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Research paper

Assessing the ecological health of rivers when they are dry

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ABSTRACT

Rivers and streams that dry up are found on every continent, and can form a large proportion of river networks. When rivers are dry, traditional indicators of river health – such as aquatic macroinvertebrates, fish or water quality – cannot be measured. Aquatic health indicators are widely used to assess wetted habitats, but currently no universally applicable indicators have been developed or applied to assess dry riverbed health. Dry riverbeds are often the 'typical' state of many intermittent rivers and streams; however, the ecological health of these habitats is rarely, if ever, assessed in monitoring programs. Resource managers have called for indicators of intermittent river health during the dry phase. The use of terrestrial invertebrate biota (e.g. ants, beetles, and spiders) as indicators in this study provides a novel solution to assessing rivers when they are dry.

We developed a conceptual model of human-induced stressors (i.e. disturbance by livestock and feral mammals) on dry riverbed biota, which guided the selection of potential health indicators. Livestock and feral mammals are one of the most significant stressors on riverine ecosystems in Queensland, and impact riverbeds by altering the substrate through compaction, rooting and pugging. We trialled the use of metrics of terrestrial invertebrate assemblages as indicators of dry riverbed health in four Australian dryland catchments: Bulloo, Paroo, Warrego and Nebine. We used quantile regression and found that terrestrial invertebrate communities responded negatively (and significantly, $p < 0.05$) to a gradient of disturbance, defined by on-the-ground field measurements of livestock and feral mammal impacts. This response to stressors was predicted by the initial conceptual model.

We conclude that terrestrial invertebrates in this study are suitable indicators of dry riverbed health, as they are impacted by disturbance from livestock and feral mammals. They can be used in the same way that indicators, such as aquatic macroinvertebrates, are traditionally used to assess river health. We also successfully combined indicators of wet and dry habitats to provide a holistic assessment of the health of intermittent river ecosystems incorporating all sections of the river network. We suggest that this approach should be adopted by other river health monitoring programs in rivers around the world.

1. Introduction

1.1. Intermittent rivers are widespread, and there will be more of them in the future

Rivers that temporarily cease to flow and dry up are a global phenomenon, being found on every continent and nearly every watershed (Datry et al., 2014). Intermittent rivers have been described as being more representative of the world's river systems than those with perennial flows (Williams, 1988). Their spatial extent is likely to further increase as a result of the combined effects of altered land-use patterns, climate change, and increased water extraction for human uses (Meehl et al., 2007; Palmer et al., 2008; Larned et al., 2010). These effects can increase the duration of dry spells in intermittent rivers, and can potentially convert perennial rivers to intermittent ones.

1.2. Dry riverbeds are not included in traditional river monitoring programs

Environmental monitoring and assessment of aquatic ecosystems is undertaken to inform management: either by identifying reductions in river health in response to anthropogenic stressors, or sometimes to demonstrate the effectiveness of restoration actions. As such, it is a

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valuable tool for directing and supporting natural resource management (Apitz et al., 2006; Field et al., 2007; Norris et al., 2007). The unpredictability of flow, and subsequently of surface water presence and distribution along intermittent rivers have been recognised as challenges for environmental monitoring (Sheldon, 2005). Despite their prevalence, intermittent rivers, and in particular dry riverbeds, have often been neglected and frequently ignored in river management, policy, and monitoring programs throughout the world (Steward et al., 2012; Acuña et al., 2014; Mazor et al., 2014). Hence, gaps often exist in monitoring data sets used to assess river health when sites are dry and consequently not sampled during particular occasions, seasons or years. This problem is particularly likely to occur in semi-arid and arid regions, areas with Mediterranean climates, during the dry season in monsoonal 'wet-dry' tropics, and in other regions during drought conditions. Under these circumstances, monitoring and assessment of intermittent river ecosystems typically seeks out and considers only the wet parts of the system (e.g. by using aquatic macroinvertebrates as biological indicators: Chessman, 1995; Reynoldson et al., 1995), and does not represent the entire river network. This is an important deficiency because wet parts of an intermittent river network may be unrepresentative of the ecological health of the system *in totum*. Furthermore, even in the absence of surface water, dry riverbed habitats can be 'healthy' and can have ecological values that may otherwise be overlooked, such as unique biodiversity, their use as dispersal corridors for terrestrial biota, and sites for the storage and processing of organic matter and nutrients (McClain et al., 2003; Steward et al., 2011, 2012; Acuña et al., 2014; Sánchez-Montoya et al., 2016). Conversely, dry riverbed habitats may be degraded by various stressors and therefore 'unhealthy' (Chiu et al., 2017; Steward et al., 2017).

