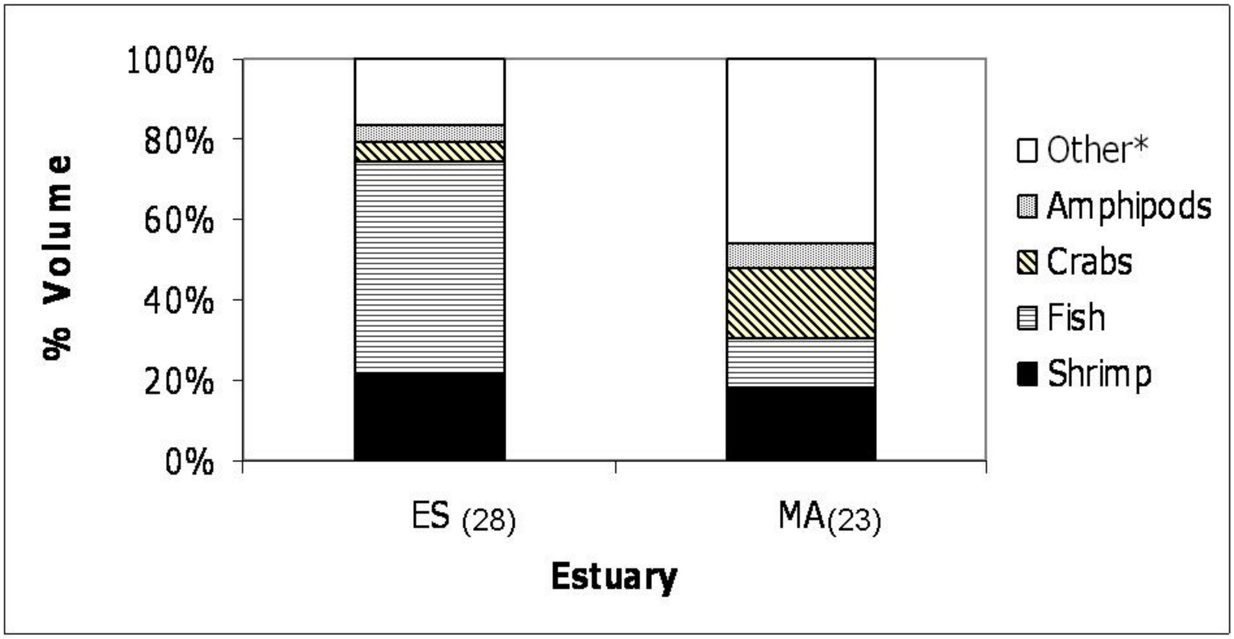


Other* is primarily detritus and unidentified material, with nominal (<3% each) amounts of terrestrial plant material, crustacean larvae, algae, adult/larval insect, nematode, gastropod, and isopod.

Figure 3.5. Percent composition (% vol.) by general categories of the stomach contents of pelagic and omnivorous fishes collected from the Espiritu Santo and Mameyes estuaries. Gut contents of the benthic fishes *D. rhombeus* and *M. curema* are presented in the text.

# CHAPTER 4:

# CONSIDERING ESTUARIES IN WATER MANAGEMENT DECISIONS:

# A STUDY OF NORTHEASTERN PUERTO RICO[1]

[1] Smith, K.L., Street, T.B., Gragson, T., Rodriguez del Rey, Z., Fowler, L., and Pringle, C.M. To be submitted to *Society and Natural Resources.*

**ABSTRACT**

Traditional frameworks of fragmented legal mandates and administrative jurisdictional overlap complicate management of estuaries, which face watershed-level threats. For some high-profile estuaries, innovative programs have been developed to advance watershed-level management, by improving communication among the multiple agencies with relevant jurisdictions. Although most estuaries are managed outside of these innovative watershed-level management programs, the majority of institutional research has focused on such programs. In contrast, factors influencing watershed-level management efforts under traditional legal and administrative frameworks have received little study. In this paper, we examine management of a watershed-level issue, inflow to estuaries, under the traditional legal and administrative framework. We focus our study on northeastern Puerto Rico, a region that falls outside of an innovative watershed management program, and where increasing water demand has drawn attention to inflow management. We first examine the legal authorities through which managers address inflows to estuaries in northeastern Puerto Rico. We next present results of manager interviews regarding (1) the current extent of management of freshwater inflows to estuaries and (2) factors influencing the management of this issue. The primary legal authorities applied to inflow management in northeastern Puerto Rico are the Clean Water Act, the Rivers and Harbors Act, and the Puerto Rico Water Law. Inflow management actions under these authorities have focused on riverine, rather than estuarine, inflow needs. Our results illustrate the role of several key factors in limiting management of inflow to estuaries: low priority of inflow to estuaries, lack of relevant scientific information, lack of a champion pushing the issue, programmatic limitations, as well as issues related to Puerto Rico's institutional and political environment that affect natural resource management in general.

*Key words: Inflow, estuaries, institutional analysis, administrative framework*

## INTRODUCTION

Addressing watershed-level threats to estuaries is difficult within the traditional management framework of fragmented, overlapping, and sometimes competing laws, jurisdictions, and mandates (Crowder et al. 2006) which are rarely applied on a coordinated, watershed scale. This is due in part to the large number of agencies with fragmented jurisdictions that are responsible for application of these authorities (Schneider et al 2003). In addition, coastal agencies often lack jurisdiction to apply legal authorities to address upstream issues affecting estuaries, and upstream agencies do not always consider or prioritize downstream impacts in their management actions.

Innovative programs and administrative structures have been developed to improve watershed-level administration and management of several high-profile estuaries. Common objectives of these programs include addressing watershed-scale issues such as nutrient pollution (e.g., Chesapeake Bay Program) or freshwater inflow (e.g., CALFED) that affect downstream estuaries (Lurie 2004; Lubell 2004; Heikkila and Gerlak 2005). A key component of such programs also includes improving communication and coordinating decision making among the multiple agencies with jurisdiction over these estuaries and watersheds (Schneider et al. 2003).

Research on the administrative factors of watershed-level management is increasing (Imperial 1999; Lurie 2004). Most research, however, has focused on innovative management programs instituted for selected, high-profile estuaries (Heikkila and Gerlak 2005) even though most estuaries are actually managed under traditional frameworks. Thus, it is important to also understand the factors that influence managers' ability to address watershed-level issues within these traditional management frameworks (Lurie 2004). This paper examines management of a watershed-level issue, inflow to estuaries, within the traditional management framework.

Ensuring adequate inflows to estuaries poses a challenge to estuarine managers in many regions due to growing demand on water resources (Montagna et al. 2002). For the purposes of this study we focus only on water quantity, defining inflow as the volume of freshwater remaining in a river per unit of time.

We examine in particular how managers address inflow to estuaries within the traditional legal and administrative framework of northeastern Puerto Rico. Recent studies illustrate the importance of inflow to estuaries in northeastern Puerto Rico (Smith et al 2007), but no innovative watershed-level estuarine management programs are currently in place in this region. We first examine the legal authorities relevant to inflow management and how these authorities are applied by the implementing agencies. We then present results from manager interviews of factors influencing management of inflow to estuaries. We conclude with recommendations to improve management of inflow to estuaries under the traditional management framework.

**METHODS**

We focus our study on the region of northeastern Puerto Rico, specifically the estuaries and watersheds located between Rio Grande and Fajardo (Figure 1). This region is mountainous, giving rise to short steep drainages with no more than 30 miles from headwaters to estuaries. While the headwaters of these watersheds are largely protected in the El Yunque National Forest, there has been considerable development in the coastal plain over the past 30 years (Thomlinson and Rivera 2000, Ramos Gonzales 2001). In addition, development of water resources has increased in this region, primarily for municipal uses (March *et al*., 2003; Ortiz-Zayas and Scatena 2004; Crook et al. 2007).

