Damming Tropical Island Streams: Problems, Solutions, and Alternatives

JAMES G. MARCH, JONATHAN P. BENSTEAD, CATHERINE M. PRINGLE, AND FREDERICK N. SCATENA

The combination of human population growth, increased water usage, and limited groundwater resources often leads to extensive damming of rivers and streams on tropical islands. Ecological effects of dams on tropical islands can be dramatic, because the vast majority of native stream faunas (fishes, shrimps, and snails) migrate between freshwater and saltwater during their lives. Dams and associated water withdrawals have been shown to extirpate native faunas from upstream reaches and increase mortality of downstream-drifting larvae. A better understanding of the effects of dams and the behavior of tropical island stream faunas is providing insights into how managers can mitigate the negative effects of existing dams and develop alternatives to dam construction while still providing freshwater for human use. We review the ecological effects of dams on tropical island streams, explore means to mitigate some of these effects, describe alternatives to dam construction, and recommend research priorities.

Keywords: conservation, diadromy, impoundments, insular, lotic

Human population growth and increased water usage are placing greater demands on the world's freshwater supplies (Postel 2000). Despite their geographic isolation, tropical islands are not immune to this global phenomenon (Hunter and Arbona 1995, Pringle and Scatena 1999). In fact, islands, which frequently have less access to freshwater and less land area for potential expansion of human populations, often have more challenging water resource problems than do continental areas. Because of high demand for freshwater, governments on tropical islands are frequently under immense pressure to allow increasing exploitation of freshwater resources. The groundwater resources of many tropical islands are not sufficient to meet demand and are in danger of being irrevocably lost because of overpumping and subsequent saltwater intrusion (e.g., Hunter and Arbona 1995). Consequently, governments increasingly turn to surface water, primarily rivers and streams, for their freshwater supplies. The effects of hydrologic alterations of rivers and streams from dams, reservoirs, and water withdrawals are well documented for continental streams, with most of the literature coming from temperate locations (e.g., Rosenberg et al. 2000). Tropical continental streams have also received some recent attention (e.g., Bonetto et al. 1989, Pringle et al. 2000). In contrast, very little research has been done on the effects of dams on tropical island streams. Furthermore, alternatives to damming and to increased water withdrawal are often not considered when making water resource management decisions.

In this article, we summarize some of the ecological problems associated with damming tropical island streams, suggest solutions to these problems, and review some alternatives. First, we summarize the general life history characteristics of tropical insular riverine faunas that make them particularly vulnerable to the negative effects of damming. Second, we review effects of both large (spillway height greater than 15 meters [m]) and small (low-head) dams on tropical island streams. Third, we discuss ways to mitigate the negative effects of existing dams. Fourth, we present alternatives to dam construction and compare representative effects of a traditional low-head dam to those of alternative methods of water withdrawal and storage. Finally, we outline information

James G. March (e-mail: jmarch@washjeff.edu) is an assistant professor in the Biology Department, Washington and Jefferson College, Washington, PA 15301. Jonathan P. Benstead is a postdoctoral scientist at The Ecosystems Center, Marine Biological Laboratory, Woods Hole, MA 02543. Catherine M. Pringle is a professor in the Institute of Ecology, University of Georgia, Athens, GA 30602. Frederick N. Scatena was a research hydrologist at the International Institute of Tropical Forestry, US Department of Agriculture Forest Service, Río Piedras, Puerto Rico, when this article was being prepared; he is now a professor and chair of the Department of Earth and Environmental Science at the University of Pennsylvania, 240 South 33rd Street, Philadelphia, PA 19104.

needed by water resource managers to make ecologically sound decisions and translate this information into a set of scientific research priorities.

Life history characteristics of insular riverine faunas

The vast majority of native macrofaunas (fishes, shrimps, and snails) found on islands worldwide have a diadromous life cycle, such that they migrate between rivers and coastal zones over the course of their lives. For example, freshwater shrimps (figure 1), gobiid fishes (figure 2), and neritinid snails are amphidromous (*sensu* McDowall 1992). Adults live and breed in rivers and streams, where they release larvae (shrimps; figure 3) or lay eggs that later hatch into larvae (gobies and snails). The larvae drift downstream to saltwater (e.g., Iguchi and Mizuno 1990, Ha and Kinzie 1996, March et al. 1998), where they metamorphose into postlarvae and then begin to migrate upstream into freshwater (Fievet and Le Guennec 1998, Benstead et al. 2000). Many other fishes native to islands have a catadromous life cycle; adults live in freshwater but return to oceanic or estuarine habitats to breed. Examples of catadromous fishes typical of island streams include eels *(Anguilla* spp.), flagtails *(Kuhlia* spp.), mullets *(Agonostomus* spp.), and sleepers (Eleotridae). Many of these migratory animals play important roles in determining the community composition and ecosystem properties of headwater streams; they are also a large component of the diet of commercially important coastal fishes (Corujo 1980, Pringle 1997, March et al. 2001, 2002). They are also harvested locally for food and recreation. Therefore, understanding the effects of dams on migratory faunas is critical to tropical island management and conservation.

Effects of dams on tropical island streams

In order to examine the effects of dams on tropical island streams, it is instructive to separate dams into two size classes: large and small. Large dams are defined as those with a spillway height greater than 15 m (ICOLD 1998). Recent estimates suggest that there are approximately 42,000 large dams in the world (1996 data; ICOLD 1998). The overwhelming majority of research on dams has focused on the effects of large dams. Small dams have received very little scientific attention, although their overall impact may be far greater than that of large dams. There are approximately 800,000 small dams worldwide, and estimates for the United States suggest that small dams have three to four times the reservoir area of large dams (Rosenberg et al. 2000). While the numbers of large and small dams on islands have yet to be quantified, small dams are likely to be even more abundant on islands than they are elsewhere, because most island watersheds are relatively small.

Figure 1. The migratory freshwater shrimp **Xiphocaris elongata.** *Photograph: Jonathan Benstead.*

Large dams can significantly alter the distribution and abundance of island faunas by blocking migratory pathways (Miya and Hamano 1988, Holmquist et al. 1998, Concepçion and Nelson 1999). However, the extent of alteration depends on characteristics of both the dam and the native faunas. For example, in Puerto Rico, large dams without spillways are impermeable barriers to migratory organisms and result in complete extirpation of all native fishes and shrimps from upstream habitat (Holmquist et al. 1998). In contrast, large dams with spillways (structures allowing water to flow over the face of a dam) allow the passage of some native fishes and shrimps. Many native fishes and shrimps of tropical islands have evolved to migrate over high waterfalls. Shrimps simply walk over dams with spillways, sometimes leaving the water but remaining in the wetted area near the stream. Fishes such as gobies and some eleotrids use modified pelvic fins as suction cups to climb vertical rocks and waterfalls. While these native fishes and shrimps are able to climb, they need flowing water as a cue to direct them (Hamano and Hayashi 1992, Benstead et al. 1999). Without it, they are unable to determine the direction of water flow, and they remain below the dam.

