

1 Multidecadal Biological Monitoring and Abatement Program assessing human impacts on aquatic
2 ecosystems within the Oak Ridge Reservation in eastern Tennessee, USA.

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18 ABSTRACT

19 Human activities can be powerful drivers of ecosystem change within catchments. While most long-term
20 catchment studies have been conducted at pristine sites, such studies are less common from sites more
21 impacted by human activity. The Oak Ridge National Laboratory's Biological Monitoring and Abatement
22 Program (BMAP) was developed in the mid-1980s to (1) assess compliance with environmental
23 regulations, (2) identify causes of adverse ecological impacts, (3) provide data for human and ecological
24 risk assessments, and (4) evaluate the effectiveness of remedial actions taken to mitigate the impacts of
25 contaminants in soils, groundwater, and surface water by documenting ecological recovery on the Oak
26 Ridge Reservation (ORR), a federally owned 33,476-acre site in eastern Tennessee, USA, managed by the
27 U.S. Department of Energy. The ORR is composed of multiple watersheds containing many small to mid-
28 size streams. BMAP uses an integrated approach for determining stream health; its databases include
29 long-term seasonal records of contaminant concentrations in water and biota, data from aquatic toxicity
30 testing, and surveys of macroinvertebrate and fish assemblages from impacted and reference streams.
31 These long-term data provide valuable records of degradation and recovery in catchment ecosystems.
32 Our objective here is to describe our study system and data series in order to increase awareness of the
33 availability of these long-term data to the catchment science community.

34

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36 1 DATASET NAME

37 Oak Ridge Reservation Biological Monitoring and Abatement Program data

38

39 2 INTRODUCTION

40 Long-term abiotic and biotic observations are crucial for understanding natural ecosystem dynamics and
41 identifying and quantifying the impacts of ecological perturbations across multiple temporal and spatial
42 scales (Lindenmayer et al., 2012; Lovett et al., 2007). Unfortunately, the high costs in both labor and
43 time required to establish scientifically rigorous datasets over long time scales drive their relative
44 scarcity. As such, it is important to take stock of high-quality, long-term data that are presently available.
45 This is particularly true within catchment systems, where a wide range of chemical, geological, physical,
46 and biological processes may be driving environmental observations (Bogena, White, Bour, Li, & Jensen,
47 2018), but the availability of long-term datasets may not be equally represented across these disciplines.
48 For instance, while studies focused on hydrology and water quality monitoring are prevalent within
49 catchment science, similar studies providing long-term data on biotic parameters including toxicant
50 exposure, taxonomic composition, and the uptake and cycling of heavy metals are less abundant.
51 Datasets including such biotic parameters, especially those based on rigorous scientific methodologies
52 that integrate wide spatial coverage both within and among multiple catchments, can be valuable
53 additions that elevate our understanding of variations within and across catchment ecosystems. Our
54 goal here is to describe the catchments that comprise our study system and the data that are collected
55 as part of long-term monitoring of human impacts and remediation in eastern Tennessee, USA.

56 3 SITE DESCRIPTION & METHODS

57 3.1 Oak Ridge Reservation & History of Human Impacts

58 Physical location and hydrology

59 The Oak Ridge Reservation (ORR) encompasses 33,476 acres of federally owned land located in the
60 Great Valley of East Tennessee, USA. Due to geologic processes, this fold-and-thrust belt area is
61 comprised of parallel ridges and valleys that trend along a southwest to northeast axis with bedrock
62 composed primarily of dolomite and limestone. The ORR contains several catchments with multiple
63 streams that range from 1st- to 5th-order and ultimately drain to the Tennessee River (Figure 1).
64 Catchment basins range in size from 0.1 km² (Scarboro Creek) to 352 km² (Poplar Creek) (Table 1), with
65 headwater streams primarily fed by springs located on the hillslopes and higher-order streams
66 influenced by a combination of storm water runoff and groundwater infiltration (ASER, 2018).

67 History of human activities and biological monitoring

68 The ORR has a long history of human activity, though the greatest anthropogenic impacts began in 1942,
69 when the area was selected for use in the Manhattan Project as a facility for testing methodologies for
70 uranium-235 (²³⁵U) enrichment and the radiochemical separation of plutonium for atomic weapons
71 (ASER, 2018). Discharges to surface waters from human activities have included cooling water, coal yard
72 runoff, and treated and untreated process waters containing complex mixtures of heavy metals, organic
73 solvents, polychlorinated biphenyls (PCBs), and mercury (Loar, Stewart, & Smith, 2011), some of which
74 were found to be present at high levels within stream fishes (Southworth, 1990).