Data for this research were collected through in-person, semi-structured interviews using a protocol developed to ensure that questions were focused and systematic (Schensul et al. 1999; Bernard 2002). Interview questions were based on results from exploratory interviews with key local managers in 2006. Major themes addressed in the interviews included: management activities in northeastern Puerto Rico regarding inflow to estuaries; the legal basis or mandates for these activities; and interactions between managers in different agencies (e.g., coastal and inland agencies) regarding inflow to estuaries (Appendix 4.1). Prior to conducting any interviews, the protocol was reviewed for clarity by both academic and management experts within and outside Puerto Rico. Small adjustments to the interview questions were made as the interviews progressed, primarily to improve discussion flow.

The number of managers in Puerto Rico with a role in inflow management is small so we used a purposive sampling design to select from the universe of all managers with a potential role in such management (Bernard 2002). Thus, we interviewed both technical experts (e.g., planners, biologists, hydrologists) and administrators (e.g., program managers, administrators, lawyers) from each relevant agency involved in water/estuarine management. Key informants were selected based on their knowledge and involvement in inflow or estuarine management. Additional informants were identified by interviewees during the course of the study. For logistical reasons we limited our interviews to managers actively working in Puerto Rico, however, some Federal agencies (e.g., the National Marine Fisheries Service and the U.S. Environmental Protection Agency) have relevant staff both within and outside of this U.S. dependent territory.

Interviews were conducted in person and recorded when permission was granted. Digital transcripts were produced from all interviews and then coded iteratively. Key concepts were identified then grouped into categories in successive analyses of the transcripts (Bernard 2002). Categories and concepts were modified as review of the transcripts continued. In addition to interview data, a variety of documents and laws related to estuarine and upstream water management were also examined.

## LEGAL FRAMEWORK

Inflow management in the Commonwealth of Puerto Rico, a non-incorporated dependent territory of the United States of America, is covered by relevant federal, commonwealth, and local environmental and resource laws. Here, we focus only on the federal and commonwealth laws that serve as the framework through which managers in the various agencies may address inflows to estuaries. In our synthesis of this legal framework, we focus on the authorities which are currently applied to the management of inflow to estuaries. Because limited management of this resource has actually occurred, we also include those authorities which, although relevant, have not been applied to this issue.

### Federal laws

Of the federal authorities, the Federal Water Pollution Control Act of 1973, known more generally as the Clean Water Act[2] (CWA), and the Rivers and Harbors Act[3] (RHA) have the greatest relevance to inflow management in northeastern Puerto Rico.[4] Section 404 of the CWA covers the discharge of any dredged materials into navigable waters, and Sections 9 & 10 of the RHA address construction in navigable waters, including the permitting of new dams and water

[2] 33 U.S.C. §§ 1251-1276 (2000).
[3] 33 U.S.C. § 403 (2000).
[4] Although technically separate, the RHA has largely been subsumed into the CWA.

intake structures.[5] Construction and operation of these structures ultimately affects the quantity of freshwater remaining instream and thus inflow to estuaries.

The U.S. Army Corps of Engineers (COE) regulates these activities through the issuance of CWA and RHA permits. The COE issues these permits in consultation with federal and commonwealth natural resource management agencies as required by the Fish and Wildlife Coordination Act[6] (FWCA). This procedural statute mandates that all federal agencies consult with the U.S. Fish and Wildlife Service (FWS), the National Marine Fisheries Services (NMFS), and the relevant state fish and game department whenever a stream or other water body is proposed or authorized to be modified so as to prevent or mitigate the loss of fish and wildlife resources. Because several major rivers in Northeastern Puerto Rico originate within the El Yunque National Forest, the U.S. Forest Service (USFS) also plays a role in the administrative framework affecting inflows to estuaries by suggesting conditions for the COE permits and issuing Special Use Permits for construction of water intakes located within the Forest boundaries. The Puerto Rico Aqueducts and Sewers Authority (PRASA), the governmental corporation charged with supplying Puerto Rico's water, is the primary applicant for CWA and RHA permits for dams and water intakes.

One federal authority, although relevant, has not yet been applied to the management of inflows to estuaries in northeastern Puerto Rico. This authority, the Magnuson-Stevens Fishery Conservation and Management Act[7] (MSFCMA), requires federal agencies to consult with the National Marine Fisheries Service (NFMS) on all actions that may adversely affect essential fish habitat (EFH). EFH is defined as "waters and substrate necessary to fish for spawning, breeding,

[5] Under the National Environmental Policy Act (NEPA), issuance of a permit for large projects or those with potentially significant environmental impacts may require an Environmental Assessment (EA) or an Environmental Impact Statement (EIS).
[6] 16 U.S.C. §§ 661-667e (2000).
[7] 16 U.S.C. §§ 1801-1882 (2000).

feeding, or growth to maturity." As will be discussed later, although estuaries in northeastern Puerto Rico are designated as EFH for several species, NMFS has not addressed yet addressed inflow to estuaries under this authority.

Another authority, the Endangered Species Act[8] (ESA), has been used to designate inflow criteria for certain flow dependent species in several regions of the U.S. (Ward and Booker 2003) but is not currently relevant to this issue in northeastern Puerto Rico. The ESA provides NMFS (marine species) and FWS (non-marine species) the authority to take actions protect to endangered or threatened species and their habitats. While many freshwater and estuarine species are influenced by freshwater inflows in Puerto Rico (March et al. 2003; Smith et al. 2007), none of these species are currently ESA listed.

**Commonwealth laws and agencies**

The U.S. Congress has delegated to Puerto Rico the right to self-govern local issues. Thus, Puerto Rico has primary authority over water allocation, the authority most relevant to management of inflow to estuaries. In Puerto Rico, authority for water allocation falls under the Act of the Conservation, Development, and Use of the Water Resources of Puerto Rico,[9] referred to more generally as the Water Law. The Water Law declares that all waters of Puerto Rico are the property and patrimony of the commonwealth and are to be administered and protected by the government as a public good.

The Puerto Rico Department of Natural and Environmental Resources (DNER) Water Franchises Office currently oversees water allocation via issuance of water franchise permits. Permits are issued based on a technical review to ensure that 50% of Q99 as well as a sufficient

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[8] 16 U.S.C. §§ 1531-1543 (2000).
[9] La Ley Num. 136 de 3 de junio de 1976.

quantity of water to supply downstream intakes will remain instream. Q99 refers to a discharge (i.e., amount of water) that is equaled or exceeded 99 percent of the time. It is derived from a flow duration curve, a method of displaying the complete range of river discharges, from lowest flows to flood events (Smakhtin 2001). A policy of 50% of Q99 ensures that only a very small percentage of water that is unlikely to provide sufficient inflows for many aquatic species will remain instream (Scatena and Johnson 2001). No studies have examined the adequacy of this instream flow criteria for estuarine species.

The Water Law grants the DNER the authority to develop a water plan to conserve, develop, and regulate water uses. The DNER Office of Water has completed a draft Water Plan,[10] however, the Plan is not yet finalized and implemented, and thus not immediately of relevance to inflow management. In addition, criteria in the Plan currently focus on riverine, rather than estuarine inflow needs. Nevertheless, the Water Plan development is important to the legal and policy framework for management of inflow to estuaries in northeastern Puerto Rico for several reasons. First, the Water Plan development process has lead to several workshops devoted to inflow management. Second, managers from many agencies have been involved in developing inflow criteria for the Water Plan. Third, the Plan is mandated by law and when implemented, will be the basis for inflow management in Puerto Rico. Thus managers' efforts to include inflow provisions in the Water Plan will likely influence the legal and policy framework for inflow management in Puerto Rico.

Under another relevant authority, the federal consistency provision of the Coastal Zone Management Act[11] (CZMA), no efforts have been made to address inflow to estuaries in northeastern Puerto Rico. The Puerto Rico Coastal Management Program (CMP) has authority

[10] http://www.drna.gobierno.pr/oficinas/arn/agua/negociadoagua/planagua/oficina-del-plan-de-aguas (accessed March 10th, 2008)
[11] 16 U.S.C. §§ 1451-1464 (2000).

under this statue to require that federal actions and activities in its designated Coastal Zone[12] be consistent with enforceable policies of approved state coastal management programs. This authority also applies to inland activities (e.g. dam construction) that may affect the Coastal Zone. As will be discussed later, the CMP has not used this authority to address inland water management decisions affecting inflow to estuaries.

