Urban Ecosyst (2012) 15:315–325
DOI 10.1007/s11252-011-0214-3

Urban impacts on tropical island streams: Some key aspects influencing ecosystem response

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Published online: 12 November 2011

Abstract Improving our understanding of the impacts of urbanization on tropical island streams is critical as urbanization becomes a dominant feature in tropical areas. Although the "urban stream syndrome" has been successful in summarizing urban impacts on streams, the response of some island streams is different to that expected. Here we review available information on urban impacts to tropical island streams and describe unique responses to urbanization. We identified three key aspects that play particularly important or unique roles in determining tropical-island stream integrity: biotic response to water pollution, movement barriers along the stream network, and altered geomorphology that results in habitat loss. As expected, water pollution negatively impacts stream ecosystems in tropical islands and in some regions impacts can be severe, as untreated wastewaters are directly discharged into streams. While aquatic insects show the expected responses to pollution, other native fauna (e.g., shrimps and fishes) appear to be less impacted by moderate levels of pollution. Movement barriers along the stream network are especially important as much of the tropical island fauna have diadromous (either amphidromous or catadromous) life histories. Most native freshwater mollusks, shrimps, and fishes inhabiting tropical islands are diadromous and depend on unimpeded connections between freshwater and marine environments to complete their life cycles. The presence of these species in urban streams is best explained by longitudinal connectivity rather than by the degree of urban impact. Finally, in streams that remain connected to marine environments, the presence of native shrimps and fishes is strongly related to the physical habitat. Fish assemblages in channelized and severely altered stream reaches are almost completely devoid of native fauna and tend to be dominated by non-native species. In contrast, relatively diverse shrimp and fish assemblages can be found in reaches that retain their physical habitat complexity, even when they are impacted by urbanization. Our

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understanding of urban impacts on tropical island streams remains limited. However, the identification of key aspects can help us better understand urban impacts on streams in tropical islands, and best focus our management and research efforts to protect these unique ecosystems.

Keywords Urban streams · Tropical island urban streams · Urban stream syndrome · Stream pollution · Longitudinal connectivity · Habitat heterogeneity

Introduction

Urbanization is rapidly increasing in tropical regions. It is expected that by 2030 all tropical regions will have more urban than rural inhabitants (Montgomery 2008). Tropical islands are no exception and urban land cover has been increasing at a rapid pace (Grau et al. 2003) with a concomitant impact on the environment. In tropical islands this pressure is accentuated by the limited and often unique natural resources present and the already large rates of extinction (Vitousek 1988). Stream biota often contains endemic species, in particular among aquatic insects, with unique life history strategies and empty niches that might facilitate the establishment of non-native species (Smith et al. 2003). Understanding the effects of urbanization on tropical island streams is an important step towards avoiding the loss of these valuable ecosystems.

Urban impacts on stream ecosystems are summarized in the "urban stream syndrome" (Meyer et al. 2005; Walsh et al. 2005), a model that helps conceptualize the mechanisms by which urbanization alters stream ecosystems. According to the model, stream responses to urbanization follow a particular pattern, regardless of geographic location. For example, the large amount of impervious surfaces in urban areas results in altered hydrological regimens, rapid fluctuations in water level, and flashier hydrographs. Similarly, channel morphology is altered due to changes in the rate of sediment inputs, which tend to be high during urban construction and low once most of the watershed is covered with impermeable surfaces (Paul and Meyer 2001). Water quality is also impaired with increased concentration of nutrients and contaminants. Although the syndrome applies to urban streams in many locations, most of our understanding of urban impacts is the result of research in continental streams in temperate regions (e.g., Roy et al. 2003; Chadwick et al. 2006).

