Factors Influencing Tropical Island Freshwater Fishes: Species, Status, and Management Implications in Puerto Rico

ABSTRACT: Anthropogenic effects including river regulation, watershed development, contamination, and fish introductions have substantially affected the majority of freshwater habitats in Europe and North America. This pattern of resource development and degradation is widespread in the tropics, and often little is known about the resources before they are lost. This article describes the freshwater resources of Puerto Rico and identifies factors that threaten conservation of native fishes. The fishes found in freshwater habitats of Puerto Rico represent a moderately diverse assemblage composed of 14 orders, 29 families, and 82 species. There are fewer than 10 species of native peripherally-freshwater fish that require a link to marine systems. Introductions of nonindigenous species have greatly expanded fish diversity in freshwater systems, and native estuarine and marine species (18 families) also commonly enter lowland rivers and brackish lagoons. Environmental alterations, including land use and development, stream channelization, pollution, and the impoundment of rivers, combined with nonnative species introductions threaten the health and sustainability of aquatic resources in Puerto Rico. Six principal areas for attention that are important influences on the current and future status of the freshwater fish resources of Puerto Rico are identified and discussed.

Factores que influencian a los peces tropicales de agua dulce: especies, estado actual e implicaciones para el manejo en Puerto Rico

RESUMEN: Las actividades de origen humano como la regulación de los ríos, desarrollos en cuencas hidrológicas, contaminación e introducción de peces, han afectado sustancialmente la mayoría de los hábitats de agua dulce en Europa y Norteamérica. Este patrón de desarrollo y degradación de recursos se extiende a lo largo de los trópicos, y a veces se alcanza a conocer muy poco acerca de los recursos antes de que éstos desaparezcan. En este artículo se describen los recursos de agua dulce de Puerto Rico y se identifican los factores que amenazan la conservación de los peces nativos. Los peces que se encuentran en los hábitats dulceacuícolas de Puerto Rico representan asociaciones de moderada diversidad, compuestos por 14 órdenes, 29 familias y 82 especies. Existen menos de 10 especies nativas periféricas-dulceacuícolas que poseen un componente marino. Las introducciones de especies foráneas han incrementado grandemente la diversidad íctica en los sistemas de agua dulce, y las especies nativas marinas y estuarinas (18 familias) comúnmente también ingresan a los ríos y lagunas salobres. Las alteraciones del ambiente, que incluyen uso de suelo y desarrollos, canalización, contaminación y represamiento de rios, combinadas con la introducción de especies exóticas, amenazan la salud y sustentabilidad de los recursos acuáticos de Puerto Rico. Se identificaron seis áreas principales de atención y se discute su influencia en la evaluación del estado actual y futuro de los recursos de agua dulce de Puerto Rico.

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Freshwater systems are dynamic environments, both ecologically and geomorphologically, but they are especially vulnerable to human influences. Multiple anthropogenic pressures including water extractions; industrial, agricultural, and domestic effluents; nonindigenous species; altered hydrology; habitat degradation; and overexploitation threaten ecosystem integrity in these environments (Allan and Castillo 2007; Jelks et al. 2008). These pressures have been particularly evident in developed countries in the Northern Hemisphere, but are becoming increasingly prevalent worldwide. Resource degradation is a major issue in the tropics, and often little is known about the resources before they are lost. In Puerto Rico, there have been few published accounts of the freshwater fish species, and these accounts either focused primarily on introduced fishes (Erdman 1984; Neal et al. 2004), or were reports with limited circulation (e.g., Bunkley-Williams and Williams 1994). There have been no attempts to summarize threats to the freshwater systems of Puerto Rico in the primary literature.

The island of Puerto Rico is not known for a high diversity of freshwater fishes and habitats. Due to its young age and volcanic origin, coupled with its relative isolation from potential sources of colonizing species, no truly freshwater fish species are native to the island (Erdman 1984). Instead, a handful of peripherally-freshwater species that require a

link to marine systems have colonized its rivers. Intentional and unintentional introductions of nonindigenous species have greatly expanded fish diversity in freshwater systems on the island, with both positive and negative effects. This article describes the freshwater resources and fish species of Puerto Rico and identifies factors that threaten their conservation. The ecological and management environments that we review for Puerto Rico represent a microcosm of similar conditions that are less well studied and understood in other Caribbean and tropical island communities.

