Regular paper

Pebbled places preferred by people and pipefish in a World Heritage protected area

by

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Abstract. – Although the ecological impacts of recreational activities in clear tropical streams are occasionally acknowledged and addressed, frequently they remain unmanaged, despite the fact that such streams are highly sought-after destinations for leisure pursuits. Here, we provide a case study on the ecological characteristics of the Indo-Pacific freshwater pipefish *Microphis leiaspis* Bleeker, 1854, which is a habitat specialist with little available information aside from its reproductive biology and the downstream migration patterns of its larvae. Drawing from our collective experiences, we describe the distribution and habitat of *Microphis leiaspis* and examine the potential impacts of various small-scale human activities on its livelihood, including those occurring within protected areas. In particular, we document incidental observations of human disturbances to adult *Microphis leiaspis* habitat in clear freshwater streams located within the Australian Wet Tropics (AWT) World Heritage Area. Using these observations as a foundation, we conceptualize human interactions with this species in the AWT streams and more broadly across the tropical Indo-Pacific Ocean. *Microphis leiaspis* occurs in the lower-mid course of short-steep-coastal-streams, in association with pebble fields, where it feeds on microscopic benthic invertebrates. We observed three distinct human behaviours in the pipefish habitat within the AWT, including stone-stacking, the construction of boulder-cobble dams, and stone-skimming. Additionally, we report on other small-scale human activities that may potentially impact this pipefish species in streams across Pacific Island nations and select coastal regions of continents. Our recommendation is to promote a ‘leave no trace’ approach to the public, which can be effectively communicated by key individuals such as indigenous custodians, national park managers, locals, and tourism operators. This approach aims to minimize rock movement by people, thereby aiding in the protection of diadromous pipefish and other aquatic species residing in short-steep-coastal-streams.

Résumé. – Les fonds rocheux et de galets des aires protégées : des zones très prisées des hommes et des syngnathes d’eau douce.

L’impact écologique des activités récréatives dans les rivières tropicales est occasionnellement reconnu mais peu géré malgré le fait que ces zones paisibles en font des lieux de détente très prisés. Nous présentons ici un cas d’étude sur les caractéristiques écologiques d’un syngnathe d’eau douce de l’Indo-Pacifique, *Microphis leiaspis* Bleeker, 1854, une espèce spécialiste, pour laquelle il y a peu d’informations publiées à l’exception de quelques éléments sur sa reproduction et sur le comportement de dévalaison des larves. Nous décrivons, la distribution et

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l'habitat de *Microphis leiaspis* et nous discutons de l'impact que peuvent avoir les comportements humains sur sa survie, et ce, à plusieurs échelles et y compris dans des zones protégées. Plus spécifiquement, à l'aide d'observations faites de manière opportuniste, nous décrivons les perturbations que peuvent provoquer les humains sur l'habitat des syngnathes adultes dans une rivière tropicale australienne au sein d'une aire protégée (AWT, Wet Tropics World Heritage Area). Nous généralisons ces observations en les utilisant comme une base pour la conceptualisation des interactions entre l'Homme et cette espèce dans les îles tropicales de l'océan Pacifique. Cette espèce de syngnathe se trouve dans les cours inférieurs à moyens de rivières qui sont courtes, pentues et proches des côtes et ce sur un substrat rocheux et caillouteux. Cette espèce se nourrit de vertébrés benthiques microscopiques. Nous rapportons trois types de pratiques humaines principales au sein de l'habitat des syngnathes de l'AWT, à savoirs la construction de cairns, la construction de petits barrages à l'aide de rochers et les ricochets. Nous rapportons aussi d'autres pratiques à petite échelle humaine qui pourraient impacter les populations de syngnathes dans les rivières des îles du Pacifique et aux marges continentales. Ces observations préliminaires nous mènent à recommander une sensibilisation auprès du public (tribus locales, gestionnaires de parcs naturels, opérateurs touristiques) qui ne doit "laisser aucune trace" afin que ces personnes minimisent le déplacement des roches et cailloux des cours d'eau. Une telle action pourrait aider à la protection des syngnathes diadromes et de toutes les autres espèces présentes dans ce cours d'eau.

INTRODUCTION

Relative to terrestrial systems, freshwater ecosystems commonly lag in the level of protection that they receive (Hermoso *et al.,* 2016). In part, this is because of the terrestrial affinity that humans have as land occupants and also relates to fundamental differences in human capacity for understanding the properties of lotic systems (*e.g*., linearity, connectivity, directionally nested hierarchies) (Abell *et al.,* 2007; Melles *et al.,* 2012). Disrupting catchment-scale processes such as flow and flooding patterns, exchanges between streams and riparian areas, animal migration routes, and increased sedimentation have long been identified as significant threats to freshwater ecosystems. (*e.g*., MacKinnon *et al.,* 1986; Keith, 2003; Abell *et al.,* 2007). In addition, a lack of scientific understanding of the function and requirements of aquatic biodiversity can itself be viewed as a threatening process to aquatic fauna (Pusey *et al.,* 2004).

