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Landscape Based Identification of Human Disturbance Gradients and Reference Conditions for Michigan Streams

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Abstract Identification of reference streams and human disturbance gradients are crucial steps in assessing the effects of human disturbances on stream health. We describe a process for identifying reference stream reaches and assessing disturbance gradients using readily available, geo-referenced stream and human disturbance databases. We demonstrate the utility of this process by applying it to wadeable streams in Michigan, USA, and use it to identify which human disturbances have the greatest impact on streams. Approximately 38% of cold-water and 16% of warm-water streams in Michigan were identified as being in least-disturbed condition. Conversely, approximately 3% of cold-water and 4% of warm-water streams were moderately to severely disturbed by landscape human disturbances. Anthropogenic disturbances that had the greatest impact on moderately to severely disturbed streams were nutrient loading and percent urban land use within network watersheds. Our process for assessing stream health represents a significant advantage over other routinely used methods. It uses inter-confluence stream reaches as an assessment unit, permits the evaluation of stream health across large regions, and yields an overall disturbance index that is a weighted sum of multiple disturbance factors. The robustness of our approach is linked to the scale of disturbances that affect a stream; it will be less robust for identifying less degraded or reference streams with localized human disturbances. With improved availability of high-resolution disturbance datasets, this approach will provide a more complete picture of reference stream reaches and factors contributing to degradation of stream health.

Keywords Bioassessment · Fish · Human disturbance · Reference · Stream

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1 Introduction

Landscape anthropogenic disturbances affect stream ecosystem processes and biological assemblages through complex interactions among sources, types, and pathways of disturbances. Historically, focus has been placed on point-source pollution, such as industrial and municipal wastewater discharge into surface waters. As treatment of point-source disturbances has improved, it has become evident that non-point source pollution also has contributed to long-term cumulative impacts on stream health (Jones & Clark, 1987; McDonnell & Pickett, 1990; Wichert, 1995). The conversion of naturally vegetated land to industrial, agricultural, commercial, and residential land uses has not only generated contaminants, but also resulted in increased storm-water runoff to streams. This increased runoff, in turn, has increased flood frequency and severity, accelerated land and channel erosion, increased sediment transportation and deposition, and altered stream channel form and bed composition (Klein, 1979). Increased runoff and reduced infiltration due to increases in impervious surfaces also have modified stream base flows, altered water temperature regimes and energy inputs, and increased loadings of nutrients and toxic substances (Booth, 1991; Booth & Reinelt, 1993; Galli, 1991; Klein, 1979). These disturbances have led to major changes in stream water quality and quantity (Paul & Meyer, 2001; Wang & Lyons, 2003), biological assemblages (Moscrip & Montgomery, 1997; Wang, Lyons, Kanehl, Bannerman, & Emmons, 2000; Weaver & Garman, 1994) and overall ecosystem health (Allan, 2004; Danz et al., 2005; Wang, Lyons, Rasmussen et al., 2003).

Quantifying the influence of individual disturbance factors on biological conditions or overall stream health for specific water bodies is difficult because of complexities in disturbance sources, types, and pathways. The common approach for measuring and quantifying human disturbance on streams is through multimetric biological indicators, such as indices of biotic integrity for periphyton, macroinvertebrate, and fish. These indices are popular because of the belief that biological assemblages integrate the effects of all disturbance sources, types and pathways (Fausch, Lyons, Karr, & Angermeier, 1990; Karr & Chu, 1999). However, the use of multimetric biological indicators for quantifying anthropogenic disturbance on streams is not without challenges. First, stream health assessments can only be conducted for areas where biological data are available, which may comprise only a fraction of total stream area within a region. Second, many of the currently used biotic indices lack connection with specific human disturbances, making it difficult to pinpoint sources of ecosystem change and to prescribe preventive or restorative management actions (Norris & Hawkins, 2000; Suter, Norton, & Cormier, 2002; USEPA, 2000). Third, metrics of biological indices are often selected based upon empirical dose–response relationships observed across human disturbance gradients (Karr & Chu, 1999). However, this method has been criticized for lacking scientific rigor because human disturbance indicators are often based on qualitative data from a limited number of sources and explicit protocols for identifying disturbance factors often are lacking (Dale & Beyeler, 2001). Additionally, human disturbances may not have linear or additive effects on biological assemblages, which is an assumption made by most multimetric indicator approaches. Therefore, it would be highly desirable to develop a process for quantifying human disturbance levels that could be applied to all streams (even those without biological data) within a given area, pinpoint specific source of degradation, and incorporate potentially non-additive or non-linear relationships between disturbances and biological assemblages.

The identification of reference conditions (least disturbed stream reaches) is a critical step in assessing human disturbances of stream health. Comparison of conditions between reference and test sites allows the determination of disturbance severity for test sites. The recommended process for selecting reference sites includes identifying relatively homogeneous stream regions, evaluating occurrences and levels of disturbance for candidate catchments, selecting those sites that are least disturbed by landscape-scale anthropogenic disturbance for local habitat and biological sampling, and identifying biological expectations (reference conditions) for sites with minimal levels of localized disturbance (Hughes, 1995; Hughes, Larsen, & Omernik, 1986; USEPA, 1996; Whittier, Stoddard, Hughes, & Lomnicky, 2006). Although most of the steps can be accomplished using available landscape databases, large-scale reference site identification is challenging because many streams lack the local and landscape data needed to complete such an assessment.

In this study, we describe a novel approach for selecting stream reference sites and quantifying human disturbance gradients for Michigan streams. This approach incorporates natural environmental variability of landscapes at several spatial scales and uses publicly available data for identifying anthropogenic disturbances and site-specific biological measures for linking levels of human disturbance to biotic changes. Methods that we address in this paper include (1) the identification of a candidate pool of reference reaches based on levels of landscape-scale human disturbances, (2) assessment of human disturbance gradients for all wadeable stream reaches in Michigan based on observed relationships between human disturbance and fish assemblage measures, and (3) determination of major sources of degradation for stream reaches that are identified as being moderately to severely disturbed.

2 Data Sets

2.1 Stream reaches and their spatial boundaries

Streams in Michigan identifiable from the 1:100,000 scale national hydrography dataset (NHD) were used as the basis for this research. Our basic spatial units were individual stream reaches, which we defined as inter-confluence stretches of water. For each stream reach, we delineated spatial boundaries corresponding to network and local watersheds and riparian buffers using a geographic information system (ESRI, 2002). Network watersheds encompassed all upstream areas for the stream reaches, while local watersheds encompassed only those upstream areas draining directly into the reaches. Network and local riparian buffers were similarly delineated, except boundaries were limited to areas within 75 m on either side of the streamlines. See Brenden et al. (2006) for additional details regarding stream reach identification, spatial boundary delineation, and variable attribution to the stream reaches.