Tropical island streams have different dynamics from their continental counterparts. In particular, island watersheds are often short and steep and, if located in a rainy area, have flashy hydrological regimen (Gupta 1995). Stream fauna is often dominated by groups that migrate between freshwater and marine environments. These unique characteristics result in particular responses to urbanization with some responses differing from those proposed by the urban stream syndrome (Ramírez et al. 2009). Here we review available information on how tropical island streams are impacted by urbanization and on stream characteristics that might result in unique island responses to urbanization. Our main goal is to explore generalities that might be common to all urban streams on tropical islands and to identify aspects of island systems that might play a key role in maintaining stream integrity in urban areas in order to focus future research efforts. We draw particularly on examples from urban streams in Puerto Rico and Hawaii as these locations have been the focus of urban aquatic research, but propose that these are suitable indicator systems for tropical island streams in general. Although our emphasis is on oceanic islands, we also expect that some continental coastal streams and streams on continental islands might have similar dynamics.

Tropical island stream characteristics

There are many islands in the tropics of a variety of sizes, origins, and characteristics. The tropical Pacific has at least 30,000 islands, Indonesia alone is composed of over 13,000 islands, and the Caribbean has over 700 islands. Islands are commonly classified according to their geographic position and geology (Falkland 1992). Geographic classes include oceanic and continental islands; geologic classes include volcanic, limestone, bedrock, or mixed geologies. Most volcanic islands have complex topographies and mountains of some elevation. In contrast, limestone islands tend to be flat and of low elevation. Although surface water is not found on all tropical islands, volcanic islands are more likely to have permanent streams due to their mountainous topography. Socioeconomically, most tropical islands are within developing countries (Falkland 1992).

Volcanic island streams tend to differ from typical continental streams in being particularly flashy, due to the combination of steep slopes and heavy rainfall. Stream flashiness has been related to water-saturated soils that result in short time responses to heavy rainfall events, even in forested watersheds (Ramírez et al. 2009). While flashy streams also occur in continental areas, high flashiness seems to be a dominant characteristic of volcanic islands (Brasher 2003; Ramírez et al. 2009). Moreover, native biota is likely to be well adapted to cope with large and frequent floods (Hein et al. 2011). Adaptations include modified ventral fins that allow fishes from the family Gobiidae to secure themselves in fast flowing water (McDowall 2007), strong claws and the ability to crawl under rocks in decapods (Hein et al. 2011), and constant upstream movement in snails (Blanco and Scatena 2005).

Stream animal biota on oceanic islands differs from continental islands and coastal areas due to the strong dominance of diadromous fauna (McDowall 2007). Dispersal limits the presence of continental fauna on islands, thus among island types, oceanic island streams differ the most from continental streams. In addition, the stream fauna of oceanic islands tends to be similar in taxonomic composition and morphological adaptations. For example, fish fauna is dominated by a few families (e.g., Gobiidae, Eleotridae, Mugilidae) with pan-tropical distributions (Fitzsimons et al. 2002), which are very well adapted to inhabit flashy and steep streams (Fitzsimons et al. 2002; Hein et al. 2011).

Urban impacts to tropical island streams

Studies of urban effects on tropical island streams are still limited, but it is likely that the stressors associated with urbanization are generally similar to those occurring in temperate continental systems (Walsh et al. 2005). However, the responses to these stressors can differ substantially, due to the special characteristics of tropical island streams. For example, urban streams are generally characterized by higher flashiness than nearby forested streams, due to increased runoff from impervious surfaces (Chadwick et al. 2006). Since many tropical island streams are naturally flashy, however, it is possible that this effect may be reduced. This is a critical difference, as hydrologic alteration has been identified as the core driver of the urban stream syndrome in many temperate regions (Walsh et al. 2005; Chadwick et al. 2006; Wenger et al. 2009).

We identified three factors that appear to play important and unique roles in determining stream responses to urbanization on tropical islands. These are: biotic responses to water pollution, movement barriers along the stream network, and altered geomorphology that results in habitat loss. While any of these factors might play an important role in continental streams, in tropical islands they appear to play larger than expected roles or result in unique stream responses to urbanization. At the same time, it is important to highlight that other urban impacts also play important roles in determining stream ecosystem integrity on islands.