This study focuses on the less recognised human behaviours in tropical streams that can have potentially adverse environmental impacts, despite these streams being popular locations for recreational activities. While some ecological impacts are already known and addressed, activities such as stone-stacking, constructing boulder-cobble dams, and stone-skimming have received negligible attention in the literature in protected freshwater areas (*cf*. Rocha *et al*., 2020). These behaviours have been observed in the Australian Wet Tropics (AWT), a small area of high-rainfall mountainous coastline near Cairns, and listed as a World Heritage Area due to its exceptional natural habitat and biodiversity value (MacKinnon *et al*., 1986). World Heritage Areas serve to protect nature based on recognised universal biodiversity value and serve as places for appreciation by global citizens (MacKinnon *et al.,* 1986). The lead author recently observed these behaviours while photographing the cryptic fish species, the freshwater pipefish *Microphis leiaspis* Bleeker, 1854 (family Syngnathidae), in streams at Cape Tribulation in far north Queensland, Australia. These seemingly harmless human activities can have a significant impact on the habitat of *M. leiaspis* and other habitat specialist fauna in small streams, a situation not unique to Australia.

There are approximately 30 species of pipefish that inhabit freshwater environments, and they are primarily found in the rivers of tropical islands in the Indo-Pacific region (Dawson, 1985; Haÿ *et al*., 2023). Freshwater pipefish have not been extensively studied for more than 35 years, and their taxonomy and nomenclature are unclear, leading to frequent misidentifications. A recent taxonomic revision of the Nerophinae subfamily (trunk brooders) within Syngnathidae led to the recognition of only one genus, *Microphis* Kaup, 1853, placing the five other known genera in synonymy with *Microphis* (*Oostethus* Hubbs, 1929; *Belonichthys* Peters, 1868; *Lophocampus* Dawson, 1984; *Coelonotus* Peters, 1855 and *Doryichthys* Kaup, 1856; Haÿ *et al*., 2023). *Microphis leiaspis* is an amphidromous pipefish species that inhabits short-steep-coastal-streams (SSCSs), as defined in the following section, throughout the tropical Indo-Pacific Ocean during its adult phase. (Ishihara and Tachihara, 2008; Keith *et al.,* 2021; Fig. 1). It is a widely distributed species, with a range spanning from Indonesia, Papua New Guinea, and the Solomon Islands to Fiji, and from Okinawa to Vanuatu, New Caledonia, and the AWT in Australia (Maeda and Tachihara, 2006; Ishihara and Tachihara, 2008; Tweedley *et al*., 2013; Keith *et al*., 2021). In Australia, the species was initially misidentified as a member of *Doryichthys* (Ebner and Thuesen, 2010; Thuesen *et al*., 2011), where it has frequently been detected at Cape Tribulation for the past decade and a half (Ebner, Thuesen, Donaldson, unpubl. data), and more sporadically at locations in the central AWT including to just south of Cairns (Ebner, Donaldson, Heffernan, Thuesen, pers. obs.).

The objectives of this study are twofold: a) provide some preliminary insight into the ecology of the adult phase of this species focusing on distribution, habitat associations and feeding behaviour, and b) describe some of the human activity which potentially negatively or positively impacts

Figure 1. – Adult *Microphis leiaspis* at Cape Tribulation. **A**: Female (~160 mm TL); **B**: Male (~150 mm TL) (Photos: BE).

M. leiaspis, including via alterations to hydrology and the geomorphology of SSCSs. Regarding advancing conservation of pipefish that inhabit freshwater streams, we include some treatment of the topic of using *M. leiaspis* as a flagship species for rainforest stream ecosystems in the Pacific region. We contend that much of our approach and thinking is likely to be transferable to other aquatic species which function as habitat specialists in SSCSs and are poorly studied and prone to human disturbances.

SHORT-STEEP-COASTAL-STREAMS

While SSCSs are typically associated with tropical islands, they can also be found on continents in areas with high rainfall, steep topography, and short distances to the coast. Examples of such areas include the Wet Tropics of Australia, the Pacific Northwest region of North America, and the coast of British Columbia in Canada (*e.g.*, Ebner and Thuesen, 2010; Nip, 2010). Short-steep-coastal-streams (SSCSs), which are also referred to as insular streams on tropical islands, are flowing waters that drain mountains and hills, and empty to the sea with poorly developed estuaries. The term “insular” refers to the fact that these streams are located on isolated tropical islands that are biogeographically separated from the continents (Ebner *et al.*, 2016a). Where SSCSs occur on continents, they are often found adjacent to larger rivers, which are dominated by continental fish assemblages (Thuesen *et al.*, 2011). The SSCSs of the AWT provide high-value locations for international tourism and hold cultural significance for indigenous custodians. They are also utilized by non-indigenous local populations and support a significant diversity of aquatic fauna that are of national importance (Ebner and Thuesen, 2010; Thuesen *et al.*, 2011; WTMA 2013; Ebner *et al.,* 2016a). While the habitat use of many cryptic (and even non-cryptic) freshwater species remains to be investigated scientifically in the AWT, some of the endemic and rare amphidromous fishes are known to occupy niches with specific flow and substrate requirements (Pusey *et al.*, 2004; Donaldson *et al.*, 2013) and occupy highly specific and narrow longitudinal distributions in SSCSs (Keith, 2003; Keith *et al.*, 2015; Ebner *et al.*, 2021).