75 In the mid-1980s, the Biological Monitoring and Abatement Program (BMAP) was initiated with the
76 goals of (1) addressing regulatory requirements of the Clean Water Act, (2) providing human health and
77 ecological risk assessments related to the Comprehensive Environmental Response, Compensation, and
78 Liability Act, and (3) assessing and evaluating the effectiveness of facility pollution abatement and

79 remedial actions (Peterson, 2011). Major remedial actions that have occurred on the ORR include
80 construction of wastewater treatment facilities, elimination of untreated discharges, relining of sanitary
81 and storm sewers, closure and replacement of storage ponds, dechlorination of cooling water
82 discharges, management of stream flow, removal of contaminated soils and sediment, and stabilization
83 of stream banks (Loar et al., 2011).

84 As part of the assessment and evaluation for abatement and remedial activities, research staff in the
85 Environmental Sciences Division at Oak Ridge National Laboratory conduct annual or biannual sampling
86 of streams on the ORR using consistent monitoring protocols. Data collected from human-impacted sites
87 are compared to data from carefully selected nearby reference sites. While not necessarily pristine, the
88 reference sites share similar geological characteristics and do not have high levels of effluent discharge
89 and/or human influence (McManamay, Smith, Jett, Mathews, & Peterson, 2018). The BMAP data record
90 shows decreasing toxicity of receiving waters (Greeley, Kszos, Morris, Smith, & Stewart, 2011) and the
91 recovery of fish and macroinvertebrate communities (Adams, Ryon, & Smith, 2005; Ryon, 2011; Smith,
92 2003; Smith, Brandt, & Christensen, 2011) resulting from abatement efforts. Further, bioaccumulation
93 data from BMAP has demonstrated the complex biodynamics of mercury and methylmercury within
94 stream ecosystems, particularly regarding relationships between aqueous and tissue-bound Hg in fish
95 and consumer-driven contaminant cycling (Adams et al., 2002; Mathews et al., 2013; McManamay,
96 Linam, Mathews, Brooks, & Peterson, 2019; Southworth, Peterson, Roy, & Mathews, 2011). Associated
97 ORNL programs that stemmed from BMAP discovered genes responsible for mercury methylation (Parks
98 et al., 2013) and their presence in diverse microorganisms occupying a wide range of environmental
99 niches (Gilmour et al., 2013).

100 BMAP research and monitoring activities focus on impacts from three primary complexes located on the
101 ORR: Y-12 National Security Complex, Oak Ridge National Laboratory, and East Tennessee Technology
102 Park. BMAP maintains four primary datasets divided into two groups: (1) bioindicators of ecosystem

103 health, which includes toxicity of receiving waters and bioaccumulation of toxicants, and (2) in-stream
104 community composition, which includes macroinvertebrate and fish assemblages. Given the differing
105 regulatory requirements among projects, monitoring methodologies may vary at a site within a given
106 year, though every effort is made to maintain temporal consistency for interannual comparisons.
107 Sampling efforts and survey sites have shifted through time in some waterbodies, though records from
108 many sites – especially the community composition datasets – date back to 1986 with a total of 45 sites
109 being actively monitored at present (Figure 1; Table 1). An example subset of these data illustrates how
110 observations have fluctuated through time at two sites in East Fork Poplar Creek (Figure 2).

111 3.2 Bioindicators of ecosystem health datasets

112 Toxicity of receiving waters

113 Given the complex variety of potential contaminants found within discharged effluent, testing the
114 toxicity of discharges and receiving waters plays an important role within BMAP. This includes testing
115 both acute and chronic exposures of whole effluent and ambient receiving waters and monitoring the
116 water quality and physiological impacts of these waters on freshwater organisms. Toxicity is actively
117 monitored by BMAP at seven sites on the ORR (Table 1). Toxicity tests are regularly conducted using
118 standard aquatic test organisms, specifically the water flea, *Ceriodaphnia dubia*, and the fathead
119 minnow, *Pimephales promelas*, at least annually and more frequently in some locations following the
120 rigorous methods outlined by the EPA (EPA-821-R-02-012 and EPA-821-R-02-013 for acute and chronic
121 testing, respectively; USEPA, 2002a and b). Toxicity testing has been conducted regularly in some BMAP
122 sites since at least 1986 (Greeley et al., 2011). This testing is frequently supplemented by in-situ
123 bioassays, such as the placement of caged clams in natural waterways to measure impacts on survival
124 and contaminant bioaccumulation.