Although dams with spillways allow the passage of migratory aquatic biota, shrimp and fish abundance upstream of these dams is lower than in stream reaches downstream of dams or in comparable reaches without dams (Holmquist et al. 1998, Concepçion and Nelson 1999). Dams with spillways can also extirpate native faunas from upstream reaches if the native faunas are unable to climb or to migrate past lake-like reservoirs. For example, in Guam, the native fish *Kuhlia rupestris,* which does not have modified pelvic fins, is absent from streams upstream of Fena Dam (26 m high, with a spillway; Concepçion and Nelson 1999). Similarly, native neritinid snails are absent from streams above the dam. While neritinid snails can climb near-vertical surfaces, they also require flowing water as a directional cue to orient themselves upstream, which the low-flow conditions of the lake-like reservoir remove (Concepçion and Nelson 1999).

Dams with hydroelectric facilities can disrupt the upstream migration of faunas by altering the location of freshwater flow into the ocean. Postlarval gobies in coastal areas use the input of flowing freshwater as a directional cue to locate rivers. When hydroelectric facilities discharge river water directly into the ocean, postlarval gobies can have difficulty differentiating between river outflow and hydroelectric facility discharge. For example, in Guadeloupe, West Indies, large upstream migrations of postlarval *Sicydium*

(Gobiidae) have been observed entering canals leading to a hydroelectric facility that does not have access to the stream (Fievet and Le Guennec 1998). Postlarval gobies tend to migrate en masse, forming very long, continuous columns that are several fish wide (Erdman 1986). Therefore, confusion of hydroelectric facility discharge with river flow could potentially result in losses of entire cohorts.

Figure 2. A male freshwater goby, **Sicydium plumieri.** *Photograph: Jonathan Benstead.*

Large dams and associated reservoirs may also disrupt the downstream migration of fish and shrimp larvae by reducing water flow, thereby lengthening the time water takes to reach the estuary. First-stage larvae of amphidromous shrimps and gobies are typically nonfeeding and must reach saltwater in order to metamorphose into more advanced feeding stages. Laboratory studies have shown that amphidromous shrimp larvae die after a few days in freshwater (e.g., Lewis and Ward 1965). Similarly, gobiid larvae have limited food resources, and increased retention in freshwater can lead to starvation (Moriyama et al. 1998, Iguchi and Mizuno 1999). Although reservoir-induced starvation has not been documented, it is highly probable. Furthermore, reduced flows through reservoirs may also increase predation on larvae.

Small low-head dams also interfere with the migration of tropical island faunas (Benstead et al. 1999, Fievet et al. 2001a). The effects of low-head dams on the upstream migration of faunas appear to be similar to those of large dams with spillways. For example, a small low-head dam in Puerto Rico did not act as a complete barrier to upstream migration. Shrimps, fishes, and snails were able to scale the dam and indeed were abundant in upstream reaches (Benstead et al. 1999). However, the low-head dam did act as a bottleneck that increased the densities of upstream migrating animals below the dam. This high concentration of migrating juvenile fishes and shrimps attracted a variety of predators, such as green herons *(Butorides virescens),* adult shrimps and crabs, and mountain mullet *(Agonostomus monticola),* probably resulting in increased mortality of migrating fishes and shrimps. The bottleneck effect observed at this dam may have been exacerbated by the absence of a working shrimp or fish ladder. Upstream migrating animals at this site experienced increased difficulty during periods of low river flow, when no water was coming over the dam. During these periods, migrating shrimps lacked the directional cue provided by flowing water and became disoriented (Benstead et al. 1999).

In addition to impeding the upstream migration of migratory faunas, water withdrawal at this site resulted in significant mortality of downstream migrating shrimp larvae (Benstead et al. 1999). During periods of low river flow, all the water and thus all the shrimp larvae were entrained into the intake. Over the course of the study, 42% of the migrating shrimp larvae were entrained into the water intake (Benstead et al. 1999). Long-term estimates of larval shrimp mortality were between 34% and 62%, depending on the amount of water withdrawn.

Construction of low-head dams also alters the physical habitat and hydrological regime in reaches both upstream and downstream of dams (Fievet et al. 2001a). Areas downstream of low-head dams can experience decreased river flow and water depth (Fievet et al. 2001a). This decrease in freshwater can result in increased salinity, especially at sites near the upstream boundary of estuarine tidal influence. Areas upstream of low-head dams experience decreased flow rates and increased water depth. While the reservoir creation of low-head dams is minimal compared with that of large dams, the change in habitat upstream of low-head dams is still dramatic compared with similar undammed reaches.

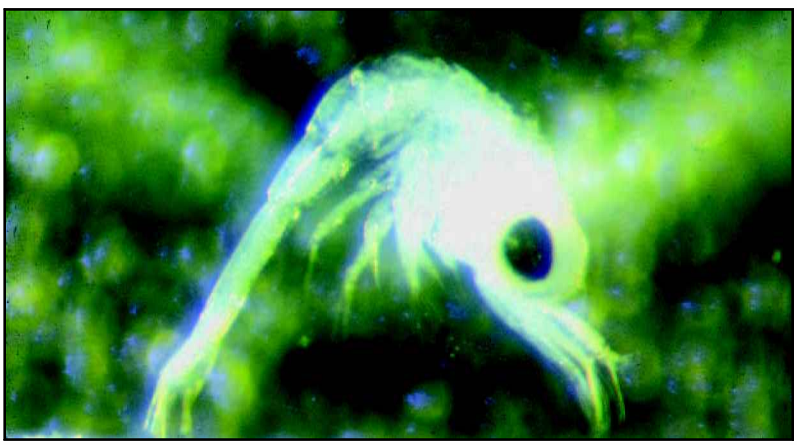

Figure 3. Larval shrimp **(Macrobrachium** *sp.). Larva is just under 2 millimeters long and is translucent in life, with dark eyespots and scattered chromatophores. Photograph: James March.*

Effects of both large and small dams on migratory faunas can have far-reaching consequences beyond altering the relative abundance and distribution of fishes and shrimps. For example, in many tropical island streams, freshwater shrimps account for the great majority of secondary production (Bright 1982) and significantly affect many aspects of benthic community composition and ecosystem processes (Pringle et al. 1999). Small-scale experimental exclusions of shrimps result in increased quantity and quality of organic matter (Pringle et al. 1999), increased sediment cover, shifts in insect and algal assemblage composition and biomass (March et al. 2002), and decreased rates of litter processing (March et al. 2001). Large-scale "experiments" caused by anthropogenic disturbance support the results of these small-scale exclusions. For example, elimination of shrimps from an entire reach due to chlorine poisoning resulted in dramatic increases in sediment cover and algal biomass. Similar patterns have been observed in preliminary studies upstream of large dams without spillways, where native shrimps and fishes have been extirpated (Freeman et al. forthcoming).