ECOLOGY OF *MICROPHIS LEIASPIS*

The prehensile tail present in many members of the Syngnathidae (Dawson, 1985) is a key adaption leading to their occupation of ecological niches in habitats with strong vertical structural elements such as seagrass, fucoid algae, gorgonian corals, and freshwater macrophytes (Kuiter, 2000; Teske and Beheregaray, 2009). On the other hand, adult *Microphis leiaspis* hook and press their tail around small pebbles or rocks, allowing them to maintain or change position, but they do not exhibit a prehensile specialization for grasping vertical structures such as seagrass. This is unsurprising as tropical SSCSs typically experience dynamic flows and high discharge, leading to the absence of aquatic plants and the prevalence of bedrock, boulder, cobble, and pebble benthos. *Microphis leiaspis* is amphidromous with the adult phase occupying and breeding in lowland reaches of streams (Ishihara and Tachihara, 2008; Maeda and Tachihara, 2010). It does not appear to be widespread on the Australian continent, and to date is only known from the AWT. Our group of authors have observed adult *M. leiaspis* in SSCSs throughout the AWT, where they appear to be social and are most commonly found in the larger streams of the Cape Tribulation region (*e.g.*, Hutchison, Cooper, Noah, Thompson, Myall, and Emmagen creeks). We have occasionally observed adult *M. leiaspis* in the Mossman River and in the SSCS of the central Wet Tropics. For completeness, it is important to note that the presence of estuarine crocodiles in the area, and relevant concerns for researcher safety, make it difficult to fully understand the distribution and habitat associations of cryptic fish species in the region, particularly in the larger rivers (Ebner *et al.,* 2015). The males and female pipefish mature at 105-125 and 130 mm in standard length, respectively, and females deposit eggs in the brood pouch on the abdomen of the male, where the embryos are incubated until being released as larvae (Ishihara and Tachihara, 2008). Maeda and Tachihara (2010) gathered *M. leiaspis* larvae from the drift of SSCSs during nocturnal hours, while Ishihara and Tachihara (2008) suggested that drifting marine algae may be associated with the presence of juvenile *M. leiaspis*. There is no published quantitative information on the habitat use of the juvenile and adult life history phases of this species.

In the following paragraphs, author initials are sometimes ascribed to specific observations to provide some context for our qualitative observations. Three of the authors (BE, JD, KM) have spent more than 20 hours each observing the behaviour of this species in streams in Australia, the Solomon Islands and Okinawa. However, the limited quantitative data presented here focuses on habitat associations exclusively recorded from three 50-m reaches in each of Oliver and Emmagen creeks in the AWT.

Mesohabitat

Basing our definitions of surface flow types on Newson and Newson (2000), and using two assessors in the field (BE & JD), we estimated percent cover of surface flow types in three complete 50-m subsections within each of Emmagen and Oliver creeks (Cape Tribulation, Australia) and compared this availability with that occupied by *M. leiaspis* in a 0.5 × 0.5 m quadrat (Fig. 2D). The overall availability of detected flow types from most to least was rippled (38.3%), smooth boundary turbulent (29%), scarcely perceptible flow (18%), unbroken standing waves (8%), broken standing waves (6%), chutes (1%), and upwelling (0.04%). Broken standing waves were present in all reaches. Most individuals were either found entirely within rippled (n = 10) or smooth boundary turbulent flow (n = 10) or some mix of these (n = 3). Two individuals were recorded in scarcely perceptible flow within Emmagen Creek and three individuals were found at least partly associated with unbroken standing waves.

Microhabitat

We compared substrate, water depth and flow used by *M. leiaspis* with the availability of these habitats based on point measurements in Oliver and Emmagen creeks. Microhabitat use verse availability data was collected in relation to *M. leiaspis* in parallel while studying gobioid fishes and the freshwater moray, *Gymnothorax polyuranodon*, and the relevant methods are described more comprehensively in papers pertaining to those taxa (Donaldson *et al.*, 2013; Ebner *et al.,* 2016b). At that time, *M. leiaspis* was rarely seen in the water column unless an individual was startled, and on these occasions, it was clear that the species is a very capable swimmer including in upstream and downstream directions in high flows (~1 ms^{-1}).

Microphis leiaspis was only observed occupying shallow water, with 52 cm being the deepest an individual was recorded occupying. In Emmagen Creek where most of our samples were encountered (n = 21), individuals selected for moderate flowing (0.2-0.5 sms^{-1}), moderately shallow water (0.25-0.50 cm depth), on pebble-cobble benthos (Fig. 2). In Oliver Creek, only five individuals were observed and quantified for microhabitat use. These small sample sizes precluded clear indications of selectivity but reinforced that *M. leiaspis* occupies pebble-cobble habitat receiving intermediate benthic flows (Fig. 2A, C). Individuals in Oliver Creek inhabited very shallow water (Fig. 2B). Of the gobioids studied, this microhabit niche most aligns with *Schisma-*