125 Bioaccumulation of toxicants

126 The long-term focus of toxicant bioaccumulation monitoring is on human health concerns and fish-
127 eating wildlife. Fish and invertebrates are useful bioindicators of contaminant exposure in freshwater
128 systems (Karr, 1981; Lenat, 1988). For example, muscle tissue samples are used to identify temporal and
129 spatial trends of recent contaminant exposure, whereas whole-body contaminant concentrations are
130 used to quantify maximum food-chain exposure. Bioaccumulation samples are actively collected by
131 BMAP at 17 sites on the ORR (Table 1). Collection methods vary based on site and target species;
132 angling, gill nets, backpack electrofishing, and boat electrofishing are used on an annual basis.
133 Bioaccumulation monitoring focuses primarily on mercury and PCBs. Samples may also be analyzed for
134 methylmercury, trace and heavy metals (e.g., antimony, arsenic, barium, beryllium, cadmium,
135 chromium, copper, lithium, nickel, silver, thallium, uranium, and zinc, among others), and various
136 radioactive isotopes (e.g., cesium, uranium, and strontium), depending on the location. Samples are
137 collected annually or biannually from multiple waterbodies at source sites where contaminant exposure
138 is greatest and at multiple downstream sites to assess potential spatial patterns.

139 3.3 In-stream community datasets

140 Macroinvertebrates

141 Macroinvertebrates are a diverse taxonomic group that play important ecological roles within stream
142 ecosystems (Wallace & Webster, 1996; Covich, Palmer, & Crowl, 1999). Certain taxa, such as those
143 within the orders Ephemeroptera, Plecoptera, and Trichoptera (EPT), are commonly used as
144 bioindicators given their sensitivities to pollution (Lenat, 1988). Macroinvertebrate communities are
145 actively sampled by BMAP at 28 sites on the ORR (Table 1). Two different methodologies are used when
146 sampling macroinvertebrates: a quantitative protocol developed and used by ORNL staff since 1986
147 during spring and fall surveys using a Hess or Surber sampler to collect from three to four randomly

148 selected cells within a permanent riffle at each site; and a semi-quantitative single habitat summer
149 survey protocol developed by the Tennessee Department of Environment and Conservation using a riffle
150 kick approach, in which >200 individuals are collected on a 500 µm net (TDEC, 2017). Following
151 collection using either protocol, samples are drained of excess water, placed in glass jars, and preserved
152 in 95% EtOH. Samples are sorted and enumerated in the laboratory to the lowest practical taxon by
153 trained taxonomists. Apart from oligochaetes, nematodes, and chironomids, most taxa are identified to
154 the genus level.

155 Fish

156 Fish represent important members of aquatic ecosystems and are valued by the general public (Lynch et
157 al., 2016). Fish communities are a useful bioindicator of ecosystem health, with changes in species
158 richness and assemblage diversity commonly used as metrics for detecting impairment (Karr, 1981). Fish
159 communities are actively sampled by BMAP at 29 sites on the ORR (Table 1). Waterbodies are surveyed
160 one to two times per year, depending on project requirements for each waterbody. During each survey,
161 fish communities are quantitatively sampled at a given site via electrofishing within an ~100-m reach
162 bounded by two 0.64-cm mesh seine nets. Up to three consecutive upstream passes are made within
163 the sampling area, with stunned fishes placed in seine-net boxes. Sampled fishes are anaesthetized and
164 identified to the species level by trained taxonomists and measured for total length and weight. Given
165 the potentially high densities encountered at some sites, weights are only recorded for the first five to
166 ten captured individuals of each species within each 1-cm size class; all additional captured fishes within
167 a size class are only measured for total length. After the length and weight measurements are complete,
168 all fishes are allowed time to recuperate after which they are released back into the stream reach.

169 3.4 Complimentary Datasets

170 Two additional complimentary datasets from the ORR are also included within this special issue. One
171 dataset focuses on the highly impacted East Fork Poplar Creek: high-frequency observations of stream
172 discharge and water quality data beginning in 2012 (Brooks et al. 2021). The second dataset provides
173 long-term observations of climatology, hydrology, and biogeochemistry from the less-impacted Walker
174 Branch watershed, with some records dating back to 1969 (Griffiths & Mulholland, 2021).

175 4 Contributors and ownership of the data

176 The BMAP datasets were initiated and contributed by a large team of researchers within the
177 Environmental Sciences Division at Oak Ridge National Laboratory. Data are the property of the project
178 sponsor, which may differ across waterbodies, and are under the supervision of UT-Battelle, LLC, under
179 contract DE-AC05-00OR22725 with the US Department of Energy (DOE).By presenting an overview of
180 our monitoring program, we hope to increase awareness of the availability of this extensive data
181 resource to fuel new research as well as provide an example of the power of long-term datasets and the
182 efforts required for their establishment, perpetuation, and preservation, which can be of great utility for
183 emerging programs.

