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Using a process-based catchment-scale model for enhancing field-based stream assessments and predicting stream fish assemblages

ADAM KAUTZA* and S. MAŽEIKA P. SULLIVAN
The Ohio State University, School of Environment and Natural Resources, Columbus, OH 43210, USA

ABSTRACT

1. Catchment-modelling techniques, although not yet widely used in biological contexts, may be a valuable tool in the management and conservation of stream fishes. This study was undertaken to evaluate the potential of a catchment-scale hydrologic model, the Soil and Water Assessment Tool (SWAT), to explain characteristics of stream fish assemblages and to enhance current field-based stream assessments.
2. Stream fish assemblages, instream habitat, geomorphology, and water quality were surveyed in 16 study catchments in Ohio, USA. Subsequently, SWAT was used to model stream discharge, sediment flux and concentration, and nitrogen and phosphorus yields for each catchment.
3. Principal component analysis (PCA) and multiple linear regression were used to explore potential relationships between environmental factors (both reach-level measurements and SWAT-modelled catchment-scale processes) and fish assemblage descriptors assessed within the framework of an Ohio fish-based Index of Biotic Integrity (IBI).
4. Reach-level factors contributed to three of the four significant regression models, explaining 12% to 14% of the variation in fish species richness, the number of darter (*Etheostoma*) species, and the number of sensitive/intolerant species. SWAT-modelled parameters including minimum and mean annual flow and sediment yields explained significant variation in total IBI scores (57%), species richness (63%), the number of darter species (60%), and the number of sensitive/intolerant species (61%).
5. The results support the utility of SWAT as a complement to field-based surveys. It is proposed that process-based catchment-modelling techniques such as SWAT could improve stream fish management and conservation efforts when used as a screening tool to target streams and catchments for subsequent field surveys and as a method to model potential impacts to stream ecosystems and fish assemblages in highly sensitive areas and/or inaccessible catchments.

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KEY WORDS: agriculture; catchment; fish; landscape; modelling; stream; urban development

INTRODUCTION

The fundamental relationships between aquatic biota and their local, physical environment are well documented and have been synthesized in reach-scale assessments of habitat quality, many stemming from the US Environmental Protection Agency's Rapid Bioassessment protocols (Plafkin *et al*., 1989; Barbour *et al*., 1999). In Ohio (OH) for example, the Qualitative Habitat Evaluation Index (QHEI) is widely used to evaluate instream, bank, and riparian habitat (Rankin, 2006). In addition to physical descriptors of habitat, water quality measurements such as pH and conductivity are commonly used in some stream monitoring protocols (USEPA, 2006). Increasingly, stream

*Correspondence to: A. Kautza, The Ohio State University, School of Environment and Natural Resources, 2021 Coffey Road, 210 Kottman Hall, Columbus, OH 43210, USA. E-mail: kautza.1@buckeyemail.osu.edu

evaluations also include a fluvial geomorphic component (VTDEC, 2003).

Despite evidence describing the importance of habitat (Lau *et al*., 2006; Sullivan and Watzin, 2008; Hrodey *et al*., 2009), water quality (Deacon and Mize, 1997; Sutela *et al*., 2010), and geomorphology (Walters *et al*., 2003b; Sullivan *et al*., 2006) to aquatic biota at the local scale, the influence of broad-scale landscape characteristics might also be important (Frissell *et al*., 1986; Poff, 1997). Remotely sensed data and geographic information systems (GIS) have enabled increasingly detailed investigations of landscape-scale influences on stream biota, particularly relative to the influence of land use and land cover (Roth *et al*., 1996; Allan and Johnson, 1997; Sutherland *et al*., 2002; Allan, 2004; Sullivan *et al*., 2007).

Landscapes characterized by agriculture and urban, suburban, and exurban development (hereafter; development) are widespread throughout much of the USA. For example, by the early part of the 21st century land cover in the 'Corn Belt' states of Ohio, Indiana, Illinois, and Iowa consisted of more than 58% in agricultural crops and about 5% in development (Lubowski *et al*., 2006). Agriculture and development modifies hydrological regimes and sediment dynamics, which can alter the downstream transport of nutrients and organic matter (Newbold *et al*., 1982), fluvial geomorphic processes (Leopold, 1968; Schumm *et al*., 1984; Landwehr and Rhoads, 2003) and instream habitat heterogeneity (Pizzuto *et al*., 2000; Walters *et al*., 2003a). In turn, these alterations can have profound impacts on stream fish assemblages, often reducing diversity and the distribution of sensitive species (Landwehr and Rhoads, 2003; Lau *et al*., 2006). In some cases, landscape-scale environmental characteristics have been shown to exert a greater influence on stream fish assemblages than reach-scale factors (Snyder *et al*., 2003; Kautza and Sullivan, unpublished data). For instance, fish species richness and a fish-based Index of Biotic Integrity (IBI) were both highly influenced by urban land-use with the percentage of impervious surface in the catchment implicated as the primary driver (Wang *et al*., 2001).

Given the influence of broad-scale factors on stream functioning and fish assemblages, the potential for catchment-modelling techniques to complement existing reach-based stream evaluations is significant. In particular, the Soil and Water Assessment Tool (SWAT), a physically based hydrological model, may represent a valuable addition to current field-based protocols. SWAT was designed to quantify the cumulative impacts of land-management practices on water, sediment, and nutrient yields in catchments with diverse land cover, land use, soils, and climate (Arnold *et al*., 1998). In spite of its widespread use in modelling the potential effects of climate change and alternative land-management practices on nutrient and sediment fluxes, catchment hydrology, and stream flow (Douglas-Mankin *et al*., 2010), SWAT has received relatively little attention as an explicit tool relative to aquatic biota (but see Cianfrani *et al*., 2010).

The goal of this study was to explore the potential of SWAT to complement field-based stream assessments in explaining patterns of fish assemblages in OH wadeable streams. More specifically, the study was designed to investigate whether (1) SWAT-modelled variables relating to hydrologic, sediment, and nutrient processes or (2) field-based measures of water quality and stream habitat and geomorphic assessments explained greater variation in species richness, composition, abundance, and condition of fish assemblages. Based in part on preliminary work in study catchments, we hypothesized that catchment-scale processes would be highly predictive of fish assemblage characteristics and, in some cases, would explain greater variation than data collected in the field at the reach scale (10^2 m). Of the various fish descriptors considered, we anticipated that SWAT-modelled sediment and nutrient inputs would most strongly influence fish IBI scores, which represent an integrated snapshot of fish assemblages including both structural (e.g. abundance and richness) and functional (e.g. feeding guilds) information and, therefore, might be expected to be linked to broad-scale mechanisms. For instance, we considered that elevated sediment inputs across the catchment, expressed at the reach scale, would lead to a reduction in the abundance of simple lithophils and benthic insectivores, thereby lowering IBI scores through changes in species composition and relative abundances.

METHODS

Study area

Sixteen catchments were selected across the southern half of OH, USA (Figure 1). Study catchments were located across three ecoregions (Level III; Omernik, 1987) (Figure 1). In each