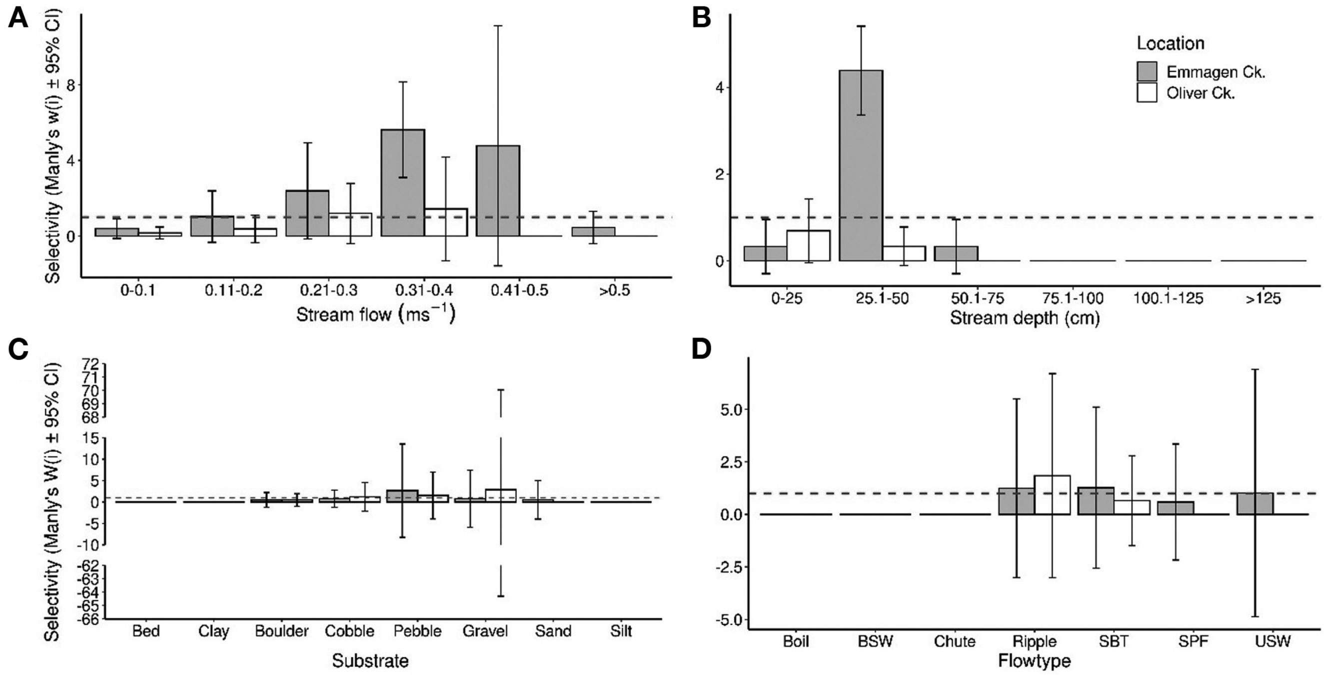

Figure 2. – Selectivity (± 95% confidence interval (CI)) of *Microphis leiaspis* for categories of **A**: Flow velocity; **B**: Depth; **C**: Substratum type and **D**: Flow type, used v. availability across two streams. Selectivity values greater than or equal to 1.0, indicated by the red dashed line (including 95% CI) indicate positive selection by *M. leiaspis* toward a given category, while values less than 1.0 (including 95% CI) indicate negative selection.

togobius hoesei, but the latter prefers a greater proportion of sand in which to bury (*cf.* Donaldson *et al.*, 2013).

Occasionally, the larger streams in Cape Tribulation exhibit isolated patches of the macrophyte *Blyxa*, typically in partially sandy areas. However, a general absence of aquatic macrophytes is a notable feature of the short-steep-coastal-streams within the AWT. Nevertheless, *M. leiaspis* has not been observed associating with *Blyxa*.

Additional behavioural and habitat use observations of adult *M. leiaspis* come from our collective experiences over a much wider temporal and spatial window in several streams in Australia (*e.g.*, BE & JD snorkelling in SSCS between 2009-2022) (JH in the Mossman River 2019-2022), in Okinawa, Japan (KM 1996-2022), the Solomon Islands (RH 2015-2022) and opportunistically across the Pacific Islands (DB, CL, PK, KM, JD, BE). These observations confirm that the longitudinal distribution of adult *M. leiaspis* is the lower-middle course of perennial streams. They also confirm that *M. leiaspis* is rarely seen where sand is available, nor where bedrock and boulders are the dominant features of the benthos. Pebbles, and to a lesser degree cobbles, are the dominant feature of their core range. Occasionally individuals are seen moving into or out from boulder fields and cascades at the head of pools (*e.g.*, in Noah Creek, Cape Tribulation, Australia, BE). The behaviour and habitat associations of *M. leiaspis* may therefore be more boulder associated than is acknowledged here, and in fact, there may be a quasi-subterranean component to their existence in a subset of streams (*i.e*,. complex boulder stream beds where the surface water passes below the upper boulder surface). In larger rivers of the Solomon Islands, the species does occur on the floodplain sills but only where exposed cobble and pebble habitat exist as a function of regular fluctuations in discharge rather than on silted or muddy floodplains (RH, pers. obs.).

Behaviour

When observed from a distance (1-5 m) or once accustomed to a snorkeller, *M. leiaspis* is typically found in loose groups with a high degree of fidelity to a small habitat patch (typically a pebble-cobble benthos spanning in the order of 5-30 m in maximum dimension). Individuals occasionally forage as a moving group, but more frequently forage individually and regularly check in with one another, including by being tactile and sliding across one another (BE, pers. obs.).

The female exhibits an orange or red colour on the chin and the opercula region and commonly displays an ornate body with very fine light blue/aqua or green reticulations (Fig. 1A). The male exhibits a drab grey body coloration (Fig. 1B), which can also be brown or cream, and at times is visibly carrying embryos in the pouch. The mouth of *M. leiaspis* is small and tubular (Fig. 3A). Individuals obtain their food by focusing on solitary microscopic benthic invertebrates that inhabit the surfaces and crevices of hard sub-

Figure 3. – *Microphis leiaspis* feeding at Cape Tribulation, Australia. **A**: Front view revealing the small open mouth of an adult female; **B**: Posturing and sideways glance prior to striking small benthic prey from a cobble surface; **C**: The forward-facing foraging technique (Photos: BE).

strates, rather than consuming plankton that is suspended in the water column. On most occasions, the feeding action involves using a dominant eye and an arching and twist of the body (Fig. 3B) with the tail anchored to the substrate and then a sideways movement of the head and a scraping/tearing action with the snout and mouth. Occasionally, individuals may visually locate their prey straight ahead followed by a strike at the prey in a forward direction (Fig. 3C) (including when the prey is positioned forward and below in the pebble matrix or above on the underside of a cobble).