Methods for mitigating negative effects of existing dams

As summarized above, both large and small dams can impede the upstream and downstream migration of tropical island faunas. However, there are several options for mitigating their negative effects.

Fixing broken fish and shrimp ladders and retrofitting dams currently without ladders should be a priority. While much research has addressed ladder designs for jumping migratory fishes such as salmonids (e.g., Laine et al. 2002), comparatively little work has focused on ladders for the climbing taxa, such as shrimps, gobies, and snails (Hamano et al. 1995, Fievet 2000, Yasuda et al. 2000, Fievet et al. 2001b). The main characteristic of a functional ladder is that it must always provide some flow of water downstream to guide migrating animals (Fievet 1999, Fievet et al. 2001b). Additional characteristics of functional ladders for amphidromous biota are being developed. In Japan, where there are many amphidromous species, researchers recommend using mesh (0.5-millimeter [mm]) textiles on the floor of the fish ladder to provide traction for climbing animals (Hamano et al. 1995). They also recommend that the angle of incline of the ladder be less than 50° and that the water velocity in the fish ladder be less than 65 centimeters (cm) per second (Hamano et al. 1995). Other research in Japan found that a series of steps (each step 4 cm high) and a 19° angle of incline successfully allowed shrimps to migrate upstream (Yasuda et al. 2000). Similarly, researchers in Guadeloupe, West Indies, recommend slow to moderate water velocities and shallow water depth in a more natural cascade-like pass over or to the side of the dam (Fievet 2000, Fievet et al. 2001b). Freshwater shrimps are often observed leaving the water and migrating upstream in the mist-laden wetted surface near the stream (Fievet 1999, Benstead et al. 1999, Freeman et al. forthcoming). Therefore, future ladders should allow sufficient space adjacent to the water flow for migrating shrimps. If a dam is also used for water withdrawal, placing the upstream end of the fish ladder on the opposite bank or far away from the water intake will decrease accidental entrainment of upstream migrating faunas. Although the studies mentioned above focused on freshwater shrimps, low water depth and velocity also appear to be preferred conditions for juvenile gobies migrating upstream (Yuma et al. 2000).

Water resource managers can further mitigate the negative effects of dams and water withdrawals by incorporating ecological knowledge of the native island faunas into operating schedules. For example, understanding the temporal patterns of downstream migration of amphidromous faunas can greatly reduce dam-induced mortality (Benstead et al. 1999). The migratory drift of larval freshwater shrimps occurs primarily at night, with peaks in larval drift between 7:00 and 10:00 p.m. Similar temporal patterns have been observed in the larval drift of an amphidromous goby (Iguchi and Mizuno 1990). Benstead and colleagues (1999) demonstrated that by halting water extraction during peak larval drift, dam operators can significantly reduce shrimp mortality without sacrificing significant water yield. Using field data, a 30-year discharge record, and simulation modeling, they calculated that halting water withdrawal during 5 hours of peak drift could reduce mean daily larval mortality at the dam 62% to 20% without large losses in water yield. Increased rates of withdrawal during the day could further decrease water loss with negligible increases in larval mortality.

Another approach that may help mitigate the negative effects of dams on migratory faunas is the use of artificial lighting (Hamano and Honke 1997, Fievet et al. 2001b). Larval shrimp are attracted to light (Hunte 1975), while juvenile shrimp avoid it (Hamano and Honke 1997). Experimental results suggest that strategic placement of underwater lights downstream of dams could induce upstream migrating shrimp to cross from one side of the stream to the other, potentially leading them to the fish ladder (Hamano and Honke 1997). Additionally, illuminating the side of the river opposite to the water intake upstream of dams may attract larval shrimps away from the intake as they migrate downstream, thus decreasing entrainment (Fievet et al. 2001b). While the efficacy of these methods has yet to be determined, they are another example of the types of mitigation measures that are possible when managers have a good understanding of the biology of their river system. However, the specific mitigation methods managers choose will vary, depending on the type and use of the dam, the behavior of the native faunas, and the financial resources available.

Alternatives to dam construction

There are several alternatives to dams that may be less harmful ecologically but still contribute the services provided by a dam. In this section we focus on alternatives to the most common type of dam, the low-head dam used for municipal or agricultural water supply. We compare the effects of a low-head dam (Benstead et al. 1999) with those of a new in-channel withdrawal system that does not involve damming. We focus on the effects of these two different structures on the downstream migration of shrimp larvae, the upstream migration of fishes and shrimps, and the alteration of the physical environment. We also describe the potential advantages of off-stream water storage compared with in-stream reservoirs created by dams.

The low-head dam and the alternative in-channel withdrawal structure are located in eastern Puerto Rico on the main stems of the adjacent Río Espíritu Santo and Río Mameyes, respectively (figures 4, 5). The low-head dam is a cement wall (20.9 m wide and 1.2 m tall; figure 4) that creates a small reservoir from which water is gravity-fed into the intake structure (located on the bank of the reservoir) for the municipal water supply. There are no fine-mesh screens to prevent entrainment of biota, and no flow-measuring device exists to monitor the amount of water withdrawn (see Benstead and colleagues [1999] for a more detailed description of the site).