**Manager's role in inflow management**

In summary, legal mandates exist for addressing inflow to estuaries, but these mandates are rarely implemented. Under the CWA and RHA authorities, the COE has provided permit conditions to ensure adequate inflows for new dams and water intakes. These efforts, however, have focused on riverine rather than estuarine inflow management. While providing for riverine inflows will to some extent also provide for inflow to estuaries, inflow needs for estuaries may differ from those of rivers. The Puerto Rico Water Law provides the DNER with authority for water allocation decisions and thus the greatest potential authority over inflow management. However, the DNER Water Franchise permit criteria provide only minimal inflow protections. The Water Plan, once implemented will provide another route for inflow management; however, it too has focused on riverine rather than estuarine inflows. Finally, the two mandates that provide coastal agencies the authority to address inflow to estuaries (i.e., the MSFCMA and the CZMA) have not been applied to this issue. Given that this legal framework does not specially require that inflow to estuaries be addressed, how managers prioritize this issue and implement relevant laws is central to management of this resource. Results of our interviews illustrate

[12] The Puerto Rico CMP's designated coastal zone extends inland approximately 1 km from the mean high tide and also includes some areas of associated coastal wetlands even further inland.

factors influencing managers' actions regarding inflow to estuaries within the legal and administrative framework outlined above.

## RESULTS

Given our purposive sampling design, we attempted to interview all managers with a role in inflow management. A total of 16 interviews were conducted with 18 managers from six agencies and multiple programs within these agencies (Table 4.1).[13] Given this population, these interviewees have diverse responsibilities related to inflow management. Depending on the agency or office, biologists and hydrologists provide consultations on federal or commonwealth permits for projects that may affect inflow (e.g., construction of a new dam); review permit applications, including comments provided by managers in other offices or agencies; and/or participate in relevant research or monitoring efforts. Often these managers have diverse duties, including efforts unrelated to inflow management. Administrators make decisions regarding allocation of staff and other resources and provide overall direction for their office or program.

Analysis of interview transcripts yielded five primary factors that influence the management of inflow to estuaries in northeastern Puerto Rico: low priority of the issue; lack of relevant science and data; lack of a champion; programmatic limitations; and the larger institutional and political environment surrounding natural resource management in Puerto Rico. Evidence (number of interviewees who mentioned each factor) supporting these factors is presented in Table 4.2 and discussed in greater detail below.

[13] All individuals contacted at the agencies listed in Table 4.1 agreed to be interviewed. However, despite several emails and calls to multiple individuals, no response was received within the time frame of this study from recommended contacts at the Puerto Rico Planning Board and the Puerto Rico Aqueducts and Sewer Authority. In two offices, managers asked to be interviewed at the same time.

**Factor 1: Low priority of inflow to estuaries**

Results of manager interviews indicate that inflow to estuaries is a low management priority (n=11). Natural resource management issues frequently mentioned as higher priority included water quality and the management of inflow for riverine species. In this vein, five respondents emphasized that water quality, rather than water quantity, was either their primary concern, the primary focus of their program, or the primary threat to Puerto Rico's rivers, estuaries, and coasts. To illustrate, in response to a question about his management responsibilities regarding inflow to estuaries, an interviewee (P1) voiced his greater concern for sediment and nutrient pollution in rivers, estuaries, and coastal areas:

> Sediment is the major issue for me. If we could control sediment we would address 80% of issues impacting estuaries and coastal areas.

Another five interviewees noted that management activities regarding inflow in northeastern Puerto Rico have focused on the needs of riverine, rather than estuarine, species and habitats. However, these interviewees did not specifically note that riverine habitats were a higher priority than estuarine habitats, but simply that management efforts had focused on riverine inflows. To illustrate, an interviewee (P3) directly involved in the Water Plan development processes stated "right now we are mainly looking at issues related to streams not estuaries." Another interviewee (P1), involved in the Water Plan interagency meetings, expressed "I don't know why flow to estuaries was not addressed [in the water plan] but at least rivers are now covered."

CMP documents also reveal the low importance of inflow to estuaries. Potential effects of water management decisions on estuaries, coasts, and diadromous species are not mentioned within Puerto Rico's Coastal Management Plan (NOAA 1978). In addition, in the most recent CMP coastal zone enhancement grant work plan, freshwater inflow is stated to be sufficient for Puerto Rico's estuaries, excepting the Jobos Bay Estuary, without references or data to support this conclusion (Puerto Rico Department of Natural and Environmental Resources 2006).

**Factor 2: Lack of related science and data**

Inflow research in northeastern Puerto Rico has focused almost exclusively on riverine habitats and species. Research institutions in northeastern Puerto Rico, such as the National Science Foundation's Luquillo Long Term Ecological Research Site (LTER) and the USFS International Institute of Tropical Forestry, have conducted and funded scientific studies related to inflow needs of riverine species and habitats (Benstead et al. 1999; Scatena and Johnson 2001). Additional studies have illustrated the effects of dams and water management on riverine species (Holmquist et al. 1998; March et al. 1998; Greathouse et al. 2006). Results of these studies have informed water management decisions for riverine species (Scatena 2001; March et al. 2003). Specifically, consulting agency biologists have relied on these studies to justify and make recommendations for the conditions contained in COE permits. These studies have also motivated and informed riverine inflow provisions in the Water Plan.

In contrast, there is a lack of research on estuarine inflow needs. This issue was noted by interviewees with a role in funding aquatic research. An interviewee at the DNER (P5) specifically mentioned that they "rarely" reviewed scientific collection permits related to estuaries, in contrast to "frequent" permit applications for scientific studies of coral and riverine organisms. Another interviewee with a role in distribution of coastal research grants (P18), expressed that the only studies funded by his office regarding estuaries in northeastern Puerto

Rico or inflow to estuaries throughout the Commonwealth were those recently conducted by the lead author.[14] Supporting these interview data, no published studies of inflow to estuaries in Puerto Rico were found from a comprehensive literature review. This review included the contents of high impact journal databases (e.g., ISI Web of Science) and databases that include grey literature (e.g., Google Scholar).

Lack of biologists with estuarine expertise was also mentioned by interviewees. When asked, interviewees could not refer the authors to an estuarine biologist/ecologist in Puerto Rico; although two interviewees did refer the lead author to agency biologists who they considered to have estuarine expertise. When interviewed, however, these biologists specifically stated that they had only limited expertise regarding estuaries. To this same end, another interviewee (P6) expressed concern regarding the lack of a local estuarine biologist:

> *I would like to see someone at DNER with an interest in estuaries. They have lots of planners and engineers but not many biologists…The water resources people want to do things right but they don't have the biological expertise…..[a university scientist] is starting to train people in estuaries. So at least there is a candle being lit in terms of estuaries.*

Many interviewees (n=8) noted that the lack of information on estuarine inflows limited management actions. For example, the lack of estuarine research was also noted by an interviewee involved in COE permit consultations (P13) who referred to estuaries and coastal streams as "a research gap." Similarly, another interviewee (P6), noted that in comparison to rivers there is very limited information about estuaries and that this lack of information hinders management efforts:

[14] Chapters 2 and 3 of this dissertation.