AQUATIC RESOURCES OF PUERTO RICO

The smallest of the Greater Antilles, Puerto Rico is a tropical island of mainly volcanic origin, measuring 175 km long by approximately 62 km wide at its widest points, with a human population of nearly 4,000,000 inhabitants (429/km^2). The capital city of San Juan and other major urban centers, such as Ponce on the south coast and Mayagüez on the west coast, are located on coastal lowlands. The interior of the island consists of an east-west running mountain chain (La Cordillera Central), and more than 50 rivers originate in this rugged terrain (Figure 1). Rivers on the north, east, and west slopes tend to be longer than those on the southern slopes of the central mountain range. The longest river (64 km) in Puerto Rico is the Río Grande de Añasco, which flows to the west coast. Streams in Puerto Rico are typically small and flashy, with rocky substrates that vary from gravel to house-sized boulders. The conductivity of Puerto Rico stream and reservoir water is moderate (50-1,000 µS/cm, with most waters 200–500 µS/cm; Díaz et al. 2005; Kwak et al. 2007), which is optimal for sampling with typical electrofishing gears (Reynolds 1996). Another primary physiographic feature is the karst region in the north, a limestone formation that covers about one-fifth of the island extending from the city of Aguadilla in the west to Loíza in the east. The hydrogeology of rivers in the karst region differs from that of rivers flowing through volcanic geology, owing to springs, subterranean channels, and permeability. Groundwater and surface waters are naturally linked in this region (Giusti 1978).

The Tortuguero Lagoon represented one of only two natural freshwater lentic systems in Puerto Rico. However, a constructed channel to the sea has converted this freshwater system to estuarine conditions, and as a result, a diversity of species ranging from native snook (*Centropomus* spp.) and tarpon (*Megalops atlanticus*) to stocked largemouth bass (*Micropterus salmoides*) and sunfish (*Lepomis* spp.) can be found there. The very shallow Cartagena Lagoon, in southwest Puerto Rico, depends on rainfall as a freshwater source, and is dominated by cattails (*Typha domingensis*). Previously, this lagoon provided important waterfowl habitat, though severe anthropogenic impacts have degraded the quality of the habitat in recent years (USFWS 2002). Many of the island's rivers have been impounded for various purposes, including irrigation, flood control, hydroelec-

Figure 1. Map of the water resources in Puerto Rico, including all primary river systems and reservoirs. Map modified and reprinted with permission of the Puerto Rico Department of Natural and Environmental Resources.

RESERVOIRS AND RIVERS OF PUERTO RICO

0 5 10 20 Kilometers

RESERVOIR NAMES

1. ACEITUNA RESERVOIR
2. ADJUNTAS RESERVOIR
3. ALTO RESERVOIR
4. BRONCE RESERVOIR
5. CAONILLAS RESERVOIR
6. CARITE RESERVOIR
7. CERRILLOS RESERVOIR
8. COAMO RESERVOIR
9. CIDRA RESERVOIR
10. DOS BOCAS RESERVOIR
11. EL GUINEO RESERVOIR
12. GARZAS RESERVOIR
13. GELY RESERVOIR
14. GUAJATACA RESERVOIR
15. GUAYABAL RESERVOIR
16. GUAYO RESERVOIR
17. GUILES RESERVOIR
18. LA PLATA RESERVOIR
19. LA TORRE RESERVOIR
20. LAS CURIAS RESERVOIR
21. LOCO RESERVOIR
22. LOIZA RESERVOIR
23. LUCCHETTI RESERVOIR
24. MATRULLAS RESERVOIR
25. MELANIA RESERVOIR
26. MOLINE RESERVOIR
27. NUMERO UNO RESERVOIR
28. NUMERO DOS RESERVOIR
29. NUMERO TRES RESERVOIR
30. NUMERO CUATRO RESERVOIR
31. NUMERO CINCO RESERVOIR
32. PATILLAS RESERVOIR
33. PELLEJAS RESERVOIR
34. PONCENA RESERVOIR
35. TOA VACA RESERVOIR
36. VISTA ALEGRE RESERVOIR
37. VIVI RESERVOIR
38. BLANCO RESERVOIR
39. FAJARDO RESERVOIR

tric power generation, and drinking-water supplies. Consequently, Puerto Rico has 13 reservoirs over 100 ha in area and numerous smaller impoundments.