Because fish assemblages in cold-water and warm-water streams are known to respond differently to human disturbances (Lyons, Wang, & Simonson, 1996; Wang, Lyons, & Kanehl, 2003; Wang, Lyons, Rasmussen et al., 2003), we classified the stream reaches into two thermal classes using a trout classification scheme developed by the Michigan Department of Natural Resources (MDNR; MDNR unpublished data). Trout streams have suitable thermal and flow regimes and physicochemical habitats for supporting self-sustaining and abundant trout or salmon populations. Marginal trout streams support low numbers of trout or salmon populations and are limited by inadequate natural reproduction, competition, siltation, and/or pollution (MDNR Stream Survey Manual, unpublished document). Non-trout streams are unable to support trout or salmon populations. For this research, trout and marginal trout stream reaches were referred as "cold-water" streams, while non-trout stream reaches as "warm-water" streams.

2.2 Human disturbance data

Human disturbance data, representing land use, population density, transportation, nutrient enrichment, agricultural pollutants, and point source pollutions, were gathered based on data availability and their known influences on stream health. We calculated 27 measures of human disturbances using data from several sources (Table I). Percentages of urban and agricultural land uses were calculated for network and local watersheds and riparian buffers from 2001 Michigan Land Use/Cover Data (http://www.mcgi.state.mi.us./mgdl). Total distance of roads and number of road crossings for network watersheds were also calculated using the Michigan Geographic Data Library (http://www.mcgi.state.mi.us./mgdl). Human population density for network watersheds were calculated from 2000 Tiger data (http://www.mcgi.state.mi.us./mgdl and esri.com/data/download/census2000_tigerline/index.html). Total nitrogen and phosphorus yields for network watersheds were obtained from US Geological Survey (USGS) data that were estimated using the spatially referenced regressions on watershed attributes (SPARROW) model (Smith, Schwarz, & Alexander, 1997; http://water.usgs.gov/nawqa/sparrow/wrr97/results.html). Number of facilities with water discharge permits and number of these facilities that were directly connected to streams within network watersheds were calculated using Michigan Department of Environmental Quality (MDEQ) data (MDEQ unpublished data). Number of facilities listed on the US Environmental Protection Agency (USEPA) toxic release inventory and number of these facilities with direct connections to streams within network watersheds were obtained from USEPA database (http://www.epa.gov/tri). Areas treated with fertilizers, herbicides, insecticides, and manure from animal feeding operations were calculated using US Department of Agriculture (USDA) 2002 Census of Agriculture database (http://www.nass.usda.gov/census_of_agriculture/index.asp) and USDA 2002–2005 Performance Results System (http://ias.sc.egov.usda.gov/prshome/default.html). Number of active mining sites within each network watershed was

Table I Mean and range of human disturbance factors for all stream reaches in Michigan, from which disturbance variables were selected and disturbance thresholds were determined

Disturbance variable	Mean	Range	Threshold	
			Cold	Warm
Variables selected for cold-water dataset				
Total nitrogen plus (phosphorus × 10) yield (kg l^{-1} $year^{-1}$)	1,400	120–9,824	800	2,000
Variables selected for warm-water dataset				
Dam density (number/100 km^2)	1	0–278	17.5	4.0
USEPA's toxic release inventory sites discharging into surface water (number/10,000 km^2)	5	0–7,959	10.0	10.0
Variables selected for cold-water and warm-water dataset				
Active mining (number/10,000 km^2)	3	0–5948	0.01	10.0
Network watershed agricultural land use (%)	36	0–100	60	65
Network watershed urban land use (%)	5	0–92	8	8
MDEQ's permitted point source facilities (number/100 km^2)	6	0–757	10.0	16.0
MDEQ's permitted point source facilities having direct connection with stream (number/100 km^2)	1	0–759	3.0	6.1
USEPA's toxic release inventory sites (number/10,000 km^2)	55	0–21808	10.0	150.0
Population density (number/km^2)	49	0–2273	50	200
Road crossing (number/km^2)	1	0–16	0.6	0.6
Road density (km/km^2)	2	0–14	2.2	2.5
Total nitrogen plus (phosphorus × 10) loading (kg l^{-1} $year^{-1}$)	1531	243–9859	800	2000
Watershed area treated with manure from barn yards (m/km)	1	0–8	1.3	0.1
Disturbance factors that were not selected				
Local buffer agricultural land use (%)	25	0–100	30	25
Local buffer urban land use (%)	5	0–100	3.8	6
Local watershed agricultural land use (%)	33	0–100	60	65
Local watershed urban land use (%)	5	0–100	4	6
Network buffer agricultural land use (%)	29	0–100	30	35
Network buffer urban land use (%)	4	0–90	3.8	6
Total nitrogen loading (kg l^{-1} $year^{-1}$)	864	173–3369	430	1200
Total nitrogen yield (kg l^{-1} $year^{-1}$)	788	86–2900	430	1200
Total phosphorus loading (kg l^{-1} $year^{-1}$)	67	7–695	25	105
Total phosphorus yield (kg l^{-1} $year^{-1}$)	61	3–692	25	105
Watershed area treated with fertilizers (%)	20	0–58	9.0	30.0
Watershed area treated with herbicides and insecticides (%)	19	0–62	6.8	30.0
Watershed area treated with manure (%)	2	0–9	3.5	2.8
Covariance variables included in the analysis				
Watershed size (km^2)	55	0.5–1598	NA	NA
Gradient (m/km)	5	0–110	NA	NA

The threshold value for each disturbance factor was the level of disturbance beyond which fish variables showed apparent impacts, which was visually determined by plotting each disturbance factor against values of index of biotic integrity and percent intolerant fish individuals.

USEPA US Environmental Protection Agency, *MDEQ* Michigan Department of Environmental Quality.

calculated from USGS mineral resource database (http://mrdata.usgs.gov/).

2.3 Fish data

Fish data were from the MDNR Fish Collection System and Michigan River Inventory databases (Seelbach & Wiley, 1997). From these databases, we used 741 stream sites (Figure 1) where fish were collected using either backpack or tow-barge electrofishing units from mid May to late September between 1982 and 2004. We included only wadeable stream sites, which we defined as streams with network watershed areas < 1,600 km^2 or stream orders < 5th

Figure 1 Fish sampling sites. *Filled circles* indicate trout-stream and *filled triangles* indicate non-trout-stream sites.

order (Wilhelm, Allan, Wessell, Merritt, & Cummins, 2005). The lengths of streams sampled were between 30 and 960 m (median=152 m) depending on the size of the streams. Fish data were collected using single-pass sampling to collect all fish observed and all captured fish were identified and counted in the field.