*Estuaries are a hard one. People recognize that these are the lower parts of rivers but no one really knows what to do with them. There have been some studies on hydrology but not much is known about what we should or shouldn't be doing. Is low inflow a big issue? When the big floods come, flow is really a non-issue. We really have no understanding of how inflow relates to fisheries. Everyone knows that flow affects dissolved oxygen in the estuary and under certain conditions there may be fish kills but we don't know what should be done for management. Much more is known about rivers and so it's easier to know what to do for their management.*

A similar concern was mentioned by another interviewee (P4):

*With regard to estuarine inflow issues there is a complete lack of data in the area. The life cycles of [freshwater diadromous] shrimps and other migratory species just aren't known. We don't even know where the shrimps are in the estuary…. Criteria [for estuarine inflows] can't be set because we just don't know.*

Lack of information regarding estuaries was also mentioned in relation to inflow considerations in the Water Plan. Interviewees involved in the Water Plan development noted both the lack of available data and lack of experts on estuarine inflow. Several interviewees acknowledged that without additional estuarine research and expertise, estuaries will remain a gap in the Water Plan:

*We know that estuaries need water or else it's no longer an estuary. Estuaries need to be studied more - there are not a lot of studies right now* (P3)

*It's really hard to get good answers in an estuary – you need a surrogate or indicator to set flows. …I don't really know anyone here in Puerto Rico who could work on these questions and get these answers in estuaries.* (P17)

*Guidelines for [inflow to] estuaries are a big hole in the Water Plan.* (P13)

Another interviewee highlighted the broader management implications of the lack of estuarine research. Because little is know about estuarine species, little is also know about their population status and trends. This interviewee suggested that greater study might lead to detection of potentially endangered species, and ultimately to additional tools (e.g., under ESA authorities) for inflow management:

> *I was recently talking to [another biologist] about a rare freshwater bivalve that may be endangered. There may also be a rare species of mullet in those estuaries…. If these or other such species were better documented it might lead to management actions – but we need more information before that could happen.* (P5)

**Factor 3: Lack of a champion**

The role of key individuals or "champions" in inflow management was frequently mentioned (n=15). Interviewees, however, only highlighted efforts of champions of *riverine* inflow management. No interviewee mentioned an individual key to the management of *estuarine* inflow. Nevertheless, these results illustrate the importance of a champion in achieving inflow considerations within the existing legal and administrative framework and, as such, the implications of lacking a champion of estuarine inflow issues.

The efforts of one specific agency biologist was mentioned by nearly every interviewee (n=14). This champion was described as a "pioneer on maintaining minimum flows for aquatic species" (P1). In describing a widely publicized debate over permitting of a proposed dam, another interviewee (P16) described the critical role of this biologist (expressed in this quote as FWS):

> *Tourism interests were for the dam, DNER was for the dam, the government was for the dam. As more information came to the table, FWS joined in making arguments for free flow of the river, for [migratory freshwater shrimp passage], now they are instrumental, they always*

*comment on maintaining minimum flow in rivers. FWS is now the protector of rivers in PR.*

An interviewee (P10) involved in the COE regulatory process noted the importance of input from natural resource management staff regarding CWA and RHA permits.

*We only look at something upon beginning of the permit process – input, competence, and affirmative action from the resource agencies is critical. If we don't get a comment, we assume there is no issue…*

This interviewee also noted the quality and reliability of the aforementioned biologist's agency:

*We always get comments from [agency]. They have a very strong staff and always provide comments.*

In addition, interviewee P10 described this biologist, who oversaw the majority of inflow consultations at this agency, as "very competent" in her interactions with the COE on permit consultations. Interviews with managers involved in the development of the Water Plan also illuminated the role of this champion in promoting the inclusion of inflow considerations and criteria in the Water Plan. Her efforts included attendance at the Water Plan development meetings, presentations on instream flows for riverine species at relevant meetings, and frequent communication regarding inflow issues with staff at the Office of Water.

Flexibility, personal interest, and expertise combined with a high level of professionalism likely contributed to this individual's role as a champion of riverine inflows. During an interview, this individual expressed several reasons for her role in riverine inflow issue. First, there was sufficient flexibility in her job description to work on an issue of "natural interest" that she had due to her academic training and research experience in invertebrate ecology.[15] Because of this interest and expertise, she was able to continue work on inflow issues via regulatory consultations and the development of the Water Plan even after taking a new and unrelated position in the same office. Second, this biologist's knowledge and skills were respected by the wider natural resource management community who acknowledged her professionalism, strong communication skills, and technical expertise. To illustrate, this biologist was noted by informants P4 and P5 as "providing high quality information," "professional," "exceptionally knowledgeable," and "great at explaining things step by step." A regulatory biologist (P11) reported receiving "consistent, high quality" comments and participation from this biologist. The lead author specifically witnessed the professionalism of this individual, who had drafted pages of notes regarding watershed and inflow activities in Puerto Rico prior to our interview.

**Factor 4: Programmatic limitations**

Programmatic issues limiting management of inflow to estuaries were identified in our analysis (n=10). These included geographic boundaries and staffing shifts that limited the ability of managers to participate in CWA and RHA inflow consultations.

*Geographic boundaries*

Geographic boundaries of the El Yunque National Forest may limit USFS managers' ability to address inflow to estuaries. Interviewees reported mixed success in USFS efforts to address estuarine inflow. A USFS biologist noted that while in the past his activities were limited to the forest boundaries, the USFS's adoption of ecosystem management principals

[15] Puerto Rico's dominate riverine invertebrates, migratory freshwater shrimps, are directly affected by dams and water management.

allowed him to contribute to research, monitoring, and regulatory consultations downstream of the Forest boundaries:

> *Up to the year 2000 my work was very much constrained to the [El Yunque National] Forest. Not any more – the USFS is very happy to go outside the Forest – and that is where the issues are. If you don't protect the estuaries and lowlands you can lose biodiversity in the Forest.* (P12)

In contrast, however, another interviewee noted that efforts to address projects affecting inflow outside the forest remain somewhat limited:

> *I spent a lot of time working on permits for water intakes in the [El Yunque National] Forest. Outside the Forest, I commented on some permits, but fewer. I could have spent all my time commenting on those [outside permits] if I tried to comment on all of them.* (P13)

An interviewee from outside the USFS (P6) who participated in COE permit negations in and around the El Yunque National Forest also noted limits to USFS staff's ability to work outside Forest boundaries to obtain inflows for low-land streams and estuaries:

> *During a meeting with COE about [a proposed water intake in the El Yunque National Forest] I pushed for PRASA to mitigate by establishing some minimum flows back at the big dam on the Espiritu Santo. Because this dam is outside the Forest there was a lot of USFS resistance about pushing for this compromise.* (P6)

*Staffing shifts*

Several key interviewees (n=4) noted a shift in personnel from implementation of mandates with potential relevance to inflow (e.g., CWA, RHA, and EFH) to implementation of the ESA. Because there are no ESA-listed species known to be affected by changes in inflow in

Puerto Rico, this programmatic shift has reduced the effort devoted to implementation of inflow related mandates. All three interviewees in NMFS and FWS, the agencies with the greatest role in CWA, RHA, or EFH permit consultations, commented that this programmatic change had limited their ability to participate in inflow related consultations. To illustrate, one of these managers (P6) stated:

> *The office has moved towards endangered species work because of lawsuits. [As a result], the habitat program was cut from three to 2/3rds of a [full time employee]. I used to comment a lot on [permits and] the coastal zone program management [when I worked on FWCA consultations full time].*

The administrator of this same program indicated that more biologists (a total of four full time employees) were assigned to ESA consultations than to CWA or RHA-related consultations (a total of less than one full time employee). In addition, given the large number of listed species in Puerto Rico, this interviewee also indicated that any new staff hired in this program would be prioritized for ESA rather than CWA or RHA consultations.