In Australian populations, *M. leiaspis* commonly co-occurs (diurnally) with other fishes including *Pseudomugil signifer*, *Stiphodon* spp., *Glossogobius illimis*, *Awaous acritosus*, *Schismatogobius hoesei, Kuhlia rupestris* and *Kuhlia marginata*. *Microphis leiaspis* observes nearby co-occurring species and can detect the presence of snorkellers and their movements from a distance of at least 4-5 metres. Due to the difficulty of conducting direct underwater observations of *M. leiaspis* in extremely shallow waters (*e.g.*, < 15 cm) and their ability to detect the presence of snorkellers from a considerable distance, utilizing fixed cameras would likely prove advantageous in future behavioural studies of this species.

THREATS

Weirs & dams

A significant amount of research has focused on the impact of in-channel dams and river regulation on aquatic ecosystems, with particular emphasis on the restoration of environmental flows and the passage of diadromous fish through weirs (*e.g.*, Winemiller *et al*., 2016; Silva *et al*., 2018; Merg *et al*., 2020). The size and positioning of barriers (including natural barriers and dams) in the stream network, including in protected areas, has been a focus of substantial theoretical and applied research, and on-ground infrastructure works (Arthington *et al.,* 2006; Melles *et al.,* 2012; Rolls *et al.,* 2014; Merg *et al.,* 2020; Thieme *et al.,* 2020; Ebner *et al.,* 2021). The number, size and position of dams is known to be of ecological relevance and notably for diadromous species (Keith, 2003; Rolls *et al*., 2014; Jones *et al*., 2021; Ebner *et al*., 2021).

Small instream barriers have the potential to influence the composition of diadromous fish populations (Jones *et al*., 2021); however, studies on fish passage typically focus on highly engineered structures constructed by humans, such as those made of concrete, steel, and bricks (Fig. 4). These structures exist widely in SSCSs in Indo-Pacific nations where they provide access and security to water for human use including drinking, cleaning, roadworks and firefighting (Fig. 4). In Tiema Stream (Okinawa, southern Japan), concrete steps in the order of 0.5-0.8 m in height (Fig. 4D) preclude *M. leiaspis* from migrating upstream (Maeda and Tachihara, 2006), and this is supported by a dataset that now extends from 1996 to 2022 (K. Maeda, unpubl. data). These steps serve functions of constraining channel direction and minimising erosion and flooding, and in some cases maintain water storage pools for agricultural extractions. Similarly, in other places, for instance in the SSCSs of the AWT, concrete weirs are installed for these purposes or to provide water supply for toilet facilities in bays of recreational value including for tourism (Fig. 4E). Concrete footholds are also placed in streams to aid bridge and/or road construction and in several cases the eroded underside of these footings create shelves (as do elevated pipe outfalls) that require challenging ascents for diadromous taxa (Fig. 4). When these structures are situated upstream of the tidal limit, they can exclude poor-climbing, diadromous species, including pipefishes, from upstream access to juvenile and adult habitat. They can also exclude excellent climbing amphidromous species such as sicydiine gobies, which can only climb providing the surface is wet as a function of using their ventral and oral suction capability or burst swimming/climbing (Blob *et al*., 2006; Maie, 2022). For instance, these gobies can climb over obstacles such as that shown in Fig. 4D when wetted, but would be blocked by structures such as elevated pipe outfalls (Fig. 4C).

Informal structures

The structures known as “recreational weirs” are informal barriers created by people during recreational or holiday activities. These ad hoc barriers are made from local materials and are typically less sophisticated than the concreted steps, weirs, and bridge footholds previously discussed (Fig. 5). These structures are typically hand-built from boulders and cobbles and tend to be porous such that the immediate upstream water level is raised (when the weir spans the width of the channel), and the upstream and downstream flow is altered, though the net stream discharge is not necessarily impeded. These temporary structures are subject to ongoing human modification and are sometimes obliterated by extreme discharge events. Recreational weirs are constructed and used (by swimmers) in many of the small to medium size streams by local people and tourists. In the AWT (as in other parts of the world), these weirs are commonly constructed as temporary swimming pools, and in some cases, the weir building itself is the entertainment for recreational users (including children). ‘Recreational weirs’ are typically located at accessible reaches, including in World Heritage Areas, national parks, state forest reserves, near resorts and caravan parks and in association with private stream frontage homes.

It is recognised that certain weirs and water extraction pits share similarities with recreational weirs, but they have been built for the purpose of aiding vehicle crossing or water extraction, or to solely serve these functions (Fig. 6C). We have also witnessed the effects of recurring vehicle passage in the freshwater habitat: rocks and pebbles are constantly moved, disturbing the species, and quite often actually squashing and killing them (CL, pers. obs.). Furthermore, vehicle crossings can alter the substrate found in these passages; notably shifts from rocks and pebbles to a finer substrate which disfavours habitation by pipefishes and sicydiines that select hard substratum. Vehicles are not always merely passing by, sometimes the vehicles are washed and cleaned thus releasing pollutants (*e.g.* dust, mud, chemicals) into the water. While there are several seemingly minor impacts and potential impacts to consider, this study primarily centres on the effects of temporary weirs and pits. It is also worth noting that certain ancient indigenous structures, such as fishways and fish traps, share similarities with these features (*e.g*,. Rose *et al*., 2016; Martin *et al*., 2023).