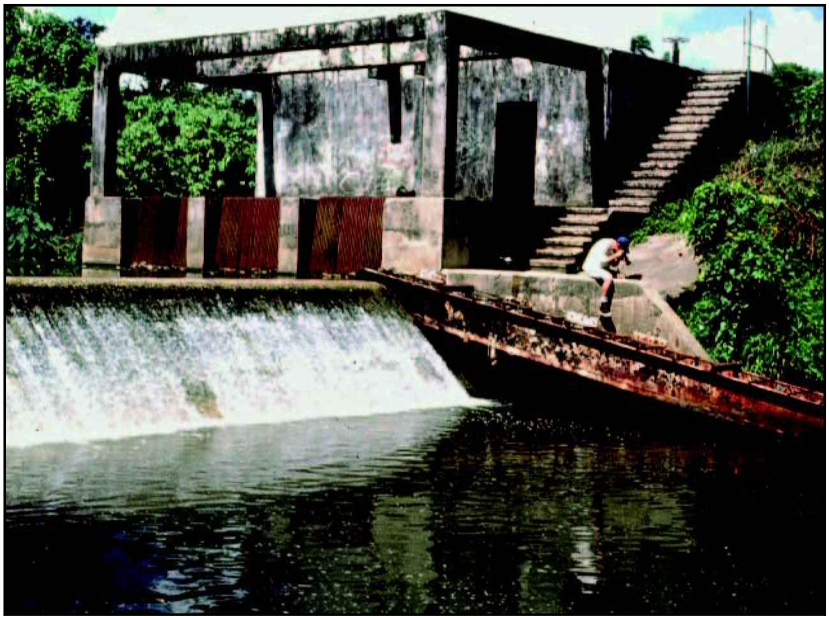

Figure 4. A typical low-head dam on the Río Espíritu Santo, Puerto Rico. Photograph: Catherine Pringle.

In contrast, the in-channel withdrawal system on the Río Mameyes consists of a series of 12 (two rows of 6) cylindrical stainless steel risers (figures 5, 6). Each riser is 1.2 m long and 0.32 m in diameter. The ends of the risers are constructed of a series of 4-mm slots (figure 6). The parallel rows of risers overlap slightly, such that the entire length of all the risers combined is approximately 11 m. Adjacent to the river channel is a pumphouse that pumps water out of the river through the risers (figure 5).

Alteration of the river channel and its physical habitat is far greater with the low-head dam on the Río Espíritu Santo than with the in-channel withdrawal system on the Río Mameyes (figure 7). For example, a slow-flowing pool extends as far as 170 m upstream of the low-head dam, with reduced channel depth and slope profile. Channel depth increases directly in front of the dam wall because of displacement of sediment during turbulent flow associated with large spates. Spates and associated scour also account for increased channel depth just below the dam (figure 7a). In contrast, very little river channel modification has occurred at the intake of the in-channel withdrawal system, and there is no alteration of upstream habitat (figure 7b).

The low-head dam also has a greater impact on the upstream migration of fishes and shrimps (figure 8; Benstead et al. 1999). While fishes and shrimps can surmount the low-head dam when water is flowing over it, the dam does appear to slow their migration, resulting in increased densities below the dam compared with those above it (figure 8). In contrast, we found no increase in shrimp and fish abundance below the pump withdrawal system (figure 8). The low-head dam also appears to entrain more downstream-drifting shrimp larvae. As mentioned previously, during a 69-day study the low-head dam caused direct mortality of 42% of downstream-drifting larvae (Benstead et al. 1999). Furthermore, during periods of low river flow, there was no discharge over the dam, causing 100% mortality of drifting larvae (Benstead et al. 1999). In contrast, we found no direct entrainment of larvae into the pump with-

Figure 5. The in-channel withdrawal structure located on the Río Mameyes, Puerto Rico. Water is pumped from the submerged stainless steel risers to the pumphouse on the bank. Photograph: James March.

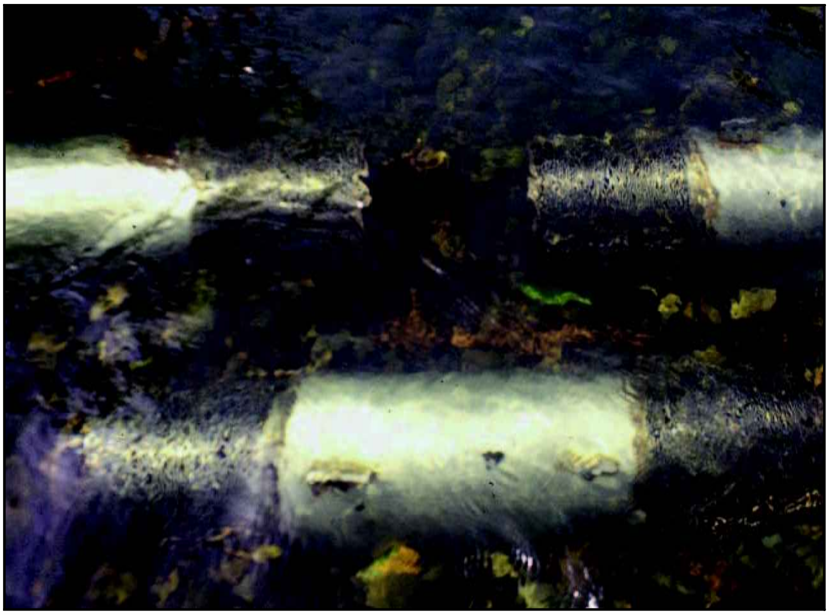

Figure 6. A close-up of the stainless steel risers of the in-channel withdrawal system on the Río Mameyes. Photograph: James March.

drawal system (figure 9). The location of the risers within the channel and the low velocity of the water entering the multiple risers may help explain the lack of larval entrainment. Intake risers were located near the center of the river but away from the bulk river flow that occurred in the deepest part of the channel near the opposite river bank. While quantitative studies measuring the cross-sectional distribution of migrating larvae are lacking, our preliminary data and observations suggest that most larvae drift downstream in the bulk flow. Therefore, positioning water intakes on the inside corner of a river bend, out of bulk flow, may decrease larval mortality caused by water withdrawal structures. The multiple openings of the 12 intake risers may also contribute to the lack of larval entrainment. The suction of water into an individual intake appeared sufficiently weak that the dominant water flow next to intake openings was in a downstream direction.