The deepest reservoir (84 m) is the recently constructed (1992) Cerrillos Reservoir. Many of the older reservoirs have lost storage capacity due to sedimentation originating from upstream areas of the drainage basins. For example, recent bathymetric mapping in Dos Bocas Reservoir has indicated sedimentation rates up to 1.4 m/yr (Soler-López 2001), and Lucchetti Reservoir has lost more than 60% of its maximum depth since impoundment in 1952 (Neal et al. 1999). Generally, Puerto Rico reservoirs are mesotrophic to eutrophic, and anoxic below approximately 3 m depth. Surface water temperature averages around 27°C, though this varies somewhat with altitude and season. Reservoir water levels can be highly variable, with annual fluctuations of 18 m or more for some systems (Neal et al. 2001). These extremes in variability are generally related to water-level management for flood control more so than variability in seasonal rainfall, which does not follow exaggerated seasonal patterns observed in many tropical climates.

Freshwater resources of Puerto Rico are not intensively developed with respect to freshwater fishing, boating, and recreational access and facilities. Of the major reservoirs, five have well-developed access and recreational and fishing facilities (La Plata, Guajataca, Lucchetti, Cerrillos, and Dos Bocas reservoirs), including a resident biologist or enforcement personnel, public boat ramps, sanitary and picnic amenities, and other facilities. The typical Puerto Rico reservoir may provide unpaved, improvised access facilities, or access is limited to private fishing club facilities.

Puerto Rico's streams have potential as recreational resources, yet stream angling is not a common practice in Puerto Rico. Most fishing involves artisanal capture of *Atya* or *Macrobrachium* shrimp, freshwater crab (*Epilobocera sinuatifrons*), or estuarine species found near river mouths. Nevertheless, several abundant native fish species inhabit the lotic systems and could support recreational fisheries if they were developed. Development of access, promotion, and additional efforts to control the point and nonpoint sources of contamination are actions that could enhance and facilitate public interest in recreational fisheries. Concern of schistosomiasis historically discouraged wading and swimming in streams, but these concerns seem to have dissipated in recent years as shrimping and swimming are common. Although Tsang et al. (1997) found relatively high seroprevalence rates of the parasite (*Schistosoma mansoni*) in the municipalities of Naguabo and Jayuya, recent localized studies point to decreasing prevalence of this parasitic disease over the past decades (Hillyer and Soler de Galanes 1999).

The freshwater resources on the island have received substantial chemical and nutrient pollution from a variety of sources (Hazen 1988; Hunter and Arbona 1995; Stallard 2001; Warne et al. 2005). With the high human population density of Puerto Rico and the fact that roughly 57% of all households rely on water supplied from reservoirs by the Aqueduct and Sewer Authority, water quality in reservoirs is a valid concern (Barbosa 2005). Floating litter, especially after storm events, is common along the shorelines and coves in many systems, and while litter is primarily aesthetically unsightly, it may indicate contamination by other more influential chemical substances and nutrients from domestic, municipal, industrial, and depositional sources (Hazen 1988; Hunter and Arbona 1995; Stallard 2001; Warne et al. 2005).

Freshwater shrimp (*Macrobrachium heterochirus*) collected during stream electrofishing assessment in Puerto Rico. Shrimp are an important component of the riverine food web and a human food source, and are impacted by the same factors that influence fish communities.

Photo: Patrick B. Cooney.

FRESHWATER FISH SPECIES

While the marine fishes of Puerto Rico have received substantial attention by scientists, the freshwater and estuarine fish fauna is much more poorly understood. Biologists from a number of commonwealth and federal natural resource agencies, public water utilities, and universities in Puerto Rico and the United States have sampled freshwater fishes or conducted surveys in Puerto Rico, but a comprehensive sampling program or monitoring for this fauna has yet to be established. The work on freshwater fishes by former commonwealth biologist Donald Erdman is most noteworthy (Erdman 1972, 1984, and references cited therein), as well as recent extensive, quantitative stream fish surveys by Kwak et al. (2007). However, most previous sampling efforts have been directed at specific research or management objectives, and island-wide fish distributions and community dynamics are not well documented or understood.