The importance of our proposed key aspects might be best appreciated in the form of testable hypotheses. Although tropical islands are very diverse in origin and form, we propose that valuable insight can be gained about the effects of urbanization on stream ecosystems by addressing the following hypotheses:

I. The high proportion of diadromous fauna (mainly shrimps and fishes) in tropical island streams means that the biotic response of such systems differs from continental streams. This is because diadromy allows the potential advantage of utilizing two separate environments during an organism's life cycle, and consequently native shrimp and fish are able to continuously colonize urban streams and maintain their populations even in heavily impacted streams, if their associated marine environment is not severely degraded. This result in an increased tolerance of shrimp and fish populations to water pollution compared to continental streams. This trend is hypothesized to not be observed in aquatic insects, which do not display diadromous life cycles, and which therefore respond similarly to continental streams.
II. Diadromy only provides the capacity for populations to be maintained if longitudinal connectivity is maintained and barriers to movement are absent, meaning that longitudinal disruption may be particularly significant in tropical island streams.
III. Given the relative tolerance of native shrimps and fishes to urbanization and the natural flashiness of island streams, the maintenance of natural stream habitats will allow for the establishment of natural faunal assemblages in urban reaches that remain connected with estuaries.

Although rigorous experimental studies are required to fully investigate these hypotheses, the following sections explore the available literature to suggest their validity and set the background for more extensive and intensive testing.

Biotic responses to water pollution Water pollution is a major negative impact of urbanization to stream ecosystems everywhere. Urban point (e.g., pipes) and non-point (e.g., runoff) sources of contaminants result in water quality degradation, changes in ecosystem function, and negative impacts on aquatic organisms (Walsh et al. 2005). More specifically, water pollution is related to changes in toxins, ionic concentrations, available nutrients, temperature, pH, dissolved oxygen, and suspended sediments, among others, that have diverse impacts on stream ecosystems (Paul and Meyer 2001). In tropical countries, stream pollution can be a severe problem and the magnitude and urgency of dealing with it was recognized by the United Nations when they declared 2008 as the “year of sanitation.” While most countries have appropriate regulations, there is a major lack of law enforcement that results in high levels of contaminants entering stream ecosystems (Ramírez et al. 2008). For example, in Latin America less than 2% of total urban sewage receives treatment before it is discharged into rivers (Pringle et al. 2000), even though negative consequences to stream and human health are well known (Cohen 2008). Serious environmental degradation resulting from uncontrolled wastewater discharges has been documented for Pacific islands (Kwai Sim and Balamurugan 1991; Cohen 2008).

While tropical island streams are not necessarily less impacted by pollution than tropical streams elsewhere, the response of biotic assemblages to pollution appears to differ. Changes in biotic assemblages from diverse to species poor are expected for urban streams in general (Walsh et al. 2005). That certainly is the case for aquatic insect assemblages in tropical island streams. Studies in Puerto Rico and Hawaii provide clear evidence for a change in insect assemblage composition from one dominated by species sensitive to pollution to one dominated by tolerant species (Brasher et al. 2004; Englund et al. 2007; De Jesús-Crespo and Ramírez 2011). In contrast to aquatic insects, shrimp and fish assemblages appear to be more tolerant to pollution and island urban streams have been found to support diverse assemblages of native species. For example, fish assemblages that maintain their native species and densities have been reported for urban streams in Hawaii (Englund et al. 2007) and Puerto Rico (Ramírez et al. 2009), as long as those urban streams maintain their channel free of major dams. A similar situation appears to be the case for freshwater shrimp assemblages (Perez-Reyes 1999). However, decreases in larval drift due to degraded water conditions have been reported, related to poor oxygen conditions (Luton et al. 2005). Given that native tropical island shrimp and fish fauna are diadromous, it can be hypothesized that this gives them the ability to tolerate higher levels of pollution than fishes in continental streams that only live in freshwater environments.