One advantage of dams is that they create a reservoir, which allows for water storage. An alternative to creating an in-stream reservoir by damming is building an off-stream reservoir away from the river channel. One such structure has recently been completed on the Río Fajardo, which is adjacent to the Río Mameyes watershed mentioned above. The Río Fajardo facility consists of a water intake on the side of the channel, which does not greatly alter the original channel morphology (PRWA 1998). After passing through a small sedimentation pond, water is transported by gravity in a buried pipe 6.5 kilometers downhill to a reservoir. The reservoir was built in a

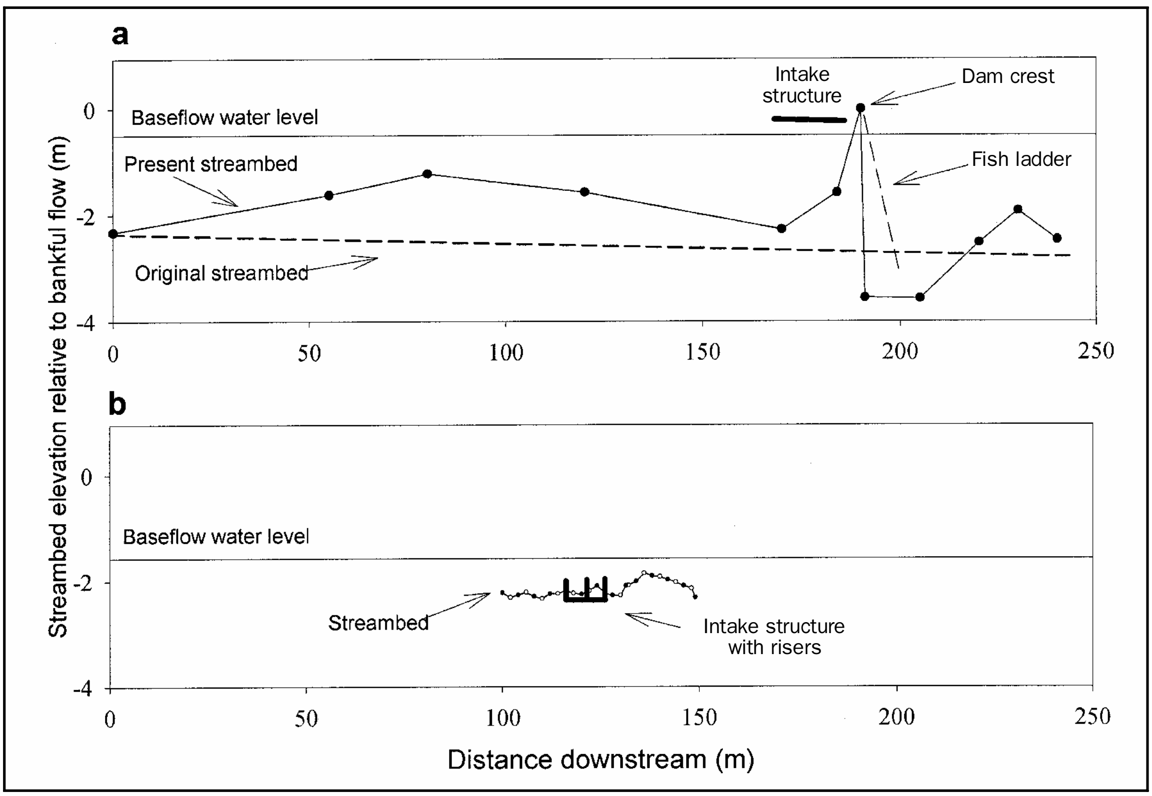

Figure 7. Longitudinal profile of (a) the low-head dam on the Río Espíritu Santo and (b) the in-channel water intake on the Río Mameyes.

small (0.57-square-kilometer) valley and holds 5.5 million cubic meters of water.

This type of water withdrawal and storage has several benefits. First, it causes less alteration of channel morphology and provides minimum water flow in the river at all times. Second, the timing of water removal from the river can be easily managed. For example, if initial field studies find that the intake does entrain larvae, withdrawals can be halted during the hours of peak migration. Water withdrawal can also be halted during large storms, when sediment levels in river flow are high. A major problem with in-stream reservoirs, especially in tropical areas with high rainfall, is that they fill up with sediment, which decreases reservoir storage capacity and alters downstream sediment load. A small sedimentation pond in front of the off-channel reservoir can further reduce reservoir sedimentation. Another benefit to off-channel reservoir water storage is that it can be less expensive to build. Because the reservoir is built away from the river in a dry valley, it can be built without temporarily diverting the river and without the difficulties of construction in saturated soil and excessive groundwater. Finally, off-channel reservoirs have greater security. Because the watershed surrounding the reservoir is relatively small, it is more easily protected from catastrophic failure due to natural or human-caused events.

While pumping and storing water out of the channel appears to be significantly less harmful than a low-head dam, additional alternatives are also important to consider. Increased efficiency in water use can provide substantial amounts of water without extracting greater quantities from rivers and streams. For example, in Puerto Rico, broken and leaky pipes, illegal taps, and faulty meters result in the loss of more than 40% of the water extracted (Pringle and Scatena 1999). Improving infrastructure and implementing water conservation measures could reduce or eliminate the need for additional water withdrawals. The city of Denver, Colorado, provides a case study of this approach. Plans to build the Two Forks Dam were canceled after Denver's water board realized it could obtain sufficient water to meet its needs by better managing its existing supplies and implementing water conservation measures (Richter and Redford 1999). This approach needs to be integrated into current water resource management on tropical islands.

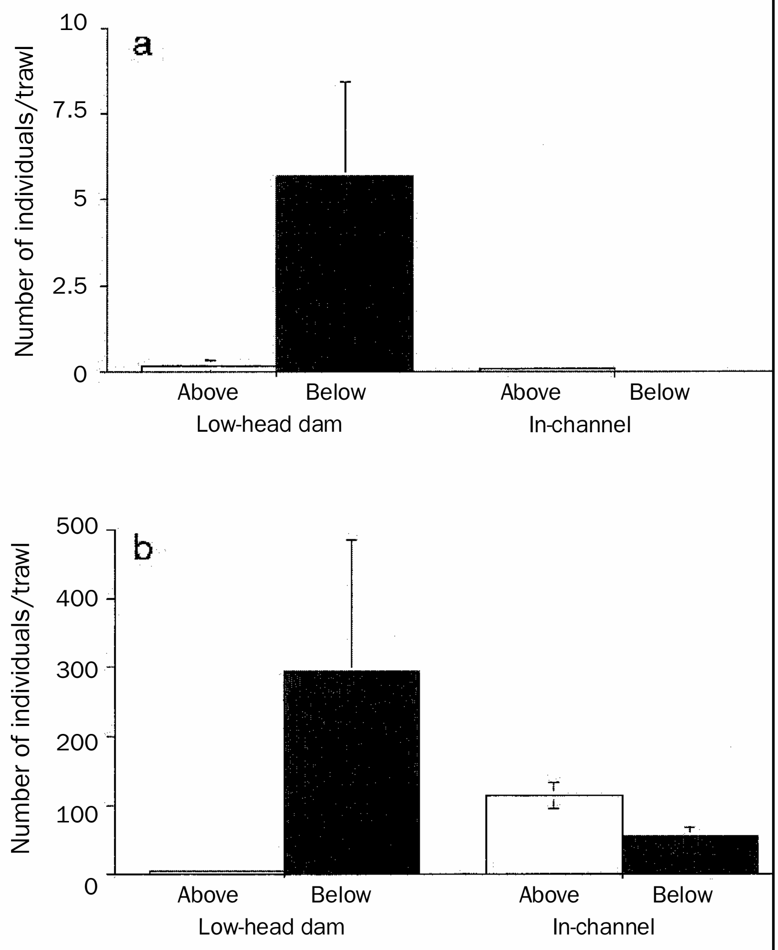

Figure 8. The number of (a) fishes and (b) shrimps found above and below the low-head dam (Río Espíritu Santo) and in-channel water intake (Río Mameyes).