From the fish data, we calculated 54 fish assemblage measures, including thermal, feeding, tolerance, and reproduction classifications, and index of biotic integrity (IBI) scores. IBI scores for cold-water stream sites were calculated using the Wisconsin cold-water IBI procedure (Lyons et al., 1996). IBI scores for warm-water stream were calculated using the 10 IBI metrics developed by the MDEQ (http://www.deq.state.mi.us/documents/deq-swq-gleas-proc51.pdf). Because number of fish species is correlated with stream size (Lyons, 1992), IBI metric scores for fish species richness were adjusted based on watershed area. The adjustment for the northern lakes and forest ecoregion was different from the adjustment used for the rest of Michigan, as preliminary analyses indicated that relationships between species richness and stream size differed between these regions. Each IBI metric was re-scaled to a 0 to 10 scale, so that the sum of the 10 IBI metrics resulted in a total IBI score with a minimum and maximum value of 0 and 100 (Lyons, 1992). For stream reaches classified as marginal trout streams, we calculated both cold and warm-water IBI scores and used the higher of the two because a cool-water IBI does not yet exist for the study region.

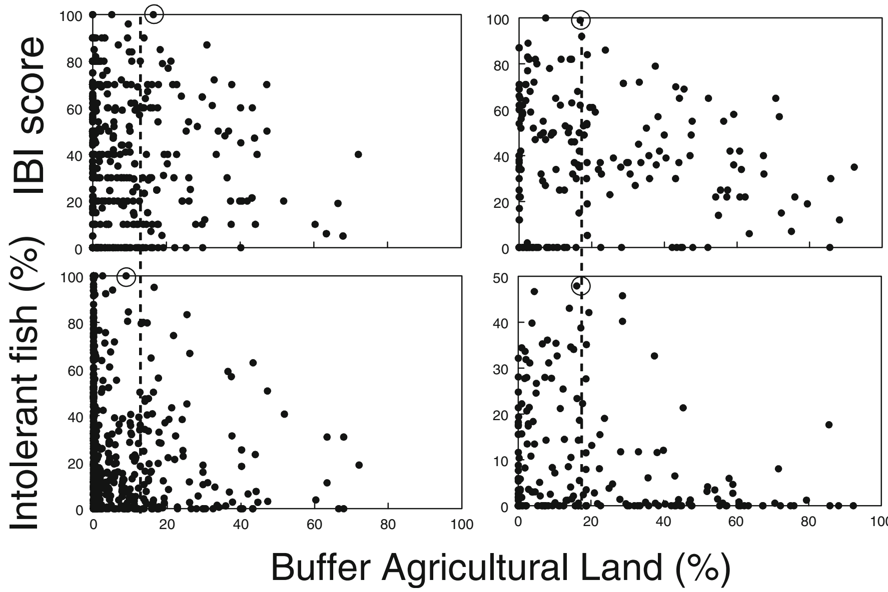
3 Identifying Reference Stream Reaches

Reference reaches were identified separately for cold and warm-water streams. Reference stream reaches were identified based on levels of all available human disturbance factors and their relation with two fish variables. We initially explored relationships between the human disturbance factors and the fish assemblage measures through Pearson pairwise correlations and visual analyses of scatter plots to identify fish measures that were most sensitive to human disturbances. We then plotted the two most sensitive fish measures (IBI and percent intolerant individuals) against each of the 27 disturbances to identify disturbance threshold values (i.e., values at which the relationship between the disturbance factor and the fish measure changes). In cases where the two fish measures had different thresholds, we calculated the mean of the threshold values. Threshold values were identified by examining upper boundaries of human disturbance and fish assemblage scatter plots. Upper boundary changes were used to identify thresholds as upper boundaries reflect direct influence of a disturbance, while mid-range or lower boundary changes reflect the influences of other disturbance or limiting factors (Cade, Terrell, & Schroeder, 1999; Figure 2). Streams with disturbance values less than thresholds for all disturbance measures were considered reference reaches. We identified reference reaches for all wadeable streams in Michigan based on the threshold values that were identified for the sites with collected fish data.

4 Calculating Disturbance Gradient

The variable selection and disturbance gradient calculation were done separately for the cold and warm-water datasets.

Figure 2 An illustration of how threshold disturbance value is determined for reference reaches for trout (*left panel*) and non-trout (*right panel*) streams separately. *Vertical lines* indicate the threshold percent of buffer agricultural land use. When the fish IBI and percent intolerant fish indicate differently (indicated by the *dots in the circles*), mean value of the two were used.



4.1 Variable selection

Fish variables believed to be sensitive to human disturbances in the Midwestern United States were identified from published literature (Lyons, 1992; Lyons et al., 1996; Wang et al., 2000; Wang, Lyons, & Kanehl, 2003; Wang, Lyons, Rasmussen et al., 2003). For pairs of fish variables with Spearman rank correlations (r)>0.71, we deleted the variable that exhibited the weakest linkage with human disturbance measures. Human disturbance factors were first identified by selecting those measures that were significantly correlated with at least one of the retained fish variables (Spearman rank correlation with Bonferroni correction, $p<0.05$). After standardizing the selected disturbance factors using method described in Section 4.2, we then identified disturbance factors that explained >50% variance of other disturbance factors ($r>0.71$) and retained only those measures had stronger correlations with fish measures.

4.2 Standardizing disturbance data

Because disturbance measurements were in different units and the relationships between fish measures and disturbance factors were not always linear, we standardized the values of each disturbance factor to a 0–10 scale, beginning with the identified threshold values for the disturbance factors. This process is visually illustrated in Figure 3. We used IBI and percent intolerant fish because these two fish measures were the most sensitive indicators of human disturbance in our preliminary analyses. The data standardization re-scaled all disturbance factors to the same unit, eliminated threshold effects, and minimized non-linear relationships between fish measures and disturbance factors.