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196

197 DATA AVAILABILITY STATEMENT

198 Data undergo quality assurance and control reviews before long-term storage within the Oak Ridge
199 Environmental Information System (OREIS) repository (Christensen, Brandt, & McCracken, 2011). Data
200 within the OREIS repository are publicly available and accessible through the UCOR
201 (<http://www.ucor.com/oreis.html>) and OREIS (<https://oreis.orcc.energy.gov>) websites. Inquiries
202 regarding these datasets can be made by contacting the Biodiversity and Ecosystem Health Group within
203 the Environmental Sciences Division at ORNL ([https://www.ornl.gov/group/biodiversity-and-ecosystem-](https://www.ornl.gov/group/biodiversity-and-ecosystem-health)
204 [health](https://www.ornl.gov/group/biodiversity-and-ecosystem-health)).

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296

297 **Tables**

298 Table 1. Description of waterbodies actively surveyed (as of Fall 2020) by BMAP including information on
 299 catchments and number of sites, and the ranges across sites in Strahler stream order (National
 300 Hydrography Dataset; USGS, 2020), upstream catchment area, and percentage of land cover types
 301 within upstream catchment (land cover types totaling <10% were excluded; Dewitz, 2019).

Catchment	Sub-catchment	Waterbody	Abbreviation	# Sites	Stream Order	Catchment Area (km ²)	Developed (%)	Forest (%)	Cultivated (%)	Datasets
Clinch River	Hinds Creek	Hinds Creek ^r	HCK	1	3	44.6	7	62	28	b, i
	Ish Creek	Ish Creek ^r	ICK	1	2	2.4	2	85	6	f
	McCoy Branch	McCoy Branch	MCK	3	2-3	1.3-2.2	9-11	77-85	6-10	f, i
	Scarboro Creek	Scarboro Creek ^r	SCK	1	3	0.1	35	50	10	f
	Walker Branch	Walker Branch ^r	WBK	1	2	1.1	0	>99	<1	i
	White Oak Creek	Fifth Creek ^r	FFK	2	1	0.6-1.0	16-38	44-59	14-20	f, i
		First Creek ^r	FCK	2	1-2	0.6-0.8	5-24	56-71	13-15	f, i
		Melton Branch	MEK	4	2-3	1.1-3.9	9-18	75-88	1-4	b, f, i
		White Oak Creek ^r	WCK	7	2-4	2.1-15.5	22-32	57-64	7-9	b, f, i, t
	Poplar Creek	Brushy Fork	Brushy Fork ^r	BFK	1	4	40.1	6	66	25
East Fork Poplar Creek		Bear Creek	BCK	3	2-4	0.3-16.0	9-58	42-86	0-11	b, f, i, t
		East Fork Poplar Creek	EFK	8	1-4	2.5-48.1	54-87	11-40	1-3	b, f, i, t
		Gum Hollow Branch ^r	GHK	2	2-3	0.8-5.5	0-4	95-100	0-<1	i
		Mill Branch ^r	MBK	1	3	2.6	11	85	<1	f, i
		North Bear Creek Tributary #1	NT1	1	1	0.2	55	29	5	t
		North Bear Creek Tributary #3	NT3	1	2	1.4	39	46	5	f, i

	Pinhook Branch	PHK	1	2	0.7	3	97	0	f	
	Mitchell Branch	Mitchell Branch ^r	MIK	5	1-2	0.5-1.6	4-47	47-81	5-12	b, f, i

302 Datasets: bioaccumulation (b); fish community (f); macroinvertebrate community (i); toxicity (t).

303 ^r indicates at least one site from water body is used as a reference site

304 [Figure legends](#)

305 Figure 1. Map of the ORR and surrounding region indicating locations of catchments and BMAP sampling
306 sites. Land cover classes are from the National Land Cover Dataset (Dewitz, 2019) and indicated by
307 colors. Waterbody names, abbreviations, and land cover summaries are listed in Table 1.

308

309 Figure 2. Example time series of BMAP data showing total PCB tissue burdens in sunfish (top panel), and
310 taxonomic richness of fish (middle panel) and benthic macroinvertebrate communities (lower panel).
311 Data are from two sites (EFK 13.8 and EFK 23.4) located in the middle and upper portions of East Fork
312 Poplar Creek, respectively (Figure 1; Table 1). CI = confidence interval.

313