Future research and management needs

While much research to date has focused specifically on the ecological effects of dams on migratory faunas, there are still large gaps in the knowledge of these effects (e.g., the horizontal distribution of migrating faunas and the survivorship of larvae and migrating catadromous adults passing through hydroelectric plants). In this section, we discuss other effects of dams that also need to be investigated in tropical island streams, including the effects of altered hydrologic regimes; the cumulative impacts of multiple dams in watersheds; the interactions among impacts of dams and other anthropogenic disturbances; and the effects of reduced riverine input of larval organisms, freshwater, and organic matter into tropical island coastal ecosystems. In addition to further examining the effects of dams, it is also imperative to develop a better inventory of the number and types of dams that exist on tropical islands (Poff and Hart 2002).

Altered hydrologic regimes. The natural flow regime is very important in sustaining the native biodiversity and ecosystem integrity of rivers and streams (Poff et al. 1997). Yet it is well known that dams and water withdrawals alter the natural flow regime of rivers (Stanford et al. 1996). Therefore, it is essential that variables such as flow magnitude, duration, frequency, and flashiness are measured to allow comparisons between dammed and undammed rivers of tropical islands. If not already in place, an adequate network of river flow gauges should be installed at water intakes and along the

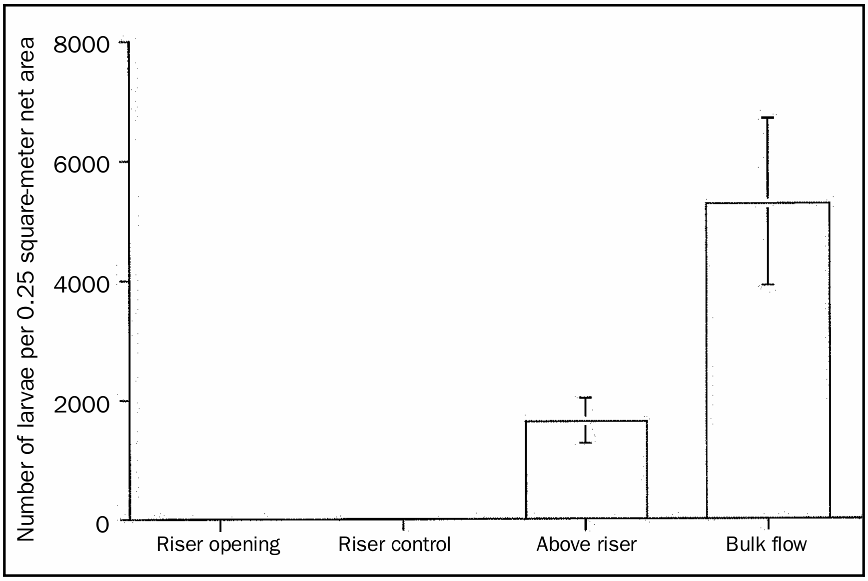

Figure 9. The number of larvae sampled at the in-channel water withdrawal structure in the Río Mameyes. "Riser opening" refers to a net placed over the slotted intake openings of the steel risers. "Riser control" refers to a net placed over the solid stainless steel portion of the riser. "Above riser" refers to a net placed above the steel risers in the water column. "Bulk flow" refers to a net placed in the deeper part of the channel, which experiences the bulk of the river flow.

course of undammed rivers. Long-term monitoring of river flow in both dammed and undammed rivers through dry and wet years will allow water resource managers to make better-informed decisions related to water use demands.

Cumulative impacts of multiple dams and interactions with other anthropogenic disturbances. Watersheds with only one dam, or with none, are becoming increasingly rare. For example, even in the relatively protected Caribbean National Forest, Puerto Rico, there are more than 31 dams or water intake structures in nine watersheds. How many dams can a watershed support? Are the effects of the tenth dam worse than those of the first, even if the dams are identical? Are the effects of one large dam on the main stem of a river greater than those of two small dams on tributaries? Resource managers need to know the answers to these questions, and therefore research scientists should try to provide them. Techniques are emerging to help researchers examine the effects of hydrologic alterations on watershed scales (Richter et al. 1998); however, much more needs to be done.

Damming and water withdrawals are rarely the only anthropogenic disturbances occurring in a watershed. Indeed, increased water demand is typically a result of increased human population growth and economic development. How do the effects of dams and water withdrawal structures vary in watersheds with different levels and kinds of land use? Will a dam have a greater effect on migrating faunas that have to migrate through a golf course, around a sewage treatment plant outflow, and over a gravel mining operation? To what extent will increased water withdrawal upstream exacerbate the effects of sewage effluent downstream?

Effects of reduced river flow into coastal ecosystems. Coastal ecosystems such as mangroves and coral reefs are an important part of the ecology and economy of tropical islands. Input of larval organisms, freshwater, and organic and inorganic matter from rivers plays a key role in determining the physical, chemical, and biological conditions of coastal ecosystems (Gillanders and Kingsford 2002). Reviews of studies of continental rivers suggest that reduction in river flow reduces the productivity of coastal fisheries (e.g., Loneragan and Bunn 1999). Negative effects on coastal fisheries could be even greater on small oceanic islands because of their isolation from other potential source populations. In weighing the pros and cons of upstream water diversion, water resource managers need to consider the economic and ecological effects of diversion on coastal ecosystems as well as rivers. Therefore, future research should further examine the effects of reduced river flow on coastal ecosystems of tropical islands. Because some consumptive water use is inevitable, researchers should also explore the "ecological rhythms" (see Scatena 2001) of coastal ecosystems to determine whether the timing (seasonal or diel) of reduced river flow into coastal ecosystems can be managed to reduce the negative effects of river flow reduction.