In this contribution, we compiled fish species lists using published reports and manuscripts (cited within) and unpublished agency and university data and technical reports. The fishes currently or previously found in freshwater habitats of Puerto Rico represent a moderately diverse assemblage composed of 14 orders, 29 families, and 82 species. These species range from primarily freshwater (Table 1), including many nonnative freshwater species (7 families) and a few diadromous native species (4 families), to native estuarine and marine species (18 families; Table 2) that commonly enter lowland rivers and brackish lagoons. Additional species are occasionally collected or have been previously reported in Puerto Rico (Table 3), likely as a result of unauthorized releases or isolated distributions. Rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) were imported and stocked in island rivers between 1934 and 1942, but did not establish (Erdman 1972; Neal et al. 2004). Two more species (warmouth *Lepomis gulosus* and bobo mullet *Joturus pichardi*) have been reported in historical records, but these species were not

Table 1. Freshwater fish species found in reservoirs and rivers in Puerto Rico. Note: the sirajo goby *Sicydium plumieri* has been split into four *Sicydium* species (*S. buscki, S. gilberti, S. plumieri,* and *S. punctatum*; Watson 2000); it is not clear which are present in Puerto Rico.

Family	Species	Common Name	Origin	Status
Anguillidae	*Anguilla rostrata*	American eel	Native	Widespread
Centrarchidae	*Lepomis auritus*	redbreast sunfish	Introduced	Widespread
	Lepomis macrochirus	bluegill	Introduced	Widespread
	Lepomis microlophus	redear sunfish	Introduced	Widespread
	Micropterus coosae	redeye bass	Introduced	Restricted to Maricao River
	Micropterus salmoides	largemouth bass	Introduced	Widespread
Cichlidae	*Astronotus ocellatus*	oscar	Introduced	Loíza Reservoir and expanding
	Cichla ocellaris	butterfly peacock bass	Introduced	Widespread
	Cichlasoma labiatum	red devil cichlid	Introduced	Expanding
	Cichlasoma managuense	jaguar guapote	Introduced	Expanding
	Oreochromis aureus	blue tilapia	Introduced	Widespread
	Oreochromis mossambicus	Mozambique tilapia	Introduced	Widespread
	Tilapia rendalli	redbreast tilapia	Introduced	Widespread
Clupeidae	*Dorosoma petenense*	threadfin shad	Introduced	Widespread
Cyprinidae	*Puntius conchonius*	rosy barb	Introduced	Locally abundant in a few systems
Eleotridae	*Dormitator maculatus*	fat sleeper	Native	Widespread
	Eleotris perniger	smallscaled spinycheek sleeper	Native	Widespread
	Gobiomorus dormitor	bigmouth sleeper	Native	Widespread
Gobiidae	*Awaous banana*	river goby	Native	Widespread
	Sicydium plumieri	sirajo goby	Native	Widespread
Ictaluridae	*Ameiurus nebulosus*	brown bullhead	Introduced	Widespread
	Ameiurus catus	white catfish	Introduced	Widespread
	Ictalurus punctatus	channel catfish	Introduced	Widespread
Loricariidae	*Pterygoplichthys pardalis*	Amazon sailfin catfish	Introduced	Expanding
Mugilidae	*Agonostomus monticola*	mountain mullet	Native	Widespread
Poeciliidae	*Gambusia affinis*	western mosquitofish	Introduced	Widespread

vouchered, remain unconfirmed, and their occurrence is questionable (Table 3).

Introduced fishes and a handful of diadromous native species comprise the majority of species collected in upland rivers and reservoirs. The number of freshwater exotic fish species and ratio of exotic-to-native freshwater fishes in Puerto Rico is among the highest for island faunas where these data are known (Tables 1–3; Erdman 1984; Vitousek et al. 1997). Only seven native species are routinely collected in freshwater systems, and all are reliant on a connection to estuarine or marine systems for at least some portion of their lives. The American eel (*Anguilla rostrata,* Anguillidae) is the only truly catadromous species in Puerto Rico, as it lives in freshwater and returns to the open ocean to spawn. The bigmouth sleeper (*Gobiomorus dormitor*), fat sleeper (*Dormitator maculatus*), and smallscaled spinycheek sleeper (*Eleotris perniger,* Eleotridae); river goby (*Awaous banana*) and sirajo goby (*Sicydium plumieri,* Gobiidae; recently split into four distinct species; Watson 2000); and mountain mullet (*Agonostomus monticola,* Mugilidae) found in freshwater rivers in Puerto Rico are believed to be amphidromous, although little has been documented on their life histories. In amphidromy, adults spawn in the rivers and the larvae migrate or are passively transported to marine environments. After a period of growth, post-larvae re-enter streams, metamorphose into juveniles, and migrate upstream (Erdman 1984). The sole exception among these native fishes is the bigmouth sleeper, which although typically amphidromous, appears to maintain a self-sustaining population in Carite Reservoir (Bacheler et al. 2004). A small population appears to inhabit Patillas Reservoir (PRDNER, unpublished data), although the size structure of the population (predominantly large individuals) and the presence of amphidromous shrimp in this water body suggest episodic connectivity with the marine environment.