4.3 Developing a disturbance index

Three steps were used to develop an overall disturbance index from the disturbance factors. First, we used canonical correlation analysis (CCA; SAS, 2004) to assess the influence of the disturbance factors on the fish assemblage measures and to assign weights to individual disturbances. This was a necessary step as disturbance factors are known to effect fish differently (Wang, Lyons, Kanehl, & Gatti, 1997; Wang et al., 2000; Wang, Lyons, & Kanehl, 2003; Wang, Lyons, Rasmussen et al., 2003). CCA is a multivariate statistical technique for analyzing relationships between a set of multiple dependent (fish measures) and a set of multiple independent (disturbance factors) variables. When a significant relationship between fish and disturbance factors is found, the linear combination of predictors represents an index of disturbance conditions. The set of weights associated with this linear combination can be used as a set of coefficients for transforming the disturbance factors from sampling units into an environmental health index (Laessig & Duckett, 1979). Because stream gradient and watershed size affect fish assem-

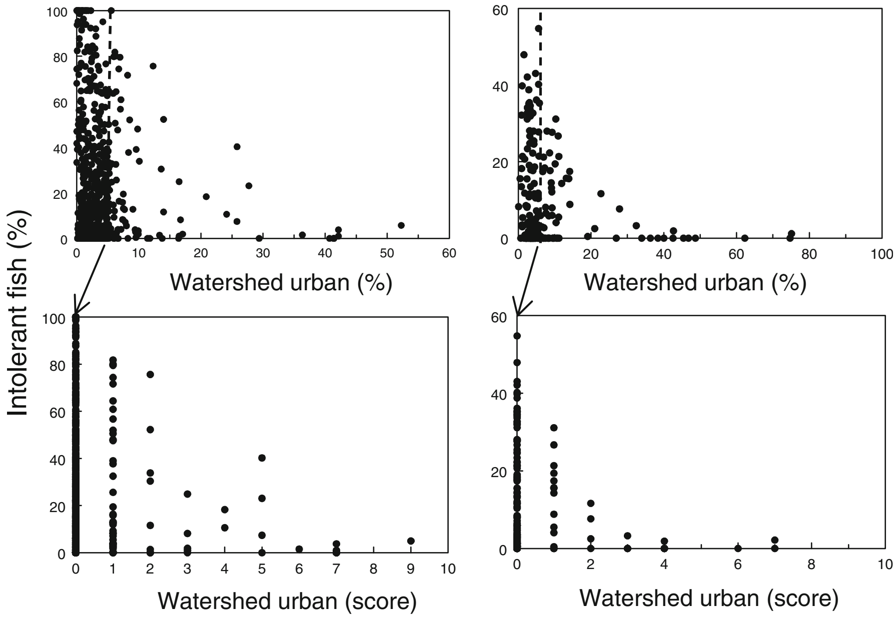


Figure 3 An illustration of how values of disturbance factors are rescaled from 0 to 10 for trout (*left panel*) and non-trout (*right panel*) streams separately. *Vertical lines* indicate threshold levels of watershed urban land use beyond which fish measure shows observable impacts. *Arrows* indicate the threshold level of urban land use that is equal to zero on the rescaled measure of the urban land use.

blage composition (Wang, Lyons, Rasmussen et al., 2003), we partialled out the effects of these variables by including these two variables in our canonical correlation analysis.

Second, we multiplied the value of each disturbance by its associated weighting factor (absolute value) derived from the CCA analysis, and summarized all the weighted disturbance factors into an overall disturbance score for each stream reach. When multiple canonical correlations were significant, we carried out this process separately for each significant CCA axis, and the average of the multiple disturbance scores was used as the final disturbance index. The disturbance index values for cold-water and warm-water streams were rescaled separately to a 0 to 100 scale.

Last, we plotted the calculated disturbance index against fish IBI scores and percentages of intolerant individuals for stream reaches where fish data were available. We then divided the disturbance index values into five tiers. The first tier was the maximum disturbance index value at which the fish measures did not show obvious decline. The other four tiers were determined by dividing the rest of the disturbance index values into even categories (Figure 4).

4.4 Identify key disturbance factors for a specific stream reach

The health of an individual stream reach was estimated by the value of its overall disturbance index. Because the overall disturbance index was a summation of multiple disturbance factors, it could easily be determined which disturbance factors were primarily responsible for poor stream health. For stream reaches that were moderately to severely disturbed, we ranked the individual disturbance factors in terms of their overall contribution to the disturbance index. The three highest ranking disturbance factors were considered the key disturbance factors for the stream reaches.

5 Results

5.1 Study stream reach conditions

Of the 28,273 stream reaches (77,393 km) with network watershed areas>0.5 km^2 that were identifiable for Michigan from the 1:100,000 scale NHD, 27,064 were wadeable reaches (network watershed area<1,600 km^2 or stream order<5th order; Wilhelm et al., 2005). This represented nearly 96% (74,375 km) of total stream length in Michigan. Twenty-eight percent of wadeable stream reaches (30% by length) were classified as cold-water streams (Table II). Mean length of cold-water reaches ($\bar{x} = 2.8$ km) was slightly greater then mean length for warm-water reaches ($\bar{x} = 2.6$ km). Network catchment areas ranged from <1 to >1,500 km^2 $\left(\bar{x} = 55\ km^2\right)$.

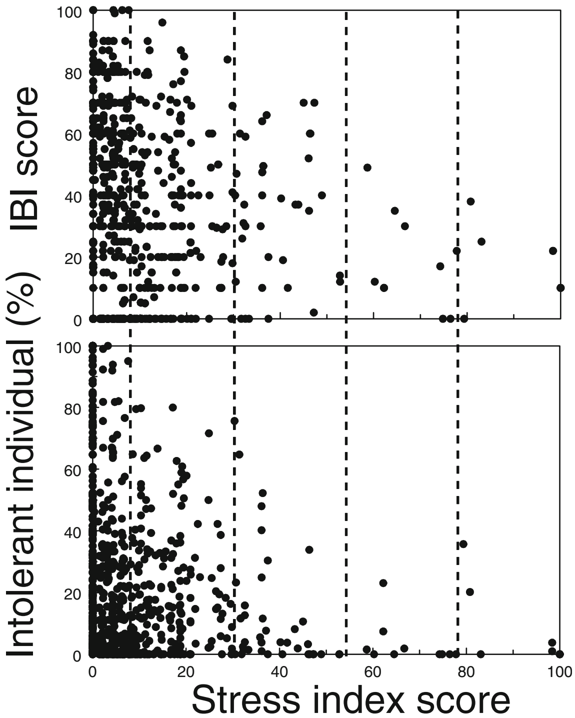


Figure 4 Relationships between disturbance index scores and fish IBI scores, and percent intolerant individuals. Stream reaches with disturbance index score < 8 (*x*-axis between 0 and first *vertical line* from the *left*), which is identified by no-observable impact on fish measures, are described as "undetectable." The rest four levels of impacts are determined by evenly dividing the remainder of the *x*-axis into "detectable" (8–31), "moderate" (32–54), "heavy" (55–77), and "severe" (> 77), represented by the *vertical broken lines*.