Recommendations for managing freshwater resources on tropical islands

Both small low-head dams and large dams are harmful to tropical island stream ecosystems. As indicated above, tropical streams are dominated by migratory faunas and thus are vulnerable to hydrologic modification. Eliminating all dams on tropical islands is not an appropriate solution, as dams provide many goods and services that are essential to human needs. However, minimizing the negative effects of existing dams through mitigation measures is essential. Moreover, water withdrawal structures on tropical island streams should be constructed only after considering all possible options, which include making more efficient use of existing water supplies by conserving water and improving infrastructure. If new water withdrawal structures are built, they should be built to minimize ecological damage.

The following general recommendations for water resource managers, research scientists, and policymakers will encourage the sustainable use of tropical island freshwater resources. Many of these recommendations are in various stages of implementation in some developed continental countries; it is important for water resource managers of tropical island streams to consider them all carefully during future planning.

Understand the ecology of the streams under management. When evaluating the effects of dams or other anthropogenic disturbances, it is important for managers to have a good understanding of the ecology of the specific streams they are managing. Studies of the basic biology of riverine faunas, such as reproduction, migration, and habitat requirements, can provide means to mitigate the negative effects of water withdrawal and still obtain the ecosystem services that streams and rivers provide (e.g, Benstead et al. 1999, Scatena 2001). Because of the amphidromous life histories of tropical island faunas and the importance of riverine inputs into coastal ecosystems, expanding these studies to include coastal ecosystems is essential.

Implement water conservation strategies. Increasing the number of dams or the amount of water extracted at individual dams is not necessarily the best or least expensive method for obtaining more water. Fixing leaky pipes and removing illegal taps should be a priority. Also, managers and policymakers should encourage water conservation through outreach and education, through government-subsidized shifts to more water-efficient technology, and through ascending water-pricing rate structures that require users to pay higher rates the more water they use (Gleick 2000).

Encourage collaborations. Effective water resource management demands interdisciplinary collaboration involving economists, ecologists, civil engineers, anthropologists, and policymakers (Ewel 2001). Ecologists need to move beyond identifying the ecological problems with dams and help identify some of the solutions. The recent increase in the number of ecologists working within engineering firms as environmental consultants may be helpful. Dam designers now share offices with ecologists who evaluate the ecological effects of dams. This may improve communication and enhance the creation of less ecologically harmful water withdrawal structures. Ecologists can also improve water resource management by collaborating with economists to provide research results that integrate the economic and ecological costs of various management scenarios (Richter and Redford 1999). Such collaboration would provide more of the information that policymakers and water resource managers need to make decisions. Furthermore, because the structure and function of tropical island rivers and coastal ecosystems are dynamically linked, marine and freshwater ecologists need to collaborate with one another and provide advice to water resource managers.

Use adaptive management. Not all management decisions are final. It is necessary to monitor the ecological and economic effects of current management decisions and compare them with other options through time. Using an adaptive management approach is essential when dealing with the many demands placed on freshwater resources. Streams and rivers of tropical islands are invaluable resources not only for local use and development but also for scientific research. Governmental officials of tropical islands need to make a commitment to use their freshwater resources as sustainably as possible. Collaboration with biologists can greatly benefit the process and improve the end product. A holistic, flexible approach based on long-term monitoring, collaboration, and communication with the public will aid the sustainable management of tropical island water resources.

Acknowledgments

We thank Anne Brasher and Gordon Smith for organizing the Conservation Research in Tropical Island Streams symposium at the 2001 Society for Conservation Biology Annual Meeting in Hilo, Hawaii, as well as this special section of *BioScience.* Gordon Smith, Anne Brasher, and three anonymous reviewers provided helpful suggestions on the manuscript. This work was partially funded by a US Department of Agriculture Forest Service grant (10-21-RR551-093) to C. M. P. and by the National Science Foundation Luquillo Long Term Ecological Research program (DEB 94-11973).

References cited

Benstead JP, March JG, Pringle CM, Scatena FN. 1999. Effects of a low-head dam and water abstraction on migratory tropical stream biota. Ecological Applications 9: 656–668.

Benstead JP, March JG, Pringle CM. 2000. Estuarine larval development and upstream post-larval migration of freshwater shrimps in two tropical rivers of Puerto Rico. Biotropica 32: 545–548.

Bonetto AA, Wais JR, Castello HP. 1989. The increasing damming of the Parana basin and its effects on the lower reaches. Regulated Rivers 4: 333–346.

Bright GR. 1982. Secondary benthic production in a tropical island stream. Limnology and Oceanography 27: 472–480.

Concepçion GB, Nelson SG. 1999. Effects of a dam and reservoir on the distributions and densities of macrofauna in tropical streams of Guam (Mariana Islands). Journal of Freshwater Ecology 14: 447–454.

Corujo IN. 1980. A study of fish populations in the Espíritu Santo River Estuary. Master's thesis. University of Puerto Rico, Río Piedras.

Erdman DS. 1986. The green stream goby, *Sicydium plumieri,* in Puerto Rico. Tropical Fish Hobbyist 34: 70–74.

Ewel K. 2001. Natural resource management: The need for interdisciplinary collaboration. Ecosystems 4: 716–722.

Fievet E. 1999. An experimental survey of freshwater shrimp upstream migration in an impounded stream of Guadeloupe Island, Lesser Antilles. Archiv für Hydrobiologie 144: 339–355.

———. 2000. Passage facilities for diadromous freshwater shrimps (Decapoda: Caridea) in the Bananier River, Guadeloupe, West Indies. Regulated Rivers 16: 101–112.

Fievet E, Le Guennec B. 1998. Mass migrations of *Sicydium* spp. (Gobiidae) in the streams of Guadeloupe island (French West Indies): Implications for the derivation race of small hydroelectric power stations. Cybium 22: 293–296.

Fievet E, Tito de Morais L, Tito de Morais A, Monti D, Tachet H. 2001a. Impacts of an irrigation and hydroelectric scheme in a stream with a high rate of diadromy (Guadeloupe, Lesser Antilles): Can downstream alterations affect upstream faunal assemblages? Archiv für Hydrobiologie 151: 405–425.

Fievet E, Roux AL, Redaud L, Serandour JM. 2001b. Conception of passage facilities for the amphidromous biota (freshwater shrimps and fishes) of the West Indies: A review. Bulletin Français de la Pêche et de la Pisciculture 357–360: 241–256.

Freeman MC, Pringle CM, Greathouse EA, Freeman BJ. Ecosystem-level consequences of migratory faunal depletion caused by dams. In Limburg KE, Waldman JR, eds. Biodiversity and Conservation of Shads Worldwide. Bethesda (MD): American Fisheries Society Symposium Series. Forthcoming.