The presence of dams excludes most native species from the resulting reservoirs or upstream river reaches (Holmquist et al. 1998; Kwak et al. 2007). As a consequence, management practices in Puerto Rico reservoirs have resulted in fish communities that are primarily a mixture of exotic species introduced to the island from various continents. These include black bass and sunfishes (Centrarchidae), catfishes (Ictaluridae), and threadfin shad (*Dorosoma petenense,* Clupeidae) of North American origin; African tilapia (Cichlidae); and South American butterfly peacock bass (*Cichla ocellaris,*Cichlidae). Fish introductions began during the 1910s when the first wave of reservoir construction began in the eastern part of the island. Biologists of local and federal government agencies endorsed these introductions, which were common practice at the time, before the potential for negative ecological interactions between exotic and native fishes had been addressed by the scientific community (Kohler and Courtenay 1986;

Select freshwater fishes common in Puerto Rico:

(A) Amazon sailfin catfish (introduced),

(B) butterfly peacock bass (introduced),

(C) red devil cichlid (introduced),

(D) bigmouth sleeper (native),

(E) sirajo goby (native), and

(F) mountain mullet (native).

Photos A, B, & C: Craig G. Lilyestrom
Photo D: J. Wesley Neal and
Photos E & F: Patrick B. Cooney.

Table 2. Primarily marine and estuarine fish species collected in coastal freshwater rivers of Puerto Rico.

Family	Species	Common Name
Achiridae	*Achirus lineatus*	lined sole
	Trinectes inscriptus	scrawled sole
Belonidae	*Strongylura timucu*	timucu
Bothidae	*Citharichthys spilopterus*	bay whiff
Carangidae	*Caranx hippos*	crevalle jack
	Caranx latus	horse-eye jack
	Oligoplites saurus	leatherjack
	Trachinotus falcatus	permit
Carcharhinidae	*Carcharhinus leucas*	bull shark
Centropomidae	*Centropomus ensiferus*	swordspine snook
	Centropomus parallelus	smallscale fat snook
	Centropomus pectinatus	tarpon snook
	Centropomus undecimalis	common snook
Clupeidae	*Harengula jaguana*	scaled sardine
	Opisthonema oglinum	Atlantic thread herring
Elopidae	*Elops saurus*	ladyfish
Engraulidae	*Anchoa parva*	little anchovy
Gerreidae	*Eucinostomus argenteus*	spotfin mojarra
	Eucinostomus melanopterus	flagfin mojarra
	Eugerres plumieri	striped mojarra
	Gerres cinereus	yellowfin mojarra
Gobiidae	*Ctenogobius boleosoma*	darter goby
	Evorthodus lyricus	lyre goby
	Gobiodes broussonetii	violet goby
	Gobionellus oceanicus	highfin goby
Haemulidae	*Pomadasys crocro*	burro grunt
Lutjanidae	*Lutjanus apodus*	schoolmaster
	Lutjanus griseus	gray snapper
	Lutjanus jocu	dog snapper
Megalopidae	*Megalops atlanticus*	tarpon
Mugilidae	*Mugil curema*	white mullet
	Mugil liza	liza
	Mugil trichodon	fantail mullet
Polynemidae	*Polydactylus virginicus*	barbu
Syngnathidae	*Microphis brachyurus*	opposum pipefish
Tetraodontidae	*Sphoeroides spengleri*	bandtail puffer
	Sphoeroides testudineus	checkered puffer

Bunkley-Williams et al. 1994). The flourish of fish species introductions ended in the late 1960s (Erdman 1984), when it was perceived that all ecological niches in reservoirs had been filled. Although intentional introductions have been curtailed, maintenance stocking of sport fish species (e.g., largemouth bass, redear sunfish *Lepomis microlophus*) continues to be a primary management technique of the Puerto Rico Department of Natural and Environmental Resources (Neal et al. 2004).