Michigan streams varied considerably in levels of human disturbance (Table I). Urban land use within network watersheds ranged from 0 to 92% ($\overline{x} = 5\%$), while agricultural land use ranged from 0 to 100% ($\overline{x} = 36\%$). Residential population density ranged from 0 to >2000 residents/km^2 $\left(\overline{x} = 49 \text{ residents}/\text{km}^2\right)$, and road density ranged from 0 to 14 km/km^2 ($\overline{x} = 2 \text{ km}/\text{km}^2$). Density of MDEQ permitted point source facilities ranged from 0 to 8 facilities/km^2 $\left(\overline{x} = < 1 \text{ facilties}/\text{km}^2\right)$.

The 741 fish sampling sites consisted of 539 cold-water (trout and marginal-trout streams) and 202 warm-water (non-trout streams) reaches. Species richness for the sites ranged from 1 to 28 species ($\overline{x} = 9$ species), and density of individuals ranged from 1 to 1,644 fish per 100 m of stream (Table III). Assemblages within reaches also varied substantially, with some reaches consisting entirely of salmonoid or intolerant species, and other stream reaches consisting entirely of warm-water or tolerant species. IBI scores for the sampled stream sites ranged from 0 (highly degraded) to 100 (excellent condition), with a mean score of 40 (fair condition).

Relative to reach occurrence across Michigan, a higher proportion of fish data were from cold-water reaches. Human disturbance gradients for streams with collected fish data were similar to the range of conditions observed across the entire state, but with lower ranges as expected. Urban and agricultural land uses within network catchments for streams with fish data ranged from 0 to 75% ($\overline{x} = 6\%$) and 0 to 90% ($\overline{x} = 44\%$), respectively. Residential population density ranged from 0 to 1,782 residents/km^2 ($\overline{x} = 118 \text{ residents}/\text{km}^2$). Road density ranged from 0.3 to 10.8 km/ km^2 $\left(\overline{x} = 2.1 \text{ km}/\text{km}^2\right)$, and density of MDEQ permitted point source facilities ranged from 0 to 1.3 facilities/km^2 $\left(\overline{x} = 0.1 \text{ facilities}/\text{km}^2\right)$.

5.2 Least disturbed reference reaches

For cold-water reaches, we identified 2,754 reaches (37%) comprising 8,610 km (38%) that were in least-disturbed condition (Table II). Conversely, for warm-water reaches, 3,126 reaches (16%) comprising 8,398 km (16%) were identified as being in least-disturbed condition. Most least-disturbed reaches occurred in the upper and northern-lower peninsulas

Table II Total number of reaches and length, least disturbed number of reaches and length, and percentages of least disturbed number of reaches and length of wadeable streams in Michigan (excluding stream reaches with watershed area<0.5 km^2)

Stream type	All reaches				Least disturbed reaches			
	Number	Percent	Length (km)	Percent	Number	Percent	Length (km)	Percent
Cold-water	7,454	28	22,445	30	2,754	37	8,610	38
Warm-water	19,610	72	51,930	70	3,126	16	8,398	16
All	27,064	100	74,375	100	5,880	22	17,008	23

Table III Fish variables and their statistics from which biological indicators were chosen

Variables	Mean	Maximum	Minimum	Stand error
Variables selected for cold-water dataset				
Brook trout individual (%)	21	100	0	1.4
Cool and cold-water (number/100 m)	28	325	0	1.5
Cool and cold-water individual (%)	34	100	0	1.3
Intolerant (number/100 m)	20	251	0	1.2
Number of cold-water species (number)	1	6	0	0.0
Number of cool and cold-water species (number)	2	10	0	0.1
Number of cool and cold-water species (%)	27	100	0	1.0
Number of tolerant species (number)	3	8	0	0.1
Top carnivores (number/100 m)	22	325	0	1.3
Variables selected for warm-water dataset				
Abundance (number/100 m)	119	1,644	0.8	5.6
Invertivore individual (%)	35	100	0	1.0
Lithophil individual (%)	26	98	0	0.8
Number of darter species (number)	1	5	0	0.0
Number of sucker species (number)	1	5	0	0.0
Number of tolerant species (%)	35	100	0	0.7
Omnivore individual (%)	12	84	0	0.5
Top carnivore individual (%)	28	100	0	1.1
Species (number)	9	28	1	0.2
Variables selected for cold-water and warm-water dataset:				
Index of biotic integrity score	40	100	0	1.1
Intolerant individual (%)	39	100	0	1.0
Tolerant individual (%)	39	100	0	1.0
Variables were not selected in the datasets				
Brook trout (number/100 m)	7	216	0	0.8
Cold-water (number/100)	25	325	0	1.5
Cold-water individual (%)	32	100	0	1.3
Invertivores (number/100 m)	45	825	0	2.8
Lithophils (number/100 m)	35	887	0	2.7
Nonnative cool and cold-water (number/100 m)	11	309	0	0.9
Number of intolerant species (number)	2	9	0	0.0
Number of native species (number)	9	27	0	0.2
Number of salmonoid species (number)	1	5	0	0.0
Number of salmonoid species (%)	18	100	0	0.8
Number of sunfish species (number)	1	6	0	0.0
Omnivores (number/100 m)	14	589	0	1.4
Tolerant (number/100 m)	54	1,052	0	4.0
Salmonoid (number/100 m)	18	325	0	1.2
Salmonoid individual (%)	24	100	0	1.1

of Michigan (Figure 5), where agricultural and urban land use is less prevalent than elsewhere in the state.

5.3 Human disturbance gradient

For cold-water streams, the effects of anthropogenic disturbances on fish were undetectable for 82% of stream reaches (83% by length), and detectable for 15% of stream reaches (14% by length). Less than 4% of reaches in terms of both number and length were moderately to severely disturbed (Table IV). For warm-water streams, the effects of anthropogenic disturbances on fish were undetectable for 62% of reaches in terms of both number and length, which was lower than that observed for cold-water streams (82%). The effects of anthropogenic disturbances

Figure 5 Reference stream reaches identified in Michigan. *Light lines* indicate non-reference reaches, *dark lines* indicate non-trout stream reference reaches, and *medium-dark lines* indicate trout-stream reference reaches.

were detectable for 35% of reaches in terms of number and length, which was considerably higher than that observed for cold-water streams (15%). Less than 4% of stream reaches in terms of numbers and length were estimated to be moderately or severely disturbed, which was similar to that observed for cold-water streams (Table IV).