Gillanders BM, Kingsford MJ. 2002. Impact of changes in flow of freshwater on estuarine and open coastal habitats and associated organisms. Oceanography and Marine Biology: An Annual Review 40: 233–309.

Gleick PH. 2000. The changing water paradigm: A look at twenty-first century water resources development. Water International 25: 127–138.

Ha PY, Kinzie RA III. 1996. Reproductive biology of *Awaous guamensis,* an amphidromous Hawaiian goby. Environmental Biology of Fishes 45: 383–396.

Hamano T, Hayashi K. 1992. Ecology of an atyid shrimp *Caridina japonica* (de Man, 1892) migrating to upstream habitats in the Shiwagi rivulet, Tokushima prefecture. Researches on Crustacea 21: 1–13.

Hamano T, Honke K. 1997. Control of the migrating course of freshwater amphidromous shrimps by lighting. Crustacean Research 26: 162–171.

Hamano T, Yoshimi K, Hayashi H, Kakimoto H, Shokita S. 1995. Experiments on fishways for freshwater amphidromous shrimps. Nippon Suisan Gakkaishi 61: 171–178.

Holmquist JG, Schmidt-Gengenbach JM, Buchanan Yoshioka B. 1998. High dams and marine–freshwater linkages: Effects of native and introduced fauna in the Caribbean. Conservation Biology 12: 621–630.

Hunte W. 1975. *Atya lanipes* Holthius, 1963, in Jamaica, including taxonomic notes and description of the first larval stage (Decapoda, Atyidae). Crustaceana 28: 66–72.

Hunter JM, Arbona SI. 1995. Paradise lost: An introduction to the geography of water pollution in Puerto Rico. Social Science and Medicine 40: 1331–1355.

[ICOLD] International Commision on Large Dams. 1998. World Register of Dams. Paris: ICOLD.

Iguchi K, Mizuno N. 1990. Diel changes in larval drift among amphidromous gobies in Japan, especially *Rhinogobius brunneus.* Journal of Fish Biology 37: 255–264.

———. 1999. Early starvation limits survival in amphidromous fishes. Journal of Fish Biology 54: 705–712.

Laine A, Jokivirta T, Katopodis C. 2002. Atlantic salmon, *Salmo salar* L., and sea trout, *Salmo trutta* L., passage in a regulated northern river—fishway efficiency, fish entrance and environmental factors. Fisheries Management and Ecology 9: 65–77.

Lewis JB, Ward J. 1965. Developmental stages of the palaemonid shrimp *Macrobrachium carcinus* (Linneaus, 1758). Crustaceana 9: 137–148.

Loneragan NR, Bunn SE. 1999. River flows and estuarine ecosystems: Implications for coastal fisheries from a review and a case study of the Logan River, southeast Queensland. Australian Journal of Ecology 24: 431–440.

March JG, Benstead JP, Pringle CM, Scatena FN. 1998. Migratory drift of larval freshwater shrimps in two tropical streams, Puerto Rico. Freshwater Biology 40: 261–273.

March JG, Benstead JP, Pringle CM, Ruebel MR. 2001. Linking shrimp assemblages with rates of detrital processing along an elevational gradient in a tropical stream. Canadian Journal of Fisheries and Aquatic Sciences 58: 470–478.

March JG, Pringle CM, Townsend MJ, Wilson AI. 2002. Effects of freshwater shrimp assemblages on benthic communities along an altitudinal gradient of a tropical island stream. Freshwater Biology 47: 377–390.

McDowall RM. 1992. Diadromy: Origins and definitions of terminology. Copeia 1992: 248–251.

Miya Y, Hamano T. 1988. The influence of a dam having no spillway on the distribution of decapod crustaceans in the Yukinoura River, Nagasaki, Japan. Nippon Suisan Gakkaishi 54: 429–435.

Moriyama A, Yanagisawa Y, Mizuno N, Omori K. 1998. Starvation of drifting goby larvae due to retention of free embryos in upstream reaches. Environmental Biology of Fishes 52: 321–329.

Poff NL, Hart DD. 2002. How dams vary and why it matters for the emerging science of dam removal. BioScience 52: 659–668.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow paradigm. BioScience 47: 769–784.

Postel SL. 2000. Entering an era of water scarcity: The challenges ahead. Ecological Applications 10: 941–948.

Pringle CM. 1997. Exploring how disturbance is transmitted upstream: Going against the flow. Journal of the North American Benthological Society 16: 425–438.

Pringle CM, Scatena FN. 1999. Freshwater resource development: Case studies from Puerto Rico and Costa Rica. Pages 114–121 in Hatch U, Swisher ME, eds. Managed Ecosystems. Oxford (United Kingdom): Oxford University Press.

Pringle CM, Hemphill N, McDowell WH, Bednarek A, March JG. 1999. Linking species and ecosystems: Effects of different macrobiotic assemblages on interstream differences in benthic organic matter. Ecology 80: 1860–1872.

Pringle CM, Freeman MC, Freeman BJ. 2000. Regional effects of hydrologic alterations on riverine macrobiota in the New World: Tropical–temperate comparisons. BioScience 50: 807–823.

[PRWA] Puerto Rican Water Authority. 1998. Declaracion de impacto ambiental del acueducto regional del noroeste. San Juan (Puerto Rico): PRWA.

Richter BD, Redford KH. 1999. The art (and science) of brokering deals between conservation and use. Conservation Biology 13: 1235–1237.

Richter BD, Baumgartner JV, Braun DP, Powell J. 1998. A spatial assessment of hydrologic alteration within a river network. Regulated Rivers: Research and Management 14: 329–340.

Rosenberg DM, McCully P, Pringle CM. 2000. Global-scale environmental effects of hydrological alterations. BioScience 50: 746–751.

Scatena FN. 2001. Ecological rhythms and the management of humid tropical forests: Examples from the Caribbean National Forest, Puerto Rico. Forest Ecology and Management 154: 453–464.

Stanford JA, Ward JV, Liss WJ, Frissell CA, Williams RN, Lichatowich JA, Coutant CC. 1996. A general protocol for restoration of regulated rivers. Regulated Rivers 12: 391–413.

Yasuda Y, Ohtsu I, Hamano T, Yasuhiko M. 2000. A proposed fishway to facilitate the upstream and downstream migration of freshwater shrimps and crabs. (6 October 2003; *www.iahr.org/e-library/beijing_proceedings/Theme_B/a%20proposed%20fishway%2 0to%20facilitate.html)*

Yuma M, Maruyama A, Rusuwa B. 2000. Behavior and distribution of upstream-migrating juvenile *Rhinogobius* sp. (the orange form). Ichthyological Research 47: 379–384.