A similar shift, from EFH to ESA-related consultations, occurred in the NMFS Puerto Rico Office as a result of budget cuts to national NMFS Habitat Program. Due to this change, responsibility for Puerto Rico's habitat-related consultations was transferred from agency biologists in Puerto Rico to biologists in a regional office in the continental United States. An interviewee in the Puerto Rico office commented on the potential impact of this shift in responsibility "Someone in the regional office is taking over the [habitat work] I used to do – but he is not familiar with the issues, language, sites in Puerto Rico." This interviewee also explained limitations in addressing inflow to estuaries via ESA consultations:

*This change [in my office's funding from EFH to ESA mandates] makes it particularly hard to get involved in habitat issues very far upstream [from the coast]. If I were working under EFH, I would be able to move future upstream to all wetlands linked to estuaries. The shift from EFH work isn't great because the EFH work is potentially much bigger than ESA work. With EFH, I can get people to alter the project more substantially. People have to respond formally [to comments on permits] under the CWA 404. COE can't go forward with the permit without responding to these comments. Under ESA we need to find that the species [in question] would be jeopardized – and this is generally hard to prove. With EFH you can act earlier – and have a lot more flexibility.*

**Factor 5: Political and administrative environment**

Issues related to Puerto Rico's political and administrative environment were noted by the vast majority (n=15) of interviewees. Frequently mentioned issues included: the influence of politics in natural resource administration; lack of communication with staff in Commonwealth agencies; and lack of regulatory capacity. These issues limited managers' ability to effectively manage natural resources, including but not limited to, management of inflow to estuaries.

*Influence of politics in management*

A commonly mentioned issue (n=9) was the high turnover of administrators in Commonwealth natural resource management agencies resulting from frequent changes in political administrations in Puerto Rico. These changes were noted to be frequent (e.g., sometime more than once a year) and extensive (both heads of agencies as well as heads of individual offices and programs). Interviewees commented on the resulting lack of continuity in management, policies, and programs. To illustrate, an interviewee (P7) describes the frequency and extent of these turnovers – and the resulting effects on long-term relationships between agencies:

*There needs to be a radical change in how the government looks at the environment. Here it is very political – the agencies change completely every 4 years because of the changes in government – so there is no long-term planning. Every four years we get a new PRASA, a new DNER. One time the DNER had four secretaries in three years...... It is not just administrators [being replaced], career people get changed – heads of some departments get replaced. Every time someone new comes in to the Environmental Quality Board or the Planning Board we have to build new relationships again.*

Another interviewee (P16) echoed concerns over the frequent changes in administration and noted that frequent turnover limited commonwealth agency effectiveness:

*The DNER approves everything. There are two problems. One, when you work for the DNER [as the Secretary] the first year you don't know what is going on, by the 2nd year you start to have a better grasp. But if the Secretary is always being changed, he can't get a hold on the job. Two, if loyalty is to governor, [16] if decisions are made on political pressure not on resources management principals, if [the Secretary] is not of stature to stand up to governor, they might get comments [on a EIS] and the comments will go in the file, but the comments will be ignored because of political pressure.*

Other managers expressed that frequent agency turnover limited agencies' effectiveness, specifically noting the resulting loss of institutional knowledge (n=4). For example, illustrating the loss of institutional knowledge arising from frequent changes in administration and administrative structure at PRASA, one interviewee recounted a conversation with a high-level PRASA administrator. This administrator was not aware of the existence of a map his agency had developed of all the water intakes in Puerto Rico, critical information to PRASA:

*It was interesting that he had never seen a copy of the intake map that [a PRASA employee] had given me years ago. I was really amazed that he didn't know about or have a copy of this map.* (P6)

[16] Who appoints the Secretary

Interviewees (n=6) also indicated that such frequent personnel changes made it difficult to build and maintain relations with staff within and among agencies. To illustrate, two interviewees noted the following difficulties in maintaining contacts within DNER due to frequent turnover:

> *The whole [DNER] water franchise office has turned over…continuity is clearly an issue.* (P13)
>
> *They reorganize so often that it is hard to know who works where and who your contact is or should be at DNER. Career positions are often subjugated when parties change.* (P9)

An area where political issues were mentioned to specifically affect management of inflow to estuaries was the political power and influence of the Puerto Rico Planning Board.[17] Five interviewees mentioned concerns regarding potential conflicts between the Planning Board decisions and the Water Plan. Specifically the Planning Board's approval of a project necessitates that PRASA supply the development with water, despite any potential conflicts with environmental flow criteria specified in the DNER water franchise permits or the Water Plan. Interviewees stressed this concern in context of the political power of the planning board, with one noting:

> *The Planning Board can approve a project without DNER approval. The hope is that once the governor approves the Water Plan, the Planning Board will take [the Water Plan] into account… The planning board has a lot of power.* (P3)

Another interviewee illustrated these concerns with an example:

> *A lot of the time, PRASA has no control because the Planning Board tells them this hotel is going to be built and you have to supply it with x amount*

[17] The Puerto Rico Planning Board, an important commonwealth agency, is charged with development of an island-wide land use plan, zoning protocols, and the issuance of construction permits for new developments.

> *of water. And that comes from the top – it's a cascade effect. So you can't always blame PRASA.* (P13)

*Lack of communication with Commonwealth agency staff*

Nine interviewees highlighted the need for increased communication with staff in Commonwealth agencies. For example, one interviewee (P13) stated:

> *Federal agencies seem to do a better job of coordinating. For example the COE did a great job with the interagency meetings. The DNER could do better.*

Five interviewees specifically mentioned limited involvement of DNER staff in COE interagency meetings regarding CWA and RHA permits. For example, interviewees expressed that DNER staff rarely attended COE regulatory meetings related to inflow, despite being invited. For example, when describing agency participation at an important COE consultation regarding a permit for a new water intake, an interviewee (P6) stated "the DNER was invited but no one [from DNER] showed up."

In contrast to limited interaction with the DNER Water Franchise Office, many interviewees referred to their frequent interactions with staff in the DNER Office of Water. In fact, an interviewee (P5) expressed that the DNER Water Plan interagency meetings had become a forum for interagency coordination on other issues including inflow. He also noted that, as a result of his participation in the Water Plan interagency meetings, he had built relationships with managers in other agencies. In addition, this interviewee's involvement in the Water Plan process had motivated him to contact outside experts regarding development of instream flow criteria.

*Limited regulatory capacity*

The effectiveness of the DNER regulatory framework for inflow management was another common theme in our analysis (n=10). Specifically, a frequently mentioned concern was the DNER's process for issuance of water franchise permits. Seven interviewees referred to DNER water franchise permits' issuance as a rote process, frequently using the term "rubber stamp." To this end, interviewees noted the following:

> *DNER has always had the responsibility for water use on the island – but they never did much but rubber stamp water use applications, if they even did that. Back in the day, most of the PRASA intakes didn't even have a permit.* (P6)

> *DNER very rarely gets involved – they are just a rubber stamp. They give PRASA whatever they want.* (P12)

> *The [DNER] franchise office could be the strongest part of water management. When issuing the permits they are supposed to make sure that the permit has enough water upstream and will leave enough water downstream – first for other existing intakes and second for the environment.* (P13)

## SUMMARY & CONCLUSIONS

Under the traditional legal and administrative framework in northeastern Puerto Rico, mechanisms exist for addressing inflows to estuaries but these have not yet been applied to the issue. Managers have addressed riverine inflow through the CWA, RHA, and the Puerto Rico Water Law, but with only limited attention to estuarine inflow needs. Other relevant mandates (i.e., the EFH provision of the MSFCMA and the federal consistency provisions of the CZMA) have not been applied to inflow management. Our analysis identified several issues that limited managers' efforts to address inflow to estuaries. These include: low priority of inflow to estuaries in comparison to other issues; lack of relevant science and data; lack of a champion pushing the issue; and programmatic limitations. Issues related to the Commonwealth's wider institutional and political environment, such as the influence of politics in natural resource management, limited communication with staff in Commonwealth agencies, and lack of regulatory capacity also affected natural resource management in Puerto Rico, including the management of inflow to estuaries.

As illustrated in Figure 4.2 many of the above-identified issues are interrelated. For example, beyond limiting management efforts, the low priority of inflow to estuaries may have an additional consequence in the lack of funding provided for research on this topic. Lack of research on the effects of reduced inflows to estuaries may in turn limit awareness of the issue, thus reinforcing its low priority. Lack of relevant science and data on which to base management recommendations, also limits managers' effectiveness ability to provide recommendations in both the Water Plan development and COE permits processes. Likewise, a lack of data will limit the effectiveness of an individual seeking to champion an issue.