Overall, landscape disturbances affected 23,623 km (31.8%) of wadeable streams, and most were distributed in southern, especially southeastern Michigan (Figure 6). Of those disturbed, 20,885 km (28.1%) were detectable, 1,652 km (2.2%) were moderately and 806 km (1.1%) were heavily influenced, and 280 km (0.4%) were severely disturbed. The rest of the 50,752 km (68.2%) of wadeable streams were minimally disturbed by landscape human activities.

5.4 Key landscape disturbances for specific stream reaches

Eight landscape disturbance factors were among the top-three disturbances for the 250 cold-water stream reaches with moderate to severe human disturbance (Figure 7). Of the disturbance factors that ranked highest in contributing to the overall disturbance index, total nitrogen and phosphorus affected the greatest number of reaches (63%), followed by road density (19%) and urban land use (9%). Densities of MDEQ permitted facilities and USEPA toxic release sites, manure application, and residential population density were the highest ranking disturbance factor for less than 4% of stream reaches. Agricultural land use was not among the highest ranked disturbance factor for any of the cold-water streams.

Of the disturbance factors that had the second highest ranking in contributing to the overall disturbance index for cold-water stream reaches, total nitrogen and phosphorous again disturbed the highest number of reaches (50%), followed by road density, urban land use, manure application, and residential population density (9–14%). Densities of MDEQ permitted facilities and USEPA toxic release sites affected <5% of cold-water stream reaches. Agricultural land use was not ranked as the second highest disturbance factor for any of the cold-water streams.

Of the disturbance factors that had the third highest ranking in contributing to the overall disturbance index for cold-water reaches, total nitrogen and phosphorous, urban land use, and manure application disturbed the highest number of reaches (19–26%). Densities of roads, MDEQ permitted facilities, and residential populations each disturbed moderate number of reaches (4–8%), while density of USEPA toxic release sites disturbed <1% cold-water stream reaches.

Nine landscape disturbance factors were ranked as top-three disturbances for the 720 warm-water reaches with moderate to severe human disturbance (Figure 7). Of the disturbance factors that ranked the highest in contributing to the overall disturbance index, urban land use disturbed the highest number of reaches (69%), followed by total nitrogen and phosphorus (16%) and residential population density (9%). Densities of MDEQ permitted facilities and USEPA toxic release sites, agricultural land use, and densities of dams and mines were each the highest ranking disturbance factor for less than 3% of stream reaches. Density of roads and manure application were not among the highest ranking disturbances for any of the warm-water reaches.

Of the disturbance factors that had the second highest ranking in contributing to the overall distur-

Table IV Total number of reaches and length, and percentages of number of reaches and length with different levels of human disturbances of wadeable streams in Michigan

Quantitative disturbance level	Qualitative disturbance level	Reaches (number)	Length (km)	Reaches (%)	Length (%)
Cold-water streams					
≤8	Undetectable	6,096	18,648	81.8	83.1
8–31	Detectable	1,108	3,082	14.9	13.7
32–54	Moderate	202	572	2.7	2.6
55–77	Heavy	40	117	0.5	0.5
>77	Severe	8	27	0.1	0.1
Total	NA	7,454	22,445	100	100
Warm-water streams					
≤8	Undetectable	12,148	32,104	61.9	61.8
8–31	Detectable	6,742	17,803	34.4	34.3
32–54	Moderate	411	1,080	2.1	2.1
55–77	Heavy	224	689	1.1	1.3
>77	Severe	85	253	0.4	0.5
Total	NA	19,610	51,930	100	100

Stream reaches with watershed area<0.5 km^2 were excluded.

bance index for warm-water streams, population density disturbed the most stream reaches (47%). Total nitrogen and phosphorous, percent urban land use, and density of MDEQ permitted facilities disturbed a moderate number of stream reaches (15–16%). Densities of roads and USEPA toxic release sites disturbed least number of reaches (2 and 3%). Manure application, percent agricultural land use, and densities of dams and mines were not among the second highest ranking disturbances for any of the warm-water streams.

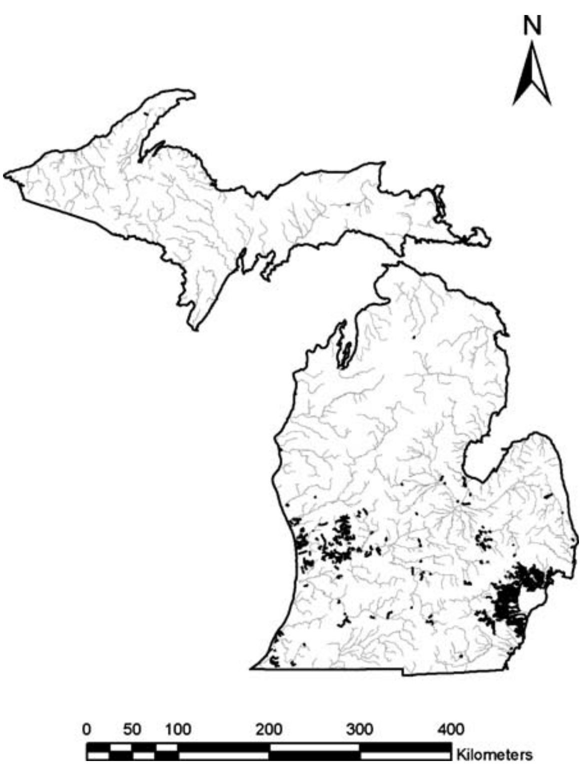


Figure 6 Disturbed stream reaches identified in Michigan. *Light lines* indicate least disturbed reaches. The *dark lines* indicate severely disturbed, and the *medium-dark lines* indicate moderately to heavily disturbed stream reaches.

Of the disturbance factors that had the third highest ranking in contributing to the overall disturbance index for warm-water streams, total nitrogen and phosphorus disturbed the greatest number of reaches (29%), followed by density of MDEQ permitted facilities (25%). Percent urban land use and densities of roads, USEPA listed toxic release sites, and residential population disturbed 8% to 14% reaches. Percentages of agricultural land use and area of manure applications and densities of dams and mines disturbed <3% of stream reaches.