The establishment of a few new exotic fish species has been documented for Puerto Rico freshwater habitats since 1970 (Tables 1-3; Erdman 1984; Bunkley-Williams et al. 1994; Kwak et al. 2007; USGS 2007). Recent introductions have been attributed to the aquaculture industry, aquarium releases, and anglers (Erdman 1984; USGS 2007). The growing list includes the Amazon sailfin catfish (*Pterygoplichthys pardalis*, Loricariidae), which continues to reproduce and proliferate in reservoirs (Bunkley-Williams et al. 1994), and several members of the family Poeciliidae, which are common and expanding in range. Recently, several species of cichlids have begun to appear in reservoir electrofishing and creel surveys, including the jaguar guapote (*Cichlasoma managuense*), red devil cichlid (*Cichlasoma labiatum*), convict cichlid (*Cichlasoma nigrofasciatum*), and Rio Grande cichlid (*Cichlasoma cyanoguttatus*). Introductions of these aggressive cichlids are of concern due to expanding populations, and they are known to impact native fishes in other freshwaters (Fuller et al. 1999; PRDNER 2006, 2007). The most recent fish introduction documented in Puerto Rico freshwaters is a population of the Chinese algae-eater (*Gyrinocheilus aymonieri*) established in the Río Grande de Loíza (Kwak et al. 2007).

FACTORS THREATENING NATIVE FISHES

Environmental Alterations

Puerto Rico's aquatic resources face many of the same anthropogenic burdens as elsewhere, but the effects are exacerbated by the spa-

Table 3. Occasionally or rarely collected fish species that result from bait, aquaculture, or aquarium releases, and species of limited or questionable record.

Family	Species	Common Name	Status
Anabantidae	*Helostoma temmincki*	kissing gourami	Occasionally collected
Centrarchidae	*Lepomis gulosus*	warmouth	Questionable record
Cichlidae	*Cichlasoma cyanoguttatum*	Rio Grande cichlid	Occasionally collected
	Cichlasoma nigrofasciatum	convict cichlid	Occasionally collected
	Oreochromis niloticus	Nile tilapia	Aquaculture species
	Oreochromis urolepis hornorum	Wami tilapia	Aquaculture species
	Oreochromis urolepis urolepis	Rufigi tilapia	Aquaculture species
Cyprinidae	*Carassius auratus*	goldfish	Occasionally collected
	Ctenopharyngodon idella	grass carp	Stocked for weed control
	Hypophthalmichthys molitrix	silver carp	Likely extirpated
	Pimephales promelas	fathead minnow	Likely extirpated
Gyrinocheilidae	*Gyrinocheilus aymonieri*	Chinese algae-eater	Occasionally collected
Mugilidae	*Joturus pichardi*	bobo mullet	Questionable record
Poeciliidae	*Poecilia orri*	mangrove molly	Common in isolated habitats
	Poecilia reticulata	guppy	Common in isolated habitats
	Xiphophorus hellerii	green swordtail	Common in isolated habitats
	Xiphophorus maculatus	southern platyfish	Common in isolated habitats
Salmonidae	*Oncorhynchus mykiss*	rainbow trout	Extirpated
	Salmo trutta	brown trout	Extirpated

tial concentration of the human population and the rapidly changing landscape. The human population of Puerto Rico has increased 72% in the last 50 years, and with the current population density of 429 inhabitants per km^2, Puerto Rico's aquatic resources are subject to increasing demand and degradation (López and Villanueva 2006). Over 2.27 billion L/d (598 million gal/d) of freshwater are dedicated to domestic use, which represents 80% of the total domestic, agricultural, industrial, and hydroelectric water usage.

The most prominent alterations to the landscape which affect aquatic resources include agricultural practices, deforestation, stream channelization, industrial and municipal pollution, land development, and the impoundment of rivers. Industrial and agricultural withdrawals of water from streams have depleted stream flows in some systems (Erdman 1984), due to the application of "minimum flow" criteria rather than "instream flow" criteria (sensu Annear et al. 2004) and removal of land cover for agriculture has increased runoff, erosion, and sedimentation rates (Clark and Wilcock 2000; Soler-López 2001). The abundance of freshwater shrimp in streams is directly related to flow (Scatena and Johnson 2001), and similar relationships likely exist for stream fishes.

Impaired water quality resulted in 51% of Puerto Rico river reaches assessed in 1988-89 to be considered moderately or severely contaminated, and 49% were inadvisable for swimming or fishing (Hunter and Arbona 1995). Bioaccumulation of heavy metals and pesticides in Puerto Rico fishes has been reported, with certain systems exceeding limits for human consumption for some species (Rodríguez and Gonzalez 1981; Olmeda Marrero 2000). Fish kills resulting from agricultural discharges and municipal sewage effluents have been documented, and salinity changes, bacterial or viral episodes, agricultural chemicals, or the loss of water from diversions also may impact aquatic resources (Hunter and Arbona 1995). However, scientists generally concur that the single greatest limiting factor to native fishes in Puerto Rico has been the presence and operation of the 26 major dams, none of which have fish passage structures (Holmquist et al. 1998; March et al. 2003; Greathouse et al. 2006).

