Ecological Engineering 84 (2015) 180–189

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Habitat and water quality as drivers of ecological system health in Central Appalachia

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ARTICLE INFO

Article history:
Received 16 April 2015
Received in revised form 29 June 2015
Accepted 3 September 2015
Available online 18 September 2015

Keywords:
Aquatic ecology
Ecological health
Conductivity
Habitat assessment
Water quality
Watershed science

ABSTRACT

Ecological mitigation in Central Appalachia often takes one of two approaches: a water quality-driven focus (TMDLs), or a geomorphological focus on stream/habitat restoration (404 permit-related requirements). While often successful at reducing in-stream pollutants or restoring stable hydrology respectively, recent studies have shown that neither approach appreciably improves aquatic ecosystem health. We report here on a field sampling campaign along the Kentucky–Virginia border aimed at identifying primary macroinvertebrate stressors in order to inform ecological remediation efforts and how those efforts might fit into the current regulatory structure. Over two years, we collected 178 observations of benthic species diversity at 36 unique sites representing watersheds of varying surface disturbance and anthropogenic activities, along with associated data from rapid bioassessment protocols (RBPs). Using land use metrics (derived from GIS data), water quality data, habitat metrics, and stream condition indices, principal component analysis (PCA) identified surface disturbance, forest cover, and specific conductivity as significant variables comprising the first PC. Habitat appears to be a secondary driver affecting community sensitivity with channel alteration, bank vegetation, riparian vegetation, and epifaunal substrate contributing significantly to the second PC. PERMANOVA analysis showed these groups to be significantly different from one another ($p = 0.001$), $R^2 = 0.44$. Change point analysis via 500 bootstrapped replications identified shifts in community composition means at 326, 609, and 1065 mS/cm along the conductivity gradient, and habitat change points at 42.6 and 58.2 along the composite habitat gradient. These findings suggest that approaches that improve water quality, upland hydrology, and localized habitat structures may simultaneously be necessary to improve aquatic ecosystem health.

Published by Elsevier B.V.

1. Introduction

The Central Appalachian Region of the United States includes eastern Kentucky, southwestern Virginia, and southern West Virginia (ARC, 2011a). While Appalachia as a whole has been a hub of resource extraction (e.g. coal mining, logging) for well over a century, Central Appalachia continues to be a major resource extraction center today. Although the recent boom in natural gas production via hydraulic fracturing technology has resulted in considerable new activity along the eastern mountain chain, other subregions of Central Appalachia are primarily dominated by remnants of past coal mining in the form of legacy sites and abandoned mine lands (US Energy Information Administration, 2012). In recent years, there has been increasing regulatory and societal pressure on the mining industry to reduce impacts on water quality and aquatic ecosystems. Concerns for the survival of sensitive aquatic species are particularly intense in this region, as cold headwater streams isolated by steep ridges provide ideal habitats that support a high diversity and density of unique North American species (Palmer et al., 2010a; Bernhardt and Palmer, 2011a; Lindberg et al., 2011; Bernhardt et al., 2012).

On a watershed scale, efforts to preserve and restore ecological stability to the region are complicated. Appalachian watersheds are often dominated in the uppermost reaches by resource extraction activities such as surface coal mining, logging, or natural gas extraction, while legacy residential communities (stemming from former “coal camps”) can be found just downstream. Because of local economic distress (ARC, 2011b), sparse population density, and the lack of distributed population centers in the region, basic sanitation services are often lacking in these communities. Untreated household waste (UHW) consisting of sewage, household cleaning chemicals, detergents, and any other substance disposed of via

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http://dx.doi.org/10.1016/j.ecoleng.2015.09.006
0925-8574/Published by Elsevier B.V.

residential drains, is frequently discharged directly to local surface waters via "straight pipes", further stressing aquatic communities in local streams (Glasmeier and Farrigan, 2003; Cook et al., 2013, 2015a,b).

The current framework for addressing impairments to aquatic life in waterways of the United States relies on the Total Maximum Daily Load (TMDL) program within the 1972 Clean Water Act (CWA). Briefly, following the assessment and classification of a particular waterway as "impaired", the TMDL process identifies the ability of the water body to assimilate the pollutant(s) of concern and estimates existing pollutant loadings from different sources. A maximum permissible loading value, including a margin of safety, is identified to meet water quality goals, and the allowable pollutant load is allocated among sources in the watershed (Yagow et al., 2006; Wagner et al., 2007). The development of these plans can be very costly in both time and dollars, actual implementation is not always mandatory, and reviews of these efforts at water quality improvements have shown them difficult to predict and/or guarantee (Birkeland, 2001; Freedman et al., 2003; Benham et al., 2008). Further, load reduction plans are generally first focused on permitted discharges, since these discharges be easily quantified and monitored and more easily targeted than non-point source or otherwise unpermitted discharges (Stephenson and Shabman, 2001). Oftentimes, implementation efforts have mixed success in reducing the priority pollutants and data demonstrating measurable aquatic life improvement are rare (NRC, 2001; Benham et al., 2008; Keller and Cavallaro, 2008).