6 Discussion

Landscape alterations associated with human disturbances in riparian and upland areas influence instream conditions, and consequently impact stream biological assemblages and overall stream health (Allan, 2004; Hughes, Wang, & Seelbach, 2006). Most stream health assessments have focused on instream physicochemical and biological conditions because of the unavailability of large-scale disturbance data and the resources required to delineate stream reaches and

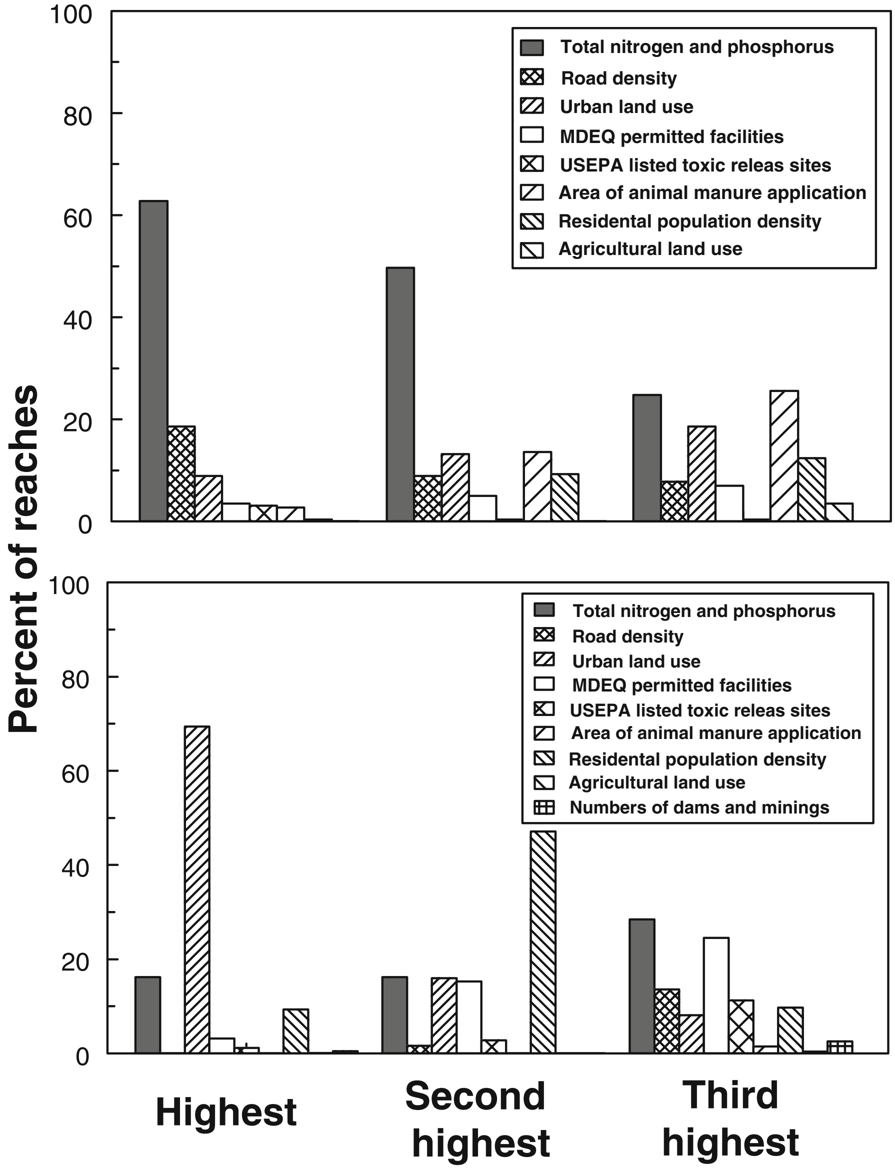


Figure 7 The top three disturbances identified for each of the stream reaches that have moderate to severe degradation. Occurrence frequencies of each disturbance are expressed as percentages of reaches. The top three disturbances were identified by ranking the disturbance factors for each stream reach based on their contribution to the value of the disturbance index. The three groups of *bars* on the *x*-axis represent the disturbance factors that are ranked highest, second highest, and third highest. The *top panel* is for trout, and the *bottom panel* is for non-trout stream reaches.

associated different scale catchment boundaries. As the availability of regional databases and the development of geographic information technologies have increased, using landscape disturbances to directly identify reference streams and to assess stream health becomes more feasible and of proven effectiveness (Hughes et al., 2006; Wang, Seelbach, & Hughes, 2006a).

Using a landscape approach to identify stream reference reaches and assess human disturbance gradients, we found that the majority of Michigan streams were in good condition (impacts of disturbances on fish were undetectable). Cold-water streams appear better protected than warm-water streams, given the higher percent of cold-water streams in reference condition. This finding is confounded, however, by the distribution of streams in Michigan. The majority of cold-water streams occur in the upper and northern-lower peninsulas of Michigan, where agriculture and urban land uses are uncommon due to unproductive soil and harsh climate. Most moderately to severely disturbed streams occur in southern Michigan, particularly in the southeastern corner, where land use is predominantly agricultural and urban. The disturbance factors that affected the majority of moderately to severely disturbed streams were nutrient loading for cold-water reaches and urban land use within network catchments for warm-water reaches.

Our approach to stream health assessment has several advantages relative to other commonly used methods. First, our approach used inter-confluence stream reaches as the basic assessment unit. Currently, most stream bioassessments are based on data collected along relatively short stream distances (typically >100 to <1000 m). Although these data provide reliable information for the areas sampled, linking this information to unsampled stream sections is difficult. The common bioassessment practice is to use biological data from such a limited number of sampled sites and their associated landscape disturbance information to assess the health conditions of an entire watershed or a subwatershed. This watershed or subwatershed level assessment is ambiguous because not all stream sections in the same watershed or subwatershed are the same, especially those in large watersheds or those crossing ecoregional boundaries. Although probability surveys, such as the USEPA Environmental Monitoring and Assessment Program, improve the accuracy and precision of regional assessments by applying a stratified random sampling design and making repopulation estimates, the data are inappropriate for generalizing to unsampled sites. This is because the sampling data are from only a small percentage of the sections of the network, and one does not know which parts of the network are represented by the collected data. For example, one does not know if data collected from a second order section of a stream represents all second order streams in the same ecoregion. Alternatively, inter-confluence stream reaches are naturally occurring spatial units with relatively homogenous physicochemical, geomorphological, and biological attributes (Seelbach, Wiley, Baker, & Wehrly, 2006). A classification of such an analytical and measuring unit allows the interpolation of data collected from one unit to other units of the same type and region.