Puerto Rico's political and administrative environment also has a multifaceted influence on management on inflow to estuaries. For example, frequent turnover and lack of continuity within commonwealth agencies may influence agencies' effectiveness. This issue is reflected in the DNER's limited regulatory capacity with respect to water franchise permits. The lack of continuity and frequent turnover in commonwealth agencies may also indirectly affect inflow management, for example, by reducing the likelihood and potential effectiveness of a champion arising within these agencies to address this issue.

Addressing the issues identified in this study provides an opportunity to improve management of inflow to estuaries within the traditional management framework in northeastern Puerto Rico. Raising priority of inflow to estuaries and changes to Puerto Rico's political and institutional environment may be more difficult to address in the short-term, but other issues, such as funding additional studies and training scientists in estuarine ecology/ hydrology, might be addressed more immediately. The Water Plan currently includes establishment of a fund to sponsor student water related research. Placing inflow to estuaries as a priority for these funds could contribute to informing estuarine inflow management decision, training future champions of the issue, and potentially raise the priority of this issue in the longer term.

Other studies have noted that addressing the effects of water management on estuaries have received limited management attention. In a survey of water managers in the Caribbean Basin, Scatena (2003) found that coastal resources were ranked as one of the lowest priorities for water permit and instream flow considerations. In a study of integrated coastal management efforts in the tropics, Westmacott (2002) found that coastal water managers interacted with interior water managers in less than 3% of locations surveyed. The issues identified to limit management of inflow to estuaries within the traditional management framework in northeastern Puerto Rico are likely relevant in other locations. For example, Heikkila and Gerlak (2005) found that the priority of the resource to stakeholders, scientific census regarding threats to the resource, and a champion(s) spreading these findings to stakeholders were key factors leading to development of innovative watershed-level estuarine management programs.

**ACKNOWLEDGEMENTS**

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Table 4.1. Description of managers interviewed in 2006 regarding management of inflow to estuaries in northeastern Puerto Rico.

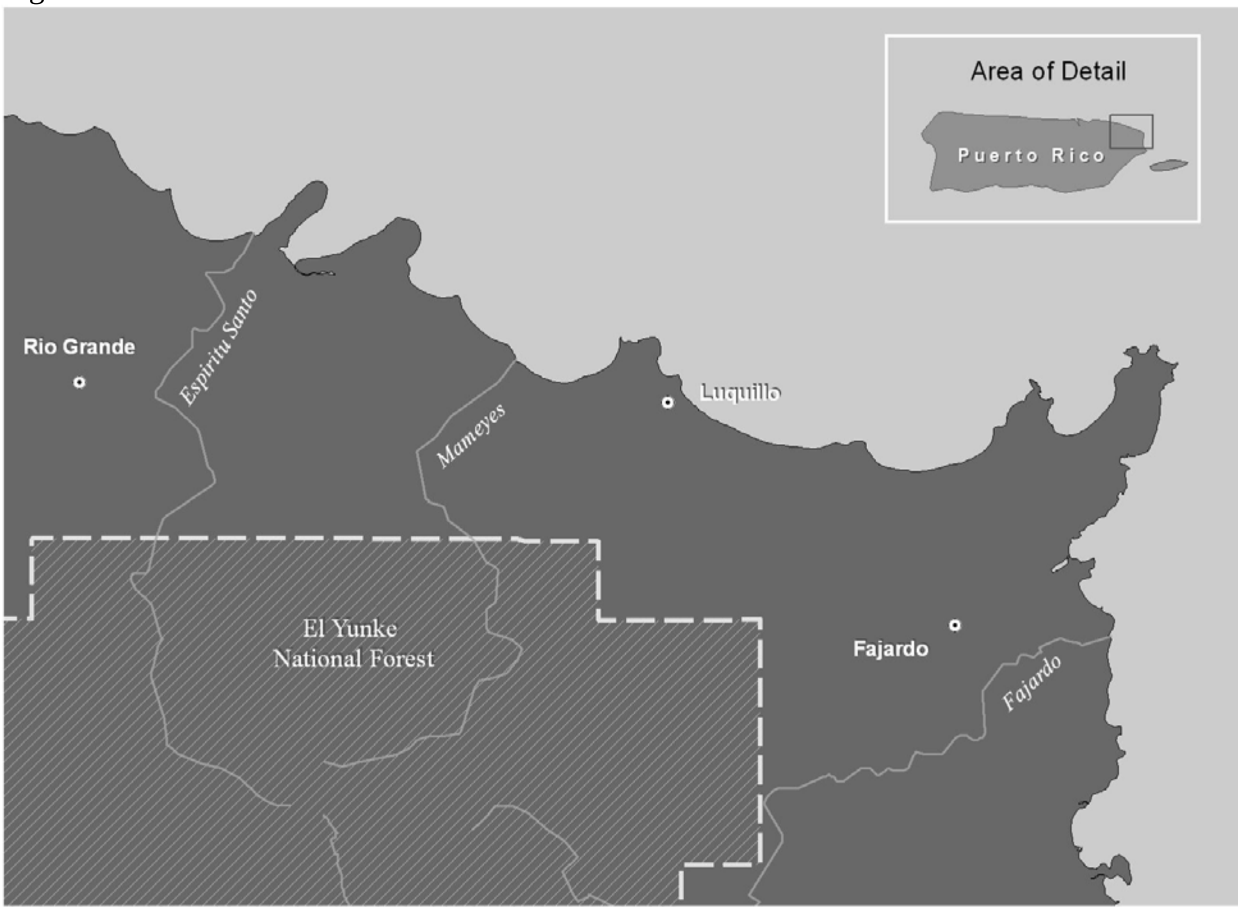
| Job Type | Agency Name | Agency Type: federal or commonwealth | Primary Focus of Management Activities |
|---|---|---|---|
| Administrator | Puerto Rico Coastal Management Program | Commonwealth | Coastal |
| Planner | Puerto Rico Coastal Management Program | Commonwealth | Coastal/inland |
| Administrator & Planner | DNER (Office of Water) | Commonwealth | Inland |
| Engineer | DNER (Office of Water) | Commonwealth | Inland |
| Biologist | DNER (Office of Marine Resources) | Commonwealth | Coastal/Inland |
| Biologist | U.S. Fish and Wildlife Service | Federal | Inland |
| Administrator | U.S. Fish and Wildlife Service | Federal | Inland |
| Administrator & Biologist | NOAA (Puerto Rico Sea Grant Program) | Federal | Coastal |
| Biologist | NOAA (National Marine Fisheries Service) | Federal | Coastal |
| Regulatory Biologist | U.S. Army Corps of Engineers | Federal | Coastal/Inland |
| Regulatory Biologist | U.S. Army Corps of Engineers | Federal | Coastal/Inland |
| Biologist | U.S. Forest Service | Federal | Inland |
| Hydrologist | U.S. Forest Service | Federal | Inland |
| Lawyer | U.S. Army Corps of Engineers | Federal | Coastal/Inland |
| Administrator | U.S. Environmental Protection Agency | Federal | Coastal/Inland |
| Administrator | U.S. Forest Service | Federal | Inland |

Table 4.2. Factors influencing management of inflow to estuaries in northeastern Puerto Rico

| Factor | Mentioned in (n= ) and % of interviews |
|---|---|
| Low priority of inflow to estuaries | 11 (70%) |
| Lack of science and data | 9 (57%) |
| Lack of a champion | 14 (88%) |
| Programmatic limitations | 10 (63%) |
| Institutional and political environment | 15 (94%) |
| Influence of politics | 11 (69%) |
| Lack of communication | 9 (57%) |
| Lack of regulation | 10 (63%) |