Diadromy is most likely what allows freshwater fishes to colonize (and re-colonize) freshwater habitats in remote islands where streams may range from large and permanent to small and seasonal (McDowall 2009). Diadromous species have the additional advantage of not relying on local populations as exclusive sources of new recruits. Thus, even if urban stream populations have reduced reproduction due to pollution, they can be maintained by recruits arriving from nearby less impacted watersheds. Fitzsimons et al. (1996) documented constant recolonization of native fish species, even after unusually harsh disturbances such as a hurricane, for Hawaiian streams. Furthermore, population genetics studies in Hawaiian Islands (with fish) (Zink et al. 1996; Chubb et al. 1998) and Puerto Rico (with fish, shrimps and gastropods) (Cook et al. 2009) described a lack of genetic structure and a high amount of gene flow between rivers and even islands. A constant flow of new recruits has an important implication for restoration of urban streams. It shows the potential for the recovery of diadromous populations, since their "healthy" counterparts could act as sources of recruits to sink populations in polluted streams.

Movement barriers and longitudinal connectivity Longitudinal connectivity is an important aspect in maintaining ecosystem integrity in tropical rivers. In tropical island streams, connectivity between freshwater and marine environments is especially important since native species of freshwater mollusks, shrimps, and fishes have amphidromous or catadromous life histories (Ford and Kinzie 1982; Ryan 1991; McDowall 2004, 2007, 2010a, b; Resh 2005). Therefore, in island streams the presence of migration barriers play a key role determining whether these groups are present in streams, regardless of watershed land use.

Island freshwater migratory fauna (e.g., mollusks, shrimps, and fishes) are well adapted to cope with most obstacles along stream channels. They can crawl (e.g., shrimps and snails) or use modified fins to climb (e.g., gobies) steep channels and the numerous waterfalls present in volcanic island streams. These adaptations also allow them to cope with the rapid fluctuations in discharge that occur naturally in many tropical island streams. However, large waterfalls (>20 m) are major migration barriers for most fish species, and upstream reaches tend to be dominated by shrimps and a few species of gobiid fishes that can climb them (Ford and Kinzie 1982; Benstead et al. 1999; Freeman et al. 2003; Strong et al. 2008). Therefore, the location of urban areas with respect to these migration barriers plays a large part in determining the biotic composition of their stream fauna.

Large dams with little or no spillway discharge are major migration barrier for native island fauna (Holmquist et al. 1998). The location of dams with respect to urban areas has a direct effect on the composition of biotic assemblages in streams (Pringle 1997; Joy and Death 2001). While large dams located upstream from urban areas are sources of hydrological alteration for urban streams, those located downstream will completely extirpate native shrimps and fishes, regardless of urban impacts (Holmquist et al. 1998; Benstead et al. 1999; Perez-Reyes 1999; March et al. 2003; Moulton and Wantzen 2006; Crook et al. 2009). Relic populations can be found upstream from dams for some time, as most shrimps and fishes are relatively long-lived organisms (up to 11 years) (Cross et al. 2008). The extirpation of migratory fauna from reaches upstream from dams may have severe consequences for ecosystem functioning. Shrimps are known to pay an important role in processing organic matter (e.g., leaf litter) and fine sediment particle transport (Pringle and Blake 1994). Reaches upstream from dams that lack shrimp accumulate more sediment and have altered benthic communities (Pringle 1996; Greathouse et al. 2006). The importance of dams in affecting the structure of stream biotic assemblages has been documented for several oceanic islands, among them: French Polynesia (Resh 2005), Guadeloupe (Fièvet 1999), Guam (Concepcion and Nelson 1999), Hawaii (Brasher 2003), Japan (Miya and Hamano 1988), New Zealand (McDowall 2010a, b), and Puerto Rico (Holmquist et al. 1998).