Second, our approach allows preliminary condition assessments for stream reaches across large geographic areas. For Michigan, we used readily available, landscape-scale human disturbance information, which permitted a health assessment for more than 27,000 stream reaches. It would be largely unfeasible to conduct a similar assessment for this number of streams using the traditional approach of site-specific collection of physicochemical and biological data. In principle, our approach is similar to a traditional bioassessment in that we used both biological and disturbance information to determine stream health conditions (biological indicator–disturbance relation model). The difference is that the factors used to determine stream conditions are not biological, but are landscape disturbance factors that can be determined without site-specific field sampling.

Third, our approach generates a single disturbance index that is a summary of biologically (fish) weighted multiple disturbance factors. The single-valued disturbance index and its associated individual components not only allow one to compare overall health conditions among streams, but also can identify the specific sources of degradation for each disturbed stream. Many studies have quantitatively linked landscape disturbance with instream physical habitat (e.g., Wang et al. 1997; Wang, Lyons, & Kanehl, 2003), water quality (e.g., Brown & Vivas, 2005; Crunkilton, Kleist, Ramcheck, DeVita, & Villeneueve, 1996; Wernick, Cook, & Schreier, 1998), and biological assemblages (e.g., Allan, Erickson, & Fay, 1997; Roth, Allan, & Erickson, 1996; Wang et al., 2000; Wang, Lyons, Rasmussen et al., 2003). However, most of those studies quantified only one or two dominant disturbances, and a single-valued landscape human disturbance index that summarizes major possible human disturbances based on their influences on biological indicators has not been quantitatively developed.

Several recent studies have attempted to qualitatively develop a single disturbance gradient. Brown and Vivas (2005) developed a landscape development intensity (LDI) index using land-use data and a development-intensity measure derived from energy use per unit area. They demonstrated the utility of LDI by showing that the index was strongly correlated with nutrient loadings and wetland quality. To assist calibrating tiered aquatic life use expectation along human disturbance gradients, the USEPA (2005) provided a conceptual model that ranked major instream stressor types from no impact to high impact and qualitatively linked instream stressors with potential landscape human disturbances. Hughes (personal communication) analyzed results from five workshops where 110 participants empirically assigned 30 stream sites into six disturbance tiers. Hughes concluded that a general human disturbance gradient can be useful for characterizing landscape quality of reference sites by placing them into easily communicated tiers. To assist field sampling design and development of biological indices, Danz et al. (2005) used six types of landscape disturbances: agriculture, atmospheric deposition, land cover, human population, point sources, and shoreline alteration. They quantitatively analyzed the variation of over 200 human disturbance factors and used principal component scores as input into a cluster analysis for stratifying sampling sites. The database used in such a study could be potentially used to quantitatively develop a human disturbance index. Wilhelm et al. (2005) developed a catchment disturbance index in order to calibrate a non-wadeable river habitat index, using several of the disturbance measures we used in this study. They did not relate their disturbance index with biological indicators.

There are also several potential shortcomings or challenges associated with our approach that require future studies. The first challenge is that some geographical datasets of human disturbances that are known or believed to affect stream health may not always be available or may exist at only coarse resolutions. We used the best available data, although we inevitably missed some disturbance factors that could have affected our findings. For example, livestock and barn yard densities, percent of logged areas, and remnant effects from past anthropogenic disturbances, are known to impact stream health (Harding, Benfield, Bolstad, Helfman, & Jones, 1998; Wang, Lyons, & Kanehl, 2002; Wang & Lyons, 2003); however, databases for these attributes were not available for Michigan. Nutrient yield and loading information were only available for 8-digit hydrologic units (HUC-8), which are inappropriate representations of catchments (Omernik, 2003), and information concerning applications of fertilizers, herbicides, pesticides, and manure were only available at a county scale. Although the availability and resolution of datasets are currently challenges that limit the value of our approach, we believe these are only temporary shortcomings that will be reduced as more geographic disturbance data become available and as dataset resolution improves.

The second challenge associated with our landscape approach for assessing stream condition is that it does not take into account impacts of localized anthropogenic disturbances. Localized human activities, such as channelization, dredging, bank trampling by livestock, and construction erosion, can significantly affect stream health (Koel & Stevenson, 2002; Schlosser, 1982; Wang et al., 2002). Plots of human disturbance and biological measures (Figures 2 and 4) show that substantial variability in stream condition occurs even in areas with relatively undisturbed landscapes; such a variability likely stem from natural variation, unmeasured landscape disturbances, and localized perturbations. Our first tier analysis provides a tool for identifying at what spatial scale the disturbances are expressed and where management activities should be focused. This is because localized management actions, such as stream bank stabilization and fencing, are most effective for stream reaches that have minimal or controlled landscape disturbances (Wang, Lyons, Rasmussen et al., 2003; Wang, Seelbach, & Lyons, 2006b). Our first-tier level analysis also provides a way for identifying streams that are minimally disturbed by landscape disturbance for stream natural-variation classification, which is essential for establishing expected natural health condition. To distinguish localized disturbance from natural variation for classification requires field visitation, which can be addressed in further studies.

The third challenge with our landscape approach for assessing stream health is that it does not consider the influence of best management practices (BMPs), which are meant to reduce or minimize human landscape disturbances. Agricultural and urban BMPs, such as stream bank fencing, bank stabilization, barnyard control, nutrient and manure application managements, crop and tillage rotations, and urban detention ponds and imperviousness-reduction practices, have been widely used in Michigan, as well as other states, for many years. Although their effectiveness in improving stream health is an active research area, large scale databases on the amounts, types, and locations of such practices are lacking (Alexander, 2005), and the extent to which those BMPs can compensate for human disturbances is uncertain (Wang et al., 2002). These areas warrant considerable further research for accurate human disturbance assessment.

It is important to recognize that our reference and disturbance-gradient identification is the main step of a multiple-step process for assessing human disturbance. The key steps identify sources of major disturbances, use a biologically-based process for estimating disturbance, and employ stream reach as assessment units, which allows the assessment of all streams statewide. Our results are most robust in the identification of highly degraded stream reaches and their associated key disturbance factors, and are relatively less robust in identifying less degraded or reference reaches because some of these identified reaches may have localized disturbances that are not accounted for. Our approach can be improved by adding more steps, such as incorporating measures of localized disturbances, increasing the resolution and accuracy of landscape disturbance databases, and identifying additional sources of disturbances that could impact stream health. As a result of current data limitations, our evaluation of Michigan streams represents only a first-tier assessment of statewide stream health. However, our process will yield improved results as additional information become available, such as field verifications.

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