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Management of headwaters based on macroinvertebrate assemblages and environmental attributes

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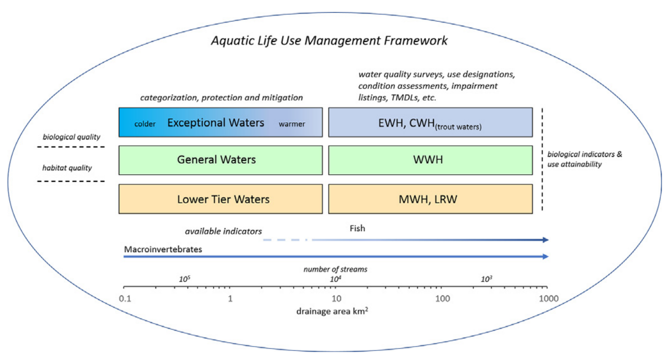
HIGHLIGHTS

- Benthic macroinvertebrates return a signal of environmental condition in headwaters draining catchments as small as 0.3 km^2.
- Distinct assemblages of sensitive macroinvertebrates were found in cold, forested headwaters.
- Readily obtained measures of habitat quality can be used to set default levels of protection.

GRAPHICAL ABSTRACT



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ABSTRACT

The ecosystem function of headwaters is important and increasingly well-recognized, but institutional structures to administer their protection and management are lacking or poorly developed. Although the reasons for this mismatch are various, one of practical concern is the potential administrative burden imposed by the sizable number of headwaters. Two essential components of an administrative framework for managing waters is classification by type so that proper expectations can be set, and development of indicators that measure whether those expectations are being met. Ordinations of macroinvertebrate assemblages sampled from 1016 sites in 934 headwater streams draining <13 km^2 across Ohio, USA, revealed a highly distinct subset of sites characterized by a combination of taxa having an affinity for cold water and sensitivity to environmental disturbance. Bayesian Network (BN) modeling revealed that several environmental variables, notably water temperature, percent forest cover, and drainage area predict membership in this subset. More generally across all streams, macroinvertebrate assemblages signaled ecological status along a stressor gradient defined by habitat quality and intensity of land uses. Collectively, these results suggest a hierarchical administrative framework wherein stream habitat quality, as measured by summary habitat index scores, can screen and assign protections to waters generally expected to support assemblages consistent with good ecological status. Forest cover and water temperature can serve as an additional screen to assign higher levels of protection consistent with higher ecological status. In cases where levels of protection based on screening are questioned or likely to be contentious, assessment of the macroinvertebrate assemblage can demonstrate the appropriate level.

1. Introduction

Identifying water bodies by type is an important first step in developing management strategies to protect or restore ecological

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condition (Nixon et al., 2012). Once identified, reference expectations can be matched to the water body type, and those expectations can be used to define restoration benchmarks, identify high quality waters, assess the condition of sampled waters, or evaluate impacts to a given reach or area. Biotic indices (Karr, 1981) or observed/expected models (Wright et al., 1989; Clarke et al., 2003; Van Sickle et al., 2005) are widely used to translate reference expectations into a common currency, and are especially practiced in perennial rivers and streams. Water quality management in Ohio has been well-served by biotic indices, but only for streams and rivers larger than 10 km^2 where reference expectations have been established. Bringing smaller headwaters into the management fold has gained a sense of urgency with the growing realization of how important headwaters are to biodiversity (Wood et al., 2005; Zbinden and Matthews, 2017; Clarke et al., 2008), along with the understanding of their chemical, physical and biological nexus with downstream waters (Alexander et al., 2015) through hydrologic connectivity (Freeman et al., 2007). However, prior to managing these waters, several practical and technical concerns need to be resolved.

One practical concern is the potentially enormous administrative burden imposed by the number of headwaters (EC, 2003). Headwaters <10 km^2 in Ohio total over 104,000 km in length and comprise 70% of the mapped stream length, yet the resources to monitor and manage the other 30% are limited. Another practical concern is that existing institutional infrastructure is not adapted to the social and political complexity imposed by headwaters interfacing so directly with various private and non-government interests (Fish et al., 2010). Acknowledging these practical concerns, Baattrup-Pedersen et al. (2018) developed an analytical approach that relies on cutoffs in macroinvertebrate assemblage quality and habitat features for deciding on whether to bring individual headwaters into the management fold. Macroinvertebrates are at least one reliable biological fixture in very small streams with permanent flow, and this includes streams with no visible surface flow but permanent pools (Wood et al., 2005; Grubbs, 2011; Burk, 2012). Although the way in which macroinvertebrates can function as a biological indicator in streams <10 km^2 has yet to be fully configured for Ohio, especially with respect to identifying impairment and restoration potential in comparison to reference conditions, their ability to position waters along a biological condition gradient (Davies and Jackson, 2006) has been demonstrated, at least for urban settings (Purcell et al., 2009), but not described for a broader range of land uses and environmental gradients. Also unknown is whether some headwaters have emblematic assemblages suggestive of distinct ecological classifications (e.g., coldwater).