There is thus a recognised need to develop indicators of intermittent river health during the dry phase (Acuña et al., 2014). Several potential solutions have been proposed, but they rely on targeting specific habitats that may not be present in all intermittent river systems, or may be unrepresentative of the overall health of the system being assessed. For example, Robson et al. (2011) suggested sampling remnant pool 'drought refuges' for aquatic invertebrates during the dry phase. These pools can have sparse, variable and patchy distributions at the catchment scale, so by their very nature are unrepresentative of the overall intermittent river network where they occur. Some reaches may not contain any surface water to sample. Variable taxonomic composition in refuge pools results from stochastic founder effects and strong biotic interactions (Sheldon et al., 2010). Furthermore, sampling itself may threaten refuge function and therefore system resilience by depleting the supply of future colonists utilising refuges, so their use as monitoring habitats may be undesirable. Leigh et al. (2013) partially overcame these issues with their suggestion to adopt hyporheic invertebrates as indicators of dry river health. However, not every dry riverbed has a functioning hyporheic zone due to a lack of hyporheic capacity (e.g. in bedrock or clay substrates), or to temporal absence due to drying subsurface water during extended periods without flow (Boulton and Stanley, 1995). To better overcome these issues we demonstrate the use of terrestrial riverbed invertebrates (*sensu* Steward et al., 2011) as sensitive dry river health indicators, followed by an approach to integrate these with more traditional aquatic indicators to assess the entire river network – representing both wet and dry reaches of an intermittent river system.

1.3. Terrestrial invertebrates as indicators for river health monitoring

For an indicator to be effective for biological monitoring it needs to be relevant and sensitive (Andersen, 1999; Dobbie et al., 2013). To be relevant for river health assessment it must be applicable to rivers and streams within the region being assessed, and to be sensitive it needs to change in a measureable way along gradients of a stressor. An ideal indicator is also specific, so that it is responsive to gradients of a single stressor, allowing for direct diagnosis of changes in river health. However, few indicators used for river health monitoring are truly specific; for example, aquatic macroinvertebrates, which are widely used as indicators, respond to many varied stressors.

The widespread occurrence of intermittent rivers and streams discussed above, together with the emerging realisation that terrestrial invertebrates of dry riverbeds are ubiquitous and contain elements of specialist fauna for this habitat (Wishart, 2000; Steward et al., 2011; Corti et al., 2013; Steward et al., 2017), suggest a broad relevance of these biota as indicators of dry river health. While terrestrial invertebrates have not previously been investigated as river health indicators, they have been successfully utilised for biomonitoring in other habitats. For example, ants (Formicidae) are routinely used as biological indicators of rehabilitated mine sites throughout Australia, including forests, semi-arid heathlands, subtropical shrublands and tropical savannah woodlands (Andersen et al., 2004; Andersen and Majer, 2004). Similarly, ground beetles (Carabidae) have been employed as biological indicators of exposed riverine sediments and riparian zones in Europe (Boscaini et al., 2000; Eyre and Luff, 2002; Kleinwächter and Rickfelder, 2007). However, the sensitivity of terrestrial invertebrates to stressors in dry riverbeds has not yet been investigated.

1.4. A conceptual model of livestock and feral mammal impacts on intermittent rivers

1.4.1. Natural intermittent rivers

To understand how stressors from livestock and feral mammals impact intermittent rivers and streams during the dry phase, we developed a conceptual understanding of their ecological structure and function (Fig. 1). Natural dry riverbeds can contain interstitial spaces which are inhabited by terrestrial invertebrates, both when the bed substrate is coarse (e.g. cobble, pebble) or fine (e.g. sand, silt/clay) (Steward et al., 2011). A diversity of substrates and other habitat types supports a comparatively diverse invertebrate fauna. Coarse substrates, such as cobbles and pebbles, can provide structural complexity and interstitial spaces for terrestrial invertebrates (Paetzold et al., 2008). Sandy substrates are used by invertebrates that dig (e.g. *Mecynotarsus* spp. (Coleoptera: Anthicidae), Hashimoto and Hayashi, 2012; Steward, 2014). Silt/clay substrates can crack once dry, and produce long furrows in which invertebrates can reside, acting as cool microhabitats. Catchment vegetation cover minimises runoff, and therefore erosion, suggesting that more substrate types are available in areas rarely smothered by sediment. Functioning riparian zones provide buffers, which minimise nutrient and sediment loads entering waterways, and inputs of leaf litter and woody debris, which provide habitat and potential food resources for terrestrial invertebrates.

1.4.2. Impacted intermittent rivers

Out of all human-mediated disturbances, land use change has one of the largest impacts on species richness (Murphy and Romanuk, 2014). The use of land for livestock grazing (particularly cattle) impacts upon both aquatic and terrestrial ecosystems (Fleischner, 1994; Agouridis et al., 2005), with 80% of rivers and riparian zones damaged by grazing in the United States (Belsky et al., 1999). Cattle grazing for meat production is the dominant land use in arid and semi-arid parts of Australia, where most of the river network is dry most of the time. More than 83% of the total area of the Australian state of Queensland, representing almost 145 million hectares, is managed for beef cattle and sheep grazing (Barson, 2013).

Dry riverbeds can be subjected to numerous stressors, such as livestock trampling, overgrazing, weed infestation, gravel and sand extraction, wastewater discharge, inundation by dams and weirs, cropping, and their use as roads (Steward et al., 2012). However, stressors caused by livestock and feral mammals appear to be both widespread and ecologically important in our study area of Queensland, and are the focus of this study. Feral mammals are common inhabitants of Queensland, and include pigs (*Sus scrofa*), goats (*Capra aegagrus hircus*),