The topography of Puerto Rico and the abundance of flowing surface water have led to the construction of many reservoirs, primarily in upland areas. These reservoirs provide a number of benefits to humans, including flood control, hydroelectric power, water supply, and creation of reservoir fisheries and associated recreational opportunities. However, the impoundment of a free-flowing stream is not without negative impact on ecological function and native fish populations (Ward and Stanford 1983). Because all native freshwater fish species and many native shrimp species in Puerto Rico are diadromous, and because few fish passage structures have been developed and implemented for these species (and none on large dams), the design and incidence of dams inhibits longitudinal instream migration and movement of these species between upland streams and marine systems. Thus, impounding streams eliminates most native freshwater fish and shrimp from above the dam structure, resulting in reduced biodiversity and impaired food webs and ecological function (Holmquist et al. 1998; Greathouse et al. 2006; Kwak et al. 2007). Furthermore, dams can alter the hydrology and ecology of the system both downstream and upstream, with impacts on native species from the headwater reaches to the marine environment that are difficult to measure and variable among regions (Pringle 1997; Pringle et al. 2000; Warne et al. 2005; Greathouse et al. 2006).

Nonnative Species

Intentional introductions of nonnative fishes to create reservoir fisheries have been occurring in Puerto Rico for nearly a century (Neal et al. 2004). While the negative ecological and economic impacts of many exotic fish introductions are clearly documented (Pimentel et al. 2000; Courtenay 2007), little is known about the relationship between the exotic and native fish faunas in Puerto Rico. Erdman (1984) reported that "With the possible exception of tilapia, there is little evidence of harmful impacts of exotic fishes on native Puerto

Rican fishes." This conclusion reflected the current understanding at the time, but since then, additional research suggests ecological effects on native species by exotics. For instance, Holmquist et al. (1998) found a negative correlation between the number of exotic fishes and the number of native fishes in a river reach in Puerto Rico; native species richness (of fish and shrimp) was also inversely correlated with exotic fish abundance.

The occurrence of centrarchids and ictalurids downstream of reservoirs is localized, affecting native fish populations only on a spatially-restricted scale. Although tilapia are most abundant in reservoirs, they are collected in significant numbers downstream and tolerate the brackish salinities of estuaries and lagoons (Stickney 1986). Tilapia may compete for spawning areas, food, and space resources with native fish, demonstrate aggressive behavior toward other species, alter aquatic vegetation, often thrive in altered conditions where natives cannot, and have been implicated in the decline of native fish and mussel populations elsewhere (Fuller et al. 1999). In fact, biologists in some tropical regions are calling for the eradication of nonnative tilapias due to serious impacts on native fishes (Eldredge 2000). Erdman (1984) suggested that other potential predators and increased fishing effort are needed to help keep tilapia populations in check in Puerto Rico, although this may require additional introductions. However, in a survey of tilapia species in a Puerto Rico estuary, Smith et al. (2008) did not detect an increase in their numbers in the Espiritu Santo River estuary between 1977 and 2004, suggesting that populations have stabilized.

The relatively recent introduction of the Australian red claw crayfish (*Cherax quadricarinatus*) to Puerto Rico inland waters poses an additional threat, as yet unquantified, to the ecological integrity and native fauna of these systems. Red claw crayfish were illegally introduced to Puerto Rico in early 1997, and escaped from a private culture facility in the Loiza River drainage in 1998 during Hurricane Georges. García (2008) reported *Cherax* from the Loiza, Carite, and Cidra reservoirs, as well as a Lajas drainage canal and the Loiza and Gurabo rivers, noting no evident environmental damage from the species, though this was not the focus of the research. The negative impacts of nonnative crayfishes have been well documented in both Europe and North America and include ecosystem alterations, damage to fisheries, and extirpation of native invertebrates (Lodge et al. 2000).