Recreational spas are a type of recreational weir that may not necessarily span across the entire stream (Fig. 5). These spas are created via an *ad hoc* combination of building walls (usually with cobble and boulders, but sometimes comprising woody debris and leaves) and deepening holes to provide a sitting space for people and or domestic animals (typically dogs). In many Pacific Island communities, these spas are used by villagers for laundry and dish washing purposes, with the use of detergents polluting the stream and also affecting the biodiversity. In SSCSs of Indo-Pacific Islands and continents, deepened pits resembling recreational spas are also created in stream beds facilitating piped water extraction to onsite storage tanks, homes, or for transport by water trucks (Figs 5B, 6C).

There have been instances where we have observed recreational weirs and spas that have negatively impacted resident aquatic fauna. One such example was observed in Emmagen

Figure 4. – Examples of heavily engineered human structures that modify short-steep-coastal-streams other than large dams. **A**: A fishway on a tributary of the Aling Aling River, Bali (Photo: PK); **B**: A concrete weir in Futuna (Photo: PK); **C**: Road crossing at Routes de sud, New Caledonia (Photo: CL); **D**: Concrete steps in Okinawa (Photo: KM); **E**: A small weir and water offtake to supply public toilets at Ellis Beach, Australia (Photo: BE); **F**: A straight linear concrete realignment of a creek in New Britain (PNG (Photo: CL)).

Figure 5. – A selection of makeshift human modifications to streams in north Queensland. **A**: A recreational weir at Emmagen Creek bifurcating habitat of *M. leiaspis*; **B**: A recreational spa on Magnetic Island; **C**: Rock stacking in Thompson Creek within *M. leiaspis* habitat; **D**: A recreational weir at low water at Rollingstone Creek in the southern AWT (Photos: JD & BE).

Creek, where high tourist visitation caused changes in water level and flow within the habitat (specifically two recreational weirs and a recreational spa). Water level was increased (by approximately 10-25 cm at baseflow) at the downstream end of a large pool resulting in loss of flow over a sill on the inside bank and in the middle of the stream (surface flow not measured but estimated to be originally in the order of 0.1-0.4 sms^{-1} reduced to 0-0.1 sms^{-1}). Pipefishes no longer occupied the upstream portion of their previous range within that specific riffle-run-pool sequence. As a result, there was a decrease in the overall density of the adult *M. leiaspis* colony at the location. It is possible that human swimming activity caused pipefish to move out of the lower pool section where they previously existed, noting that a small number of individuals remain in the run and riffle immediately downstream of the dammed reach. It is more likely that the microcrustacean fauna on which the pipefish rely as food retracted to the flowing section in the downstream portion of the range below the recreational weirs and spa. Historically, that pool-riffle-run site had frequently housed relatively large numbers of pipefish (> 10 adults) and at times has been home to large numbers of pregnant males (> 10 individuals). It appears that tourist activity has increased significantly at that stream location over the past 5-10 years, which is evident from the noticeable widening of walking tracks through the rainforest leading to the specific location where adult *M. leiaspis* reside. For completeness, we have also observed recreational weirs in other cases that are not necessarily detrimental, and

Figure 6. – Human activities that are potentially pulse disturbances to SSCSs. **A**: Post-dredging of a lowland reach of Teima Stream, Okinawa Island (Photo: KM); **B**: Gravel extraction from stream Waimaro River, Viti Levu Island in Fiji (Photo: LC); **C**: Water transport truck pumping from an instream pit in lower Emmagen Creek, Australia, late in the dry season (Photo: BE); and **D**: Signage aimed at preventing pebble removal from beachside resort are 'Pebble Beach' north of Cairns, Australia (Photo: BE).

in fact, may even be beneficial for aquatic biodiversity in creating diverse structures and flows. Clearly, the response of macroinvertebrates and fishes to recreational weirs and spas warrants more detailed investigation.

Dredging & mobile water extraction

In some rural and semi-urbanized streams, dredging of the stream bed is carried out for the purpose of improving drainage and for aesthetic reasons. In Okinawa, dredging may occur infrequently (around 10-year intervals), but this can result in the destruction of aquatic habitats in the short and medium-term (Fig. 6A). Based on our experience, it takes several years for pipefish habitat and associated colonies of *M. leiaspis* to recover from dredging events of this nature. Dredging specifically removes the benthic habitat (pebble and cobble interstices) in which pipefish refuge and feed. Subsequently, substantial discharge events are required to scour, sort/deposit and expose buried pebble fields. In contrast, water extraction temporarily reduces pipefish accessibility to these habitats by drying out the previously wetted edge of the stream bed.

Vehicle-based water extraction is sometimes overlooked in SSCSs because it is brief, taking only minutes to hours, and may be highly irregular or sporadic. It has only been observed by us occasionally as a function of spending lengthy periods at field sites. Water is sometimes extracted via a pump to a water storage vehicle for emergency purposes (*e.g.*, bushfire control) or road maintenance/construction purposes (Fig. 6C). Vehicle access to streams and associated pumping can lead to short term changes in water level and sedimentation, with effects likely most pronounced during dry periods (*e.g.*, in the dry season in the AWT). We are not aware of any studies on the effects of mobile water extraction on fauna or aquatic habitat in SSCSs.