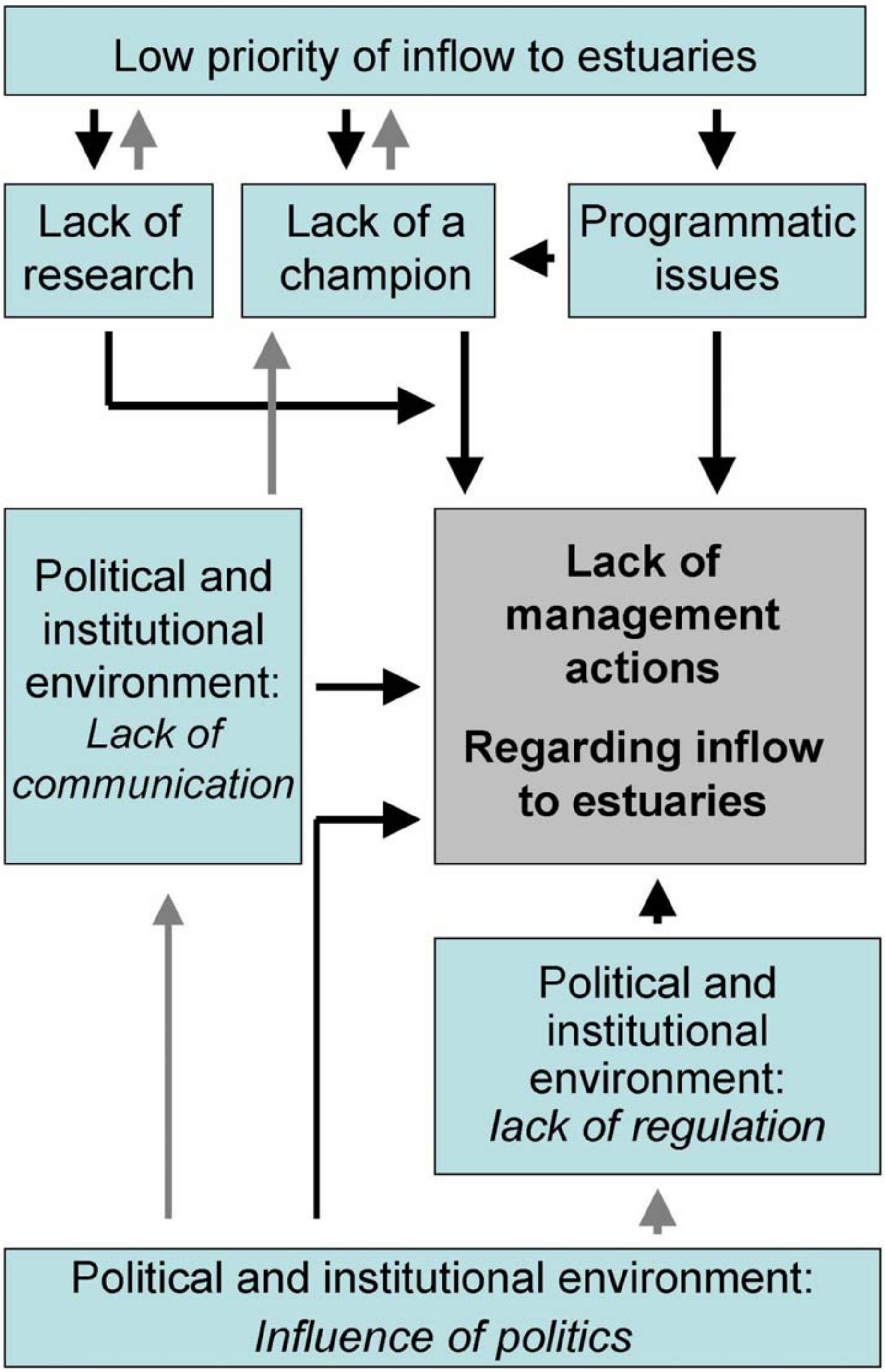
**LIST OF FIGURES**

Figure 4.1



Area of Detail
Puerto Rico
Rio Grande
Espiritu Santo
Mameyes
Luquillo
El Yunke
National Forest
Fajardo
Fajardo

Figure 4.2



Low priority of inflow to estuaries
Lack of research
Lack of a champion
Programmatic issues
Political and institutional environment: *Lack of communication*
Lack of management actions
Regarding inflow to estuaries
Political and institutional environment: *lack of regulation*
Political and institutional environment: *Influence of politics*

Appendix 4.1. Interview Protocol for coastal managers in Puerto Rico. For managers with responsibility for inland water or watershed management, the term “estuaries” was replaced with “rivers”.

1. Current job:
    a. How long have you worked in this position?
    b. What other jobs have you held in this field?
    c. What is your educational background?
    d. What are your day to day activities as [title]?

2. What are your management responsibilities related to estuaries in northeastern Puerto Rico?
    a. Under what legal mandates, policies, or programs do you undertake these activities?
    b. Do estuaries specifically fall under your office’s mission?

3. Do you consider the impact of upstream water management (e.g., dam operation, dam construction, water diversion, water allocation, the Puerto Rico water plan, instream flows) on estuaries northeastern Puerto Rico in your management plans/actions? Ask for examples.

4. Do you make, receive, or consider comments on permits that could affect inflow to estuaries in northeastern Puerto Rico? If yes, ask for examples.

5. Within your agency, who do you work with on issues related to the management of estuaries of northeastern Puerto Rico? (e.g., which departments/offices and how do you coordinate)? Ask for examples.

6. Who do you work with in other natural resource management agencies on issues related to the management of estuaries of northeastern Puerto Rico? Ask for examples.

7. Have you seen areas where increased interaction with upstream water managers or agencies could improve management of estuaries in northeastern Puerto Rico? Ask for examples.

8. Please briefly describe the resources (i.e., staff, funding) that are available for your management responsibilities.
    a. Do you have any major staffing or funding gaps related to your office’s mission?
    b. What areas would you like to cover if you had more resources?

9. Can you recommend other manager involved in management of inflow to estuaries that I might speak with?

CHAPTER 5:

# GENERAL CONCLUSION

## Project overview and significance

This study of the ecology and management of freshwater inflow to estuaries in northeastern Puerto Rico is timely given increasing demand for water in this region (March et al. 2003; Ortiz-Zayas and Scatena 2004), where on an average day over 50% of instream flow is diverted for municipal uses (Crook et al. 2007). In some heavily-used rivers such as the Espiritu Santo, an even greater proportion of the instream flow is diverted. As much as 100% of the instream flow is diverted from this river before reaching the estuary during some drought events (Benstead et al. 1999; March et al. 2003). While the inflow needs of riverine organisms have been relatively well-studied (e.g., March et al. 1998, Benstead et al. 1999; Scatena and Johnson 2001) and the results of these studies applied to water management decisions (Scatena 2001; March et al. 2003), the ecological importance of inflow to estuaries has not previously been studied in this region.

This dissertation addresses this research gap by examining the importance of inflow to estuarine fishes and food webs in two estuaries in northeastern Puerto Rico. Specifically, Chapter 2 examines differences in the salinity and fish community of the Espiritu Santo estuary in 1977 and 2004, before and after the 1984 construction of an upstream low-head dam and water intake structure. Chapter 3 examines the importance of riverine derived organic matter, including organisms, to fishes in the Espiritu Santo and Mameyes, two estuaries that differ in upstream water management practices. Lastly, the legal and administrative framework for inflow management and the factors influencing the management of this resource are presented in Chapter 4. Major findings of these studies are summarized below.

**Summary of results**

Results of Chapter 2 suggest that changes have occurred in the Espiritu Santo estuary and its fish community after construction of an upstream dam and water intake structure in 1984. Due increased upstream water abstraction at this dam, freshwater inflow to the estuary has decreased since the initial 1977 survey (Crook et al. 2007). This change has coincided with higher estuarine salinity in 2004 than in 1977, despite exceptionally high rainfall in 2004. Decreased species richness was also observed in 2004: with identical sampling methods and effort, 15 more species were detected in 1977 than in the 2004 survey. Freshwater-oriented and diadromous species demonstrated the greatest decline, with only 25% of freshwater-oriented species redetected in 2004 versus redetection of more than 50% for marine and euryhaline species. Species diversity and catch per effort, although highly variable, were also higher in 1977 than in 2004. These results indicate potential effects of reduced inflow on the Espiritu Santo estuarine fish community.