FUTURE OF FISHERIES RESOURCES IN PUERTO RICO

The Caribbean in general has very limited freshwater supplies when compared to other parts of the world. With current infrastructure, Puerto Rico supplies drinking water to 97% of the population (Barbosa 2005), and human water use on the island is projected to continue to increase (PRDNER 2008). The needs of water for human consumption and industry will always compete with those for fishing and recreational uses, and economic development may come at a cost to natural resources. However, the ecological services and economic value of maintaining ecological integrity of aquatic ecosystems are becoming increasingly recognized and incorporated into water resource planning (González-Cabán and Loomis 1997; March et al. 2003; PRDNER 2008). Those responsible for managing water and land require information about biodiversity and ecosystem health to consider when establishing policy that balances the needs of water for human uses with those for natural resources.

Based on available literature and the authors' collective experience, six principal areas have been identified that are important influences on the current and future status of the freshwater fish resources of Puerto Rico. While these may be relevant to a broad geographic landscape and other faunas, they are especially applicable to Puerto Rico resources. Specific management recommendations proposed by March et al. (2003) relate directly to Puerto Rico aquatic systems and to the six topics we present below. Some of these topics and recommendations are included in a recently developed water use plan for the island (PRDNER 2008).

1. **Point and nonpoint sources of contaminants.** Water quality is a primary requirement for freshwater fish habitat and stream ecosystem health, as well as human uses. Industrial and municipal effluents, as well as diffuse sources of chemicals and sediment from agriculture and urbanization, can be detrimental to native fish communities. Household waste may litter streams and reservoirs with potential to leach toxic chemicals.
2. **Instream habitat and river flows.** Dams are the single greatest human impact to Puerto Rico native fishes. These structures degrade river habitat and disrupt ecological function, and they are detrimental to amphidromous fish reproduction and recolonization. Remedial approaches to mitigate the effects of dams attempted elsewhere include regulation of flow releases downstream of dams, installation of fish passage devices, or dam removal and habitat restoration. Such measures are being considered and implemented on a limited basis in Puerto Rico. Stream diversions, reduced flows, and channelization, independent of dams, are also detrimental to lotic fish populations and their habitat, especially for amphidromous species that require adequate water flow for migration cues

Dos Bocas Dam impounds the Río Arecibo to form Lago Dos Bocas in Puerto Rico. High dams like this one are important for water supply, power generation, flood control, and recreation, but form barriers to fish migration that exclude native fishes from upstream river habitat and enhance the environment for exotic species.

Photo: Patrick B. Cooney

and reproduction, as well as unobstructed passage in both upstream and downstream directions.

3. **Introductions of exotics and invasive species.** Exotic and invasive species introductions in Puerto Rico have been extensive and detrimental to native fishes and other taxa. While studies conducted elsewhere have documented and elucidated negative impacts of exotic fish introductions, research on the effects on the native fishes and aquatic ecosystems of Puerto Rico is limited and needed to better understand direct and cascading mechanisms.
4. **Human interactions with resources.** Interaction of humans with freshwater fishery and aquatic resources for recreation appears limited, relative to that for marine environments. Contributing causes may be limited access, facilities, and promotion, or concerns over schistosomiasis. Public surveys could help determine perceptions about freshwater resources.
5. **Survey and research efforts.** Knowledge is the basis for successful management and conservation of natural resources. An understanding of the biology, ecology, and sociology associated with aquatic resources and their use is required for informed management. Comprehensive programs to gather, interpret, and evaluate relevant data have improved our understanding of influences on Puerto Rico aquatic resources and can justify and guide effective management activities.
6. **Environmental education and consciousness.** Native freshwater fishes are an important component of Puerto Rico's natural heritage. Interactions with public constituents while sampling fishes in rivers and reservoirs suggest that local residents are indeed interested in freshwater fishes and concerned for their conservation, but their knowledge of the resource is limited. Our personal observations were confirmed by a survey of households in Puerto Rico that indicated that although the public's knowledge of specific river systems was limited, they would be willing to pay for maintaining ecological integrity of Puerto Rico rivers (González-Cabán and Loomis 1997). Such valuations of natural resources facilitate economic comparison of management alternatives; however, the economic value of Puerto Rico freshwater fishes has not been assessed. The coquí (*Eleutherodactylus* spp.) has become a symbol of Puerto Rico pride and heritage, and this popularity facilitates its protection. If a genus of tiny tree frogs can charm the public, the same could be true for the freshwater fishes, given their morphological diversity, unique adaptations, and recreational and food values. Public support is the first step toward effective conservation.

Effective protection and conservation of Puerto Rico freshwater fish resources will require consideration of these six influential areas and sustained commitment among public officials, agency administrators, biologists, and the public toward cooperative resource management.

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