Studies in Puerto Rico provide evidence on the relative importance of longitudinal connectivity versus urban impacts in determining the composition of shrimp and fish assemblages in urban watersheds. The Rio Piedras is a heavily urbanized watershed in Puerto Rico, reaching ~50% urban cover, but remaining largely free-flowing, with only one dam in the upper part of the watershed (De Jesús-Crespo and Ramírez 2011). Despite evident urban impacts (e.g., channelization, water pollution) this urban watershed maintains large populations of native shrimps and fishes, along with several non-native species (Ramírez et al. 2009). Shrimp assemblages are dominated by predatory palaemonids, and densities are similar to those in natural rivers (Perez-Reyes, personal observation). Although fish assemblages are a mixture of native and non-native species, all seven native species are present in the Rio Piedras in abundances similar or even larger than assemblages in natural rivers (Kwak et al. 2007; Ramírez et al. 2009).

Physical habitat integrity and heterogeneity The physical habitat of urban tropical island streams plays an important role in controlling faunal assemblage structure under certain circumstances. For most native diadromous fauna, physical habitat is only significant for urban streams with unimpeded freshwater-marine connectivity. Non-migratory native invertebrates' sensitivity to pollution often excludes them from urbanized streams, regardless of physical habitat characteristics (Roy et al. 2003). As in streams everywhere, urbanization degrades the physical habitat of urban tropical island streams and channelization is a common flood control action. However, due to the unique adaptations of tropical diadromous fauna, the fact that urbanization is increasing more rapidly in the tropics than anywhere else in the world (Montgomery 2008) and the fact that flood control (often addressed by river channelization) is an especially important issue in tropical cites (Maksimovic et al. 1993), it is important to examine community responses to these two causes of physical habitat degradation.

Urbanization is expected to cause increases in stream flashiness, scouring, increases in pool depth and channel width; and decreases in channel complexity (Walsh et al. 2005). An increase in fine sediment deposition also consistently occurs in highly urbanized streams in tropical islands (Brasher 2003). All of these effects will degrade important microhabitat features and reduce habitat heterogeneity, negatively affecting individual species and overall community structure, respectively. Reduced physical habitat heterogeneity can severely impact native fauna that rely on behavioral responses to cope with frequent flash floods common in inland streams, such as taking shelter behind rocks (Fitzsimons et al. 2002). Moreover, amphidromous species even depend on flash floods for successful reproduction and upstream migratory cues (Blanco and Scatena 2005). Therefore, native diadromous species might only be strongly affected by catchment-scale urbanization if it causes severe changes to instream habitat.

Channelization commonly occurs in conjunction with urbanization and can cause direct and severe instream habitat alteration. Channelization involves riparian vegetation clearing, river course redirection and the replacement of natural substrates with cement or gabion (Brooker 1985; Brasher 2003). Channelization creates highly degraded microhabitat features: substrates becomes more embedded, uniform and may be replaced entirely with cement; depth is more shallow and homogeneous; water velocity is higher and more homogeneous with higher temporal variability; and temperature is higher during the daytime and more homogeneous (Brasher et al. 2004). The channelization of a section of an urban tropical island watershed often causes the extirpation of the majority of native shrimp and fish species in that section. This is particularly evident where concrete is used to make a smooth, high velocity channel. For example, concrete channelized reaches in an urban Puerto Rican watershed were habitat for only one native fish species and few shrimps (Engman 2011). These reaches also had extremely high abundances of fast growing, highly fecund non-native fish species (e.g., poeciliids and cichlids; Engman 2011). A similar pattern occurs in Hawaii where urbanized watersheds have a reduced native fish and crustacean assemblage, but concrete channelized reaches are fully devoid of native species and dominated by tolerant non-natives (Norton et al. 1978; Timbol and Maciolek 1978; Brasher 2003; Brasher et al. 2004). Although we draw on examples only from Hawaii and Puerto Rico, the striking morphological and taxonomic similarities of diadromous fauna on tropical islands worldwide in our opinion justify the generalization of these examples.