Stone-stacking

Rocha *et al.* (2020) recently drew attention to the rapid emergence of stone-stacking and associated photography as a threat to terrestrial biodiversity. Here, we expand the scope of concerns to include aquatic ecosystems based on our collective observations in Indo-Pacific islands. We also provide opportunistic observations regarding aquatic biodiversity from the AWT World Heritage Area, particularly from Jabalbina Country, which is a popular international tourism destination located just north of Cairns, Australia. In the AWT, there has been an increase in the practice of stone-stacking and associated photography along the coastal beaches (notably along various headlands along the Captain Cook Highway between Cairns and Port Douglas, Fig. 7) and at the edge of and within shallow streams of the AWT in the past decade (B.C. Ebner and J.D. Donaldson, James Cook University, pers. obs.) (Fig. 5C).

In freshwater habitats this practice of stone-stacking has become increasingly prevalent at Cape Tribulation in Australia over the past five years, in most of the larger streams including Emmagen Creek, Thompson Creek, and Myall Creek, and also in some of the smaller streams (*e.g.*, Oliver Creek, Mason's Creek, Rykers Creek). Boulders and cobbles are often arranged in channels or on-stream banks to form structures resembling "cairns" (as seen in Fig. 5C), which traditionally served as markers for human orientation and navigation. However, these newly created structures serve no such purpose and are a result of activities that show no appreciation for local cultural or environmental values (Rocha *et al.*, 2020). Rather, the stacking is itself a game or recreational activity commonly serving as the basis for photography and social media communication of visitation experiences (*e.g.*, Rocha *et al.,* 2020). Unfortunately, this stone-stacking is occurring globally within idyllic national park settings (Rocha *et al.,* 2020), including in World Heritage Areas. Arguably, this reflects a shift in management of nature parks to align more with human experience, rather than conservation of nature as the overarching objective.

In the area of Cape Tribulation, Australia, we have observed multiple instances of disturbance to boulders and cobbles. This includes the removal of rocks from below the waterline and their placement on banks or in-stream islands, as well as the movement of cobble and boulder into pebble habitats that house threatened species of cling goby (such as those listed on a national or state level) and/or rare aquatic species with specific habitat associations, such as pipefish. We have also observed rock-stacking in Myall Creek, specifically downstream of the main service road, which is also

Figure 7. – Stone-stacking tourism at a beach on the Captain Cook Highway between Cairns and Port Douglas, Aus tralia (Photo: BE).

within the home range of adult *M. leiaspis*. Additionally, we have observed this activity in Emmagen Creek, which houses the largest known breeding and nursery area for *M. leiaspis* in Australia. Boulders and cobbles have also been removed from locations where unique fauna rely heavily on in-stream boulders. For example, freshwater moray (*Gymnothorax polyuranodon*) use boulders in the thalweg as home-shelter and den habitat (see Ebner *et al.,* 2016b).

Skimming rocks

Pebbles have a maximum dimension of 64 mm and are a key ingredient in the timeless past time of stone-skimming or skipping (referred to as skimming hereafter for brevity) (Cummins and Lauff, 1969; Bocquet, 2003; Clanet *et al.,* 2004). A key ingredient for skimming is the availability of a smooth water surface. In the streams of Cape Tribulation, we have observed adults and children skimming pebbles. This includes unknowingly undertaking this pursuit at the pool in which the greatest aggregations of *Microphis leiaspis* have been observed in the past 15 years in an Australian context.

We suspect that human influence may disrupt rates of migration of pebbles in streams, but we do not believe that there is a consistent overall upstream or downstream bias in the direction in which stones are thrown. However, at some sites, the position of a pebble pile relative to the flat pool surface inevitably creates a local bias in this regard. For instance, at two locations where *M. leiaspis* is typically present and that we have revisited many times, there is likely a bias in the human movement of pebbles. One of the locations experiences high levels of tourism, and its pebble banks are primarily located at the downstream end of the pool. The other location is less accessible, and its pebbles are spread more evenly on the downstream end of the pool and are concentrated at the head of the pool. We almost always encounter tourists or local people swimming and/ or skimming rocks at these locations and informal conversations soon reveal their lack of awareness of the presence of pipefishes (with most people indicating that they weren't aware that pipefish live in freshwater), which is unsurprising given the cryptic behaviour of these fish.

FLAGSHIP SPECIES

Flagship species are high-profile taxa that are significant to people and are used to garner public support for the conservation of entire ecosystems, habitats, communities, and faunal and floral assemblages (*e.g.*, Caro, 2010; Verissimo *et al.,* 2011). While most flagship species are large-bodied, there are also instances where small taxa can be popular with society and target audiences (*cf.* Ebner *et al.,* 2016c). Arguably, some of the more recognisable and popular fishes of SSCSs are moderately large-bodied jungle perches (genus *Kuhlia*), which are active and curious around swimmers and snorkelers and valued by anglers for food or sport fishing. SSCSs also support small-bodied fishes that have potential as flagship species, most notably many of the stunning cling gobies (subfamily Sicydiinae) which are also food fish in some Indo-Pacific cultures (*e.g.*, Castellanos-Galindo *et al.,* 2011) and increasingly prized globally by aquarists (*e.g.*, Ebner *et al.,* 2016c). Freshwater pipefishes may also have the potential to serve as flagship species for the protection of SSCSs. This role is similar to that of seahorses and pipefishes in marine ecosystems, where they have been previously considered and/or used for this purpose (Kuiter, 2000; Shokri *et al.,* 2009; Vincent *et al.,* 2011). Our interactions with tourists and the local public regarding freshwater pipefish have been positive, as many people are fascinated and intrigued that such creatures can exist in freshwater systems. In addition to large-bodied fishes serving as flagship species for freshwater ecosystems (*e.g.*, Ebner *et al.*, 2016c), freshwater and diadromous pipefishes with their unique characteristics and behaviours may also have the potential to act as flagships for specific freshwater habitats and ecosystems. The female *M. leiaspis*, with its striking appearance (as shown in Fig. 1), is a habitat specialist that inhabits pebble beds in the lower course of tropical SSWCs of the AWT. It has the potential to be used as a flagship species for conveying important conservation messages, including how to responsibly visit and swim in national parks without causing harm to the rare and unseen aquatic species that call these habitats their homes.