To help quantify the general biological health of stream ecosystems in keeping with CWA goals, a system of benthic macroinvertebrate surveys and rapid bioassessment protocols (RBPs) were developed as numerical metrics for aquatic insect diversity and number, respectively (Barbour et al., 1999). Surveys provide an inventory of species present, while RBPs are intended to quickly quantify the hydrological, physical, and water quality aspects of the environment in which these communities of aquatic insects exist (Rogers et al., 2002). Through these two means, insights can be gained regarding the characteristics of the local environment that may promote or inhibit the success of diverse and abundant aquatic life at locations of interest. While these processes take into account the suitability of sites in terms of a variety of habitat metrics, chemical parameters, and hydrological characteristics, many efforts at site mitigation and TMDL development only aim to address a single most probable stressor (Yagow et al., 2006).

Stream restoration has become a popular mitigation strategy to improve species habitat on reclaimed mine lands in Appalachia. While restoration is generally accepted as effective in terms of stream hydrology (Bernhardt and Palmer, 2011b; Ernst et al., 2012; Ramstead et al., 2012), critics have argued that efforts in Central Appalachia have been largely geomorphological in nature and have resulted in little improvement in habitat and water quality (Palmer and Hondula, 2014). In other studies, habitat efforts have been included, but ecological effects have still generally been lacking (Bond and Lake, 2003; Palmer et al., 2010b; Louhi et al., 2011; Testa et al., 2011; Ernst et al., 2012). Reasons for this vary; the time scale of species recolonization can be long (Bond and Lake, 2003), even more so for habitats isolated by steep slopes such as those in Central Appalachia (Pond, 2010). Ecological efforts in stream restoration are largely unstandardized (Palmer et al., 2005, 2010b; Bernhardt and Palmer, 2011b), which complicates monitoring efficacy (although biological post-monitoring is a part of 404-permitting).

Recent studies by several field and laboratory researchers focus specifically on water quality parameters – most commonly, specific conductivity or total dissolved solids – as limiting efforts to improve aquatic life in the region (Echols et al., 2010; Pond, 2010; Merriam et al., 2011, 2013, 2015a; Timpano, 2011; USEPA, 2011; Cormier et al., 2013b; Suter and Cormier, 2013; Yeager-Armstead et al., 2013). Other studies suggest that physical stream stability, in both the structural and geomorphological sense, is the most important factor in promoting the return of species diversity (Asmus et al., 2009; Hall et al., 2014). Mitigation specialists that design stream restoration efforts therefore often combine geomorphological structure with habitat creation in their designs (Palmer et al., 2005, 2010b; Alexander and Allan, 2007; Petty et al., 2013).

Within a single watershed in Central Appalachia, mitigation efforts can often be described as focused on one of two approaches: the TMDL process to address identified water quality impairments (driven by state regulatory programs) and CWA Section 404 permitting as required by the Army Corps of Engineers (ACOE) in relation to local land disturbance activities (driven by industry and associated legal requirements). The TMDL process centers on the improvement of water quality or biological diversity and health (as measured by state-specific metrics) via a watershed approach, while the 404 permit-related activities primarily focus on in-kind replacement of disturbed hydrological function (wetland or stream rebuilding) on mine reclamation sites (although requirements also specify habitat and biological monitoring as well). In reality, neither of these regulatory strategies alone is likely to fully restore stable, functional ecosystems; rather, a coordinated effort to find an optimum intersection of hydrology, physical habitat, and water quality improvements may provide an alternative approach for long-term improvements to aquatic ecosystems.

The goal of the present effort was to explore the effects of both water quality and habitat on benthic macroinvertebrates. Biological and RBP data were collected during a three-year field study of five watersheds on the Virginia–Kentucky border in Central Appalachia. This study analyzed species diversity, abundance, functional feeding groups and pollution tolerance metric data expressed as Virginia stream condition index (VSCI) scores as well as RBP data collected during species surveys for relationships between VSCI scores and the related water quality and habitat data collected in RBPs. By examining these relationships, this study sought to identify the site-specific environmental variables (land use, habitat metrics, water quality parameters) driving variability in VSCI scores, as well as evaluate the existence of threshold values along the gradient of those environmental variables.

2. Methodology

2.1. Study area

Five watersheds on the border between Virginia and Kentucky were selected for inclusion in a three year monitoring study (Callahan Creek, Roaring Fork, and Pigeon Creek in Virginia; Lower Clover Fork and Looney Creek-Poor Fork in Kentucky; Figs. 1 and 2). These watersheds collectively represent mixed pollutant sources including legacy underground coal mine sources, active and legacy surface coal mining, residential UHW discharges, and highly forested reference areas. All five watersheds drain to headwater streams located in the larger Powell River Basin in Wise County, Virginia or the Cumberland River Basin in Harlan County, Kentucky. The streams are located in the Cumberland Plateau physiographic region; natural land cover consists of mixed-mesophytic hardwood forests, as is typical throughout the Appalachian region (although nearly all forest cover is not virgin timber). Geology is consistent amongst the five watersheds, and dominated by Pennsylvanian-age sandstones, shales, and coal formations. Two types of land cover dominate all watersheds: hardwood deciduous forest and various stages of surface-mining activities (active to reclamation). Forest cover varies between 50 and 90% in the five watersheds, and an inverse