Observed responses to urban stressors occur in part because components of the physical habitat, which serve specific functions for individual species, are degraded. Substrate, depth, water velocity, aquatic vegetation and riparian plant debris all mediate predator–prey interactions, resistance to disturbance, reproduction or are generally associated with the presence of fishes and invertebrates in streams (Allan and Castillo 2007). For example, many species of amphidromous gobies utilize specific substrate sizes for hydraulic and predatory refuges (Onoda 2009). Substrates (along with depth) are also used as predatory refugia by *Macrobrachium* shrimps in rainforest streams of Puerto Rico (Villamil and Clements 1976; Covich et al. 1996). Eleotrids use vegetation, root wads, coarse woody debris and floating macrophytes (Winemiller and Ponwith 1998) possibly to conceal themselves from both prey and predators. Substrates or vegetation are also important as nesting sites for amphidromous gobies in tropical islands (Keith 2003). Depth, substrate and velocity were all found to be useful in predicting the distribution of neritid snails at the habitat scale in Puerto Rico (Blanco and Scatena 2006). Finally, in a Caribbean-wide study, invertebrate species in general were found most commonly in leaf-packs (Bass 2003).

Although the habitat of an urban island stream is generally degraded, where sufficient habitat heterogeneity is maintained some native species can thrive in urbanized streams (Engman 2011). This is particularly true for sections with some riparian cover, natural substrates, and diverse water velocities and depths. Also, where physical habitat has been too severely degraded to support native fauna, remediation by actively increasing physical habitat complexity is possible. This is evidenced by successful restorations of diadromous fish populations to urbanized streams in Japan (Taginuchi et al. 2001) and New Zealand (Te Aroha 2009). The restoration of diadromous species populations may also be relatively cost-efficient because adjacent rivers are potential sources of recruits, thus negating the need for restocking. Finally, maintaining habitat integrity and heterogeneity may be important for preventing the establishment of non-native species, as many seem to be better suited to highly degraded habitats than natives (Brasher 2003).

Research needs on urban island streams in the tropics

Although our initial literature synthesis has shown some support for our hypotheses on the differential response of tropical island streams to urbanization in comparison to continental streams, further work is needed to determine whether these may be proven or not. In particular, research should focus on:

- Native fauna apparent tolerance to pollution. Almost all species of fishes and some shrimps had been found in large numbers in urban streams. However, there is a complete lack of information on their physiological tolerances and whether those populations are successful at maintaining themselves or are behaving like "sink" populations.
- Urban impacts on stream longitudinal connectivity. Urbanization can decrease longitudinal connectivity on island streams due structures such as road crossings or channelization. There is a need to quantify the effects of reductions in connectivity on the population dynamics of diadromous shrimps and fishes.
- The relation between habitat heterogeneity and stream biodiversity. Although we can assume that the maintenance of natural stream habitats will facilitate the establishment of natural faunal assemblages in urban reaches with connectivity to estuaries, there is very little information on the habitat requirements of native island fauna.
- A few tropical islands (e.g., Hawaii and Puerto Rico) are better studied than most tropical islands. Patterns found on these two islands are certainly good examples of stream dynamics in tropical islands in general. However, these examples come from islands that have advanced regulations and infrastructure in place and might be better able to protect their urban streams than many other tropical islands. Studies in Hawaii and Puerto Rico might help us understand the potential for restoration if developing countries increase their level of control on stream impacts. Further research should focus on assessing whether models from Hawaii and Puerto Rico might help guide efforts elsewhere in the tropics.
- Additional studies should focus on other urban impacts to tropical island stream ecosystems. For example, riparian zones are known to play key roles in structuring fish assemblages in tropical streams (Arthington et al. 2006). Yet there is limited information on the role of riparian zones in tropical urban streams and much less for tropical islands. Another factor that needs attention is flow alteration during the dry season. Although we know that stream flashiness changes little in urban island streams, low flows could be severely impacted by leaking pipes and waste water discharges.

Acknowledgements We thank Chip Small, Seth Wenger and an anonymous reviewer for their comments on the manuscript. We also appreciate help by Sue Engman in editing the manuscript. Our urban stream research in Puerto Rico is part of the Luquillo Long-Term Ecological Research program (NSF DEB-0620910) and the San Juan ULTRA program (NSF 0948507).

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