Results of Chapter 3 illustrate the contribution of riverine organic matter to fishes in the Espiritu Santo and Mameyes estuaries. Riverine organic matter was of little direct importance to the two pelagic fishes (*Centropomus pectinatus* and *Bairdiella ronchus*) and one of the two benthic fishes (*Mugil curema*) on which stable isotope analysis was conducted. Isosource models estimated that riverine organic matter contributed less than 33% of their diet even in upper reaches of both estuaries. In contrast, riverine organic matter appeared to be an important organic matter source for the other benthic species (*Diapterus rhombeus)* on which stable isotope analysis was conducted. For this species, Isosource models estimated a high contribution (as much as 69% of diet) throughout both estuaries.

Riverine organisms, specifically juvenile freshwater shrimps, were an important food item for many omnivorous fishes in the Espiritu Santo and Mameyes estuaries. Gut content analysis of *C. pectinatus*, *B. ronchus*, and eleven other common fishes collected from the Espiritu Santo and Mameyes estuaries demonstrated the importance of these organisms. Freshwater shrimps were frequently encountered (in 37% and 39% of guts examined) and composed an average of 18% and 22% of the gut content material of omnivorous fishes collected from the Espiritu Santo and Mameyes estuaries, respectively. Freshwater shrimps, however, were not found in the guts on the benthic fishes, *M. curema* and *D. rhombeus*. This finding is not surprising given that freshwater shrimps are planktonic (larval stage) and pelagic (juvenile stage) during their residence in the estuary. Interestingly, a marked, systematic difference in the occurrence of freshwater shrimps in fish guts was not observed between fishes collected from the Espiritu Santo and Mameyes estuaries, despite differences in upstream water management which can affect shrimps' downstream drift to estuaries (Benstead et al. 1999).

Chapter 4 illustrates the legal and administrative framework for management of inflow to estuaries in northeastern Puerto Rico and identifies factors influencing the management of this resource. The primary authorities applied to inflow management in northeastern Puerto Rico were the Clean Water Act, the Rivers and Harbors Act, and the Puerto Rico Water Law. Results of manager interviews, however, indicate that limited management of inflow to estuaries has occurred under these mechanisms. Our results further illustrate several factors limiting management of inflow to estuaries: low priority of inflow/estuaries in comparison to other issues; lack of relevant science and data; lack of a champion "pushing" the issue and programmatic limitations. Broader issues related to Puerto Rico's wider institutional and political environment, such as the influence of politics in natural resource management, limited communication among staff in Commonwealth agencies, and lack of regulatory capacity also affect natural resource management in Puerto Rico, including the management of inflow to estuaries.

**Recommendations and research needs**

Several of the issues identified in Chapter 4 to impede management of inflow to estuaries, for example changes to Puerto Rico's political and institutional environment, will be difficult to address in the short term. In contrast, providing additional research on estuarine inflow needs could be accomplished more immediately. The Puerto Rico Water Plan currently calls for the establishment of a fund to sponsor water related research. Placing inflow to estuaries as a priority for these funds could contribute to informing estuarine inflow management decisions, potentially raising the priority of this issue in the long term, and training future champions of the issue. Based on the results of Chapters 2 and 3 of this dissertation, I provide initial recommendations for future research regarding inflow to estuaries.

*Research gaps*

The role of freshwater shrimp in Caribbean Island estuaries merits additional study. Gut contents results (Chapter 3) illustrate that *C. pectinatus, B. ronchus,* and many other omnivorous fishes feed on freshwater-derived organisms, primarily juvenile freshwater shrimp. However, this is one of the only studies to examine freshwater shrimp in Puerto Rico's estuaries (March et al. 2003). In fact, despite freshwater shrimps estuarine life stage is almost a complete 'black box.' Timing of shrimp migrations; the role of freshwater inflow versus density-dependent factors in determining shrimp availability to estuarine fishes; and basic data regarding the habitat needs (e.g., stratification, size of the freshwater lens) of these shrimps are fruitful areas for future research. In addition, examining the contribution of freshwater shrimps to a wider range of the estuarine fish community and over a longer sampling period could provide valuable information on important periods of shrimp migration or fish feeding (Scatena 2001).

The contribution of riverine organic matter to a wide section of the estuarine community also merits additional attention. Isotope values of *D. rhombeus* indicated a potentially high dependence on riverine organic matter (Chapter 3). This may be due to the fact that this species is a benthic feeder. Chanton and Lewis (2002) found that a few species of polycheates and amphipods derived more than 50% of their diet from riverine organic matter in the Apalachicola Bay Estuary. Although a thick layer of terrestrial detritus (i.e., decomposing leaf litter) was observed in grab samples taken from the Espiritu Santo and Mameyes estuaries, the associated organisms were preserved in ethanol and could not be used for stable isotope analysis. Thus, the extent to which benthic invertebrates rely on riverine organic matter could not be assessed in this study. Future studies of these and other tropical, riverine estuaries should examine a larger number of species, including benthic invertebrates, to determine the extent to which the wider benthic community assimilates riverine organic matter.

Additional study, particularly during low flow periods, is needed to more completely assess the role of water management on estuarine food webs. Despite minimum flow requirements in the Mameyes River versus the Espiritu Santo River, which is characterized by a dam and large-scale water abstraction (March et al. 2003), we did not observe a systematic difference in the contribution of riverine organic matter, including organisms, to fishes between the two estuaries. This study, however, was conducted during a relatively high flow period

(Ramirez et al. 2005). Potential effects of water management might be evident during low flow or drought periods when a relatively high proportion of stream flow and drifting shrimp are abstracted from the Espiritu Santo River (Benstead et al. 1999, Crook et al. 2007).

*Need for long-term data collection and monitoring*

Establishment of a long-term monitoring program is a critical need for Puerto Rico's estuaries. Results of Chapter 2 suggest that upstream freshwater abstraction from the Espiritu Santo River has influenced the estuarine fish community. While some changes (e.g., the decline in fish species richness) observed between the 1977 and 2004 surveys were dramatic, without long term data, the possibility that these changes might be natural fluctuations cannot be discounted (Livingston 1987). Furthermore, long-term data are needed to establish empirical relations between inflow, population or ecosystem process, and species viability (Freyrer and Healey 2003). Such empirical relationships are critical for basing inflow management decisions (Montagna et al. 2002). At this time, there are no monitoring programs for Caribbean island estuarine fish communities. Given that the 1977 Espiritu Santo fish community survey represents one of the oldest and most extensive surveys of a Caribbean island estuarine fish community, this estuary is ideal for establishment of a long-term monitoring program. Information gained from such a monitoring program would contribute to management of freshwater inflow to this and other similar Caribbean island estuaries.

Fish sampling methods for a long-term monitoring program in the Espiritu Santo estuary requires additional study. The geomorphology of the Espiritu Santo and many other small riverine estuaries is such that high-efficiency sampling techniques (e.g., seines or trawls) can not be used. In both the 1977 and 2004 surveys of the Espiritu Santo estuary, use of relatively lowefficiency gill nets limited sample size and increased variability. Future monitoring efforts in this and similar estuaries would benefit from the development of more efficient fish sampling methods.

Although the majority of Puerto Rico's commercially important fishes spend at least a portion of their lives in estuaries (Center for Energy and Environmental Research 1979), the linkage between freshwater inflow and estuarine fishes continues to receive little study in these estuaries. The majority of estuarine inflow studies and relevant monitoring programs have instead focused on large temperate areas where the link between inflow and valued fisheries has been well established. Results of this dissertation illustrate the importance of considering the effects of water management on tropical island estuaries, particularly given increased pressure on freshwater resources in these regions.

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