FUTURE DIRECTIONS

Managers of protected areas, especially those dealing with freshwater ecosystems such as SSCS ecosystems, face the challenge of insufficient scientific knowledge and understanding (Pusey *et al.,* 2004; Hermoso *et al.,* 2016). The complexity of the biogeographic and ecological context makes the challenge particularly pronounced in SSCSs located on continental land masses. These ecosystems are marginal and atypical in the context of both local science and societal appreciation for the uniqueness of these ecosystems, and adults can be at low density relative to those on core Pacific Island streams (*e.g.*, Ebner and Thuesen, 2010; Nip, 2010; Donaldson *et al.*, 2023). As an example, *M. leiaspis* is a species that is widespread in the tropical Indo-Pacific islands; however, it is relatively rare and has a narrow distribution in Australia. Species that are rare and have specialist habitat associations often have limited documentation of their ecology. The purpose of this paper is to gather and compile basic unpublished information about a single species to address this gap in knowledge. The specific habitat occupied by adult *M. leiaspis* is not well understood by most fish scientists, let alone the general public. Consequently, *M. leiaspis* is currently not taken into account in local catchment management decisions or broader conservation planning efforts. Whilst *M. leiaspis* is considered of 'Least Concern' on the IUCN Redlist (IUCN, 2023), this may be partly due to a lack of information regarding the species as it is potentially threatened in some contexts (*e.g.*, AWT). Furthermore, SSCSs may be managed from surrogate information based on fish science conducted in the nearby continental river and tributary systems, rather than being based on the assemblages in SSCSs.

Despite this, the challenges associated with protecting SSSCs located outside of continental landmasses, especially for the habitat specialist taxa and endemic fauna found in these streams, are substantial. In the Indo-Pacific islands, many nations (though not all) face limited resources and capacity for taxonomic and ecological science (see Paknia and Koch, 2015), despite being located in ultra-biodiverse and high species richness hotspots (*e.g.*, Gill and Kemp, 2002; Carpenter and Springer, 2005, and references therein; Keith *et al.,* 2015). As a result, the lack of resources limits the development of sophisticated management strategies for communicating with the local population and tourists regarding the protection of overlooked specialist fauna and thereby influencing human behaviour in this regard. We recommend using a conceptual approach similar to the one described in Bessell *et al.* (2022) to advance our understanding of protection options and priorities for *M. leiaspis* and other habitat specialists in SSCSs, both in continental areas and islands. Often, local inhabitants are unaware of the fish species present in their rivers due to the small size or cryptic behaviour of these fauna. One way of raising awareness of the biodiversity present in the SSCSs is to show local villagers and stakeholders the species that occur in their streams by taking them in the field, communicating at scientific conferences and distributing educational material in schools and villages (*e.g.*, Keith *et al.*, 2015, 2021). After conducting surveys, the authors can inform the locals of their knowledge of the biology, ecology, and distribution of species and provide valuable advice on species protection measures. This is done systematically by some of the authors during each field trip, particularly in the Solomon Islands.

While activities like rock stacking and recreational weir building may have little impact on generalist fish with broad habitat preferences and distributions, they can be detrimental to small populations or colonies of habitat specialists. Tropical freshwater fishes in northern Australia often have wide distributions and generalist habitat requirements, particularly in savanna catchments near the AWT, as documented by Allen *et al.* (2002) and Pusey *et al.* (2017). However, narrow-range endemics are more commonly found in thermally stable tropical systems, resulting in relatively smaller niches available in tropical regions compared to temperate latitudes (Janzen, 1967; Chan *et al.,* 2016). Understanding the specific habitat associations of narrow-range habitat specialists in SSCSs is crucial for protecting this fauna in continental SSCS ecosystems.

Our recommendation is to conduct fish behaviour monitoring and experimental research in both high and low visitation tourism sites, particularly within World Heritage Areas such as the AWT World Heritage Area. Ideally, this research would promote the investigation of various taxa, including habitat specialists such as adult *M. leiaspis*, to human activity in SSCSs (*e.g.*, Bessa *et al.*, 2017). Specific signage conveying the concept that stones should be protected and not moved (*e.g.*, Fig. 6D), combined with educational material conveying the relationship between flagship species and their specific underwater habitats, provides a simple means of starting to address recreational culture change within protected areas.

Using charismatic flagship species (such as freshwater moray, brightly coloured cling gobies and diadromous pipefishes) on signage may aid in raising community awareness of minimum environmental standards and practices for recreational activity in streams including inside and outside of protected areas. There is also scope for using this communication to symbolize the global significance and connection among the diverse communities of the Pacific nations people. We strongly emphasize the importance of the "leave no trace philosophy" (as described in Rocha *et al.*, 2020) to be conveyed to both local communities and international tourists visiting national parks and World Heritage Areas.

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