Over the last decade, 1016 benthic macroinvertebrate samples have been collected from headwaters across Ohio with drainage areas <13 km^2. Because the sample locations reflect a wide range of land use and environmental conditions, these data allow us test if and to what extent macroinvertebrate assemblages array along environmental gradients, and whether distinct natural assemblage classes exist that correspond to a water body type. Rejection of the null in either case allows us to examine which environmental variables are important in either arraying the assemblages, or that relate to natural assemblage classes. If natural classes are found, then that allows us to identify the compositional attributes emblematic of the classes. If environmental variables are found to relate to a natural class, then that also allows us to test the ability of those variables to predict class membership. Lastly, if macroinvertebrate assemblages are demonstrated to be arrayed along an environmental continuum from low to high disturbance, then that facilitates the identification of existing conditions that need to be protected. Ultimately, our aim is to provide the basis for a management framework by identifying environmental settings where biological condition is likely to be good or better, and measurable assemblage attributes that reflect good or better ecological status.

2. Methods

2.1. Study area description

Headwater sites with drainage areas ≤13 km^2 sampled for macroinvertebrates from 2006 through 2016 throughout Ohio were included in the study (Fig. 1). Differences in land use, land cover and parent geology between the Western Allegheny Plateau (WAP) ecoregion and the glaciated portion (GLAC) of Ohio necessitated dividing sites into two frames representing the respective regions. The WAP is largely forested, historically and presently mined for coal, and lacks glacial deposits. In contrast, the glaciated portion is mostly agricultural, and large portions of the headwater drainage network have been modified for drainage. For each site, the upstream catchment was delineated, and various attributes within the catchment were summarized as either percent of the catchment (e.g., forest cover), a point estimate (e.g., unconsolidated aquifer yield), or an area-weighted average (e.g., bedrock aquifer yield). Attributes were compiled from the 2011 National Land Cover Database (Homer et al., 2015), the Glacial Geology Map of Ohio (ODNR, 2005), USGS StreamStats, SSURGO (NRCS, 2017), Unconsolidated and Consolidated Aquifer Maps, and shapefiles containing information on surface and underground mines. Precipitation and air temperature data were obtained from the Midwest Regional Climate Center, and water temperature, water chemistry and stream physical habitat data were supplied from field observations or sampling conducted synoptically with biological sampling. A list of individual attributes and a brief description of each is included in Supplement Table 1.

2.2. Biological and water quality sampling

Ohio EPA maintains a database of biological and water quality sampling results generated from a mix of targeted basin surveys and ad hoc sampling. Sites included as part of a targeted basin survey are sampled for macroinvertebrates, fish, habitat quality and water chemistry, and typically include sites with drainage areas larger than 10 km^2. Samples from targeted surveys are collected between the months of June and October, with fish, macroinvertebrate and habitat samples typically collected once, and water chemistry collected 4 to 6 times. Ad hoc biological samples are collected from March through November and typically do not include water chemistry samples, but water temperature from a hand thermometer typically accompanies macroinvertebrate samples. Most of the sites used in this study with drainage areas <10 km^2 were from ad hoc sampling of macroinvertebrates. Water samples are analyzed for nitrate + nitrite (NOx), total Kjeldahl nitrogen (TKN), ammonia nitrogen (NH3), total phosphorus (TP), and total suspended (TSS) and dissolved solids (TDS). Field parameters including dissolved oxygen (DO), temperature, pH and conductivity are measured using hand-held meters at the time of water chemistry collection. Laboratory methods followed those established by US EPA with detection limits for NOx, TKN, NH3, TP, and TSS and TDS being 0.10, 0.20, 0.05, 0.01 and 5.0 mg L^{-1}, respectively. Water chemistry values reported at less than method detection limits were assigned values of one half the respective limits. For the purposes of this study, only water chemistry parameters reported from targeted surveys for the months of July and August were used, and are expressed as averages.

Physical habitat was assessed using the Qualitative Habitat Evaluation Index (QHEI; Rankin, 1995, Ohio EPA, 2006) wherever fish samples were collected. The QHEI is a qualitative visual assessment of functional aspects of stream macrohabitat (e.g., substrate quality, amount and type of cover, riparian width, siltation, channel morphology). The overlap between fish and macroinvertebrate samples was also not complete, but more complete than the overlap between macroinvertebrates and chemistry. Table 1 lists sampling frequencies of macroinvertebrates, habitat quality and water chemistry by drainage area.

Macroinvertebrates from a given site from very small headwaters are collected using kick nets and by hand (e.g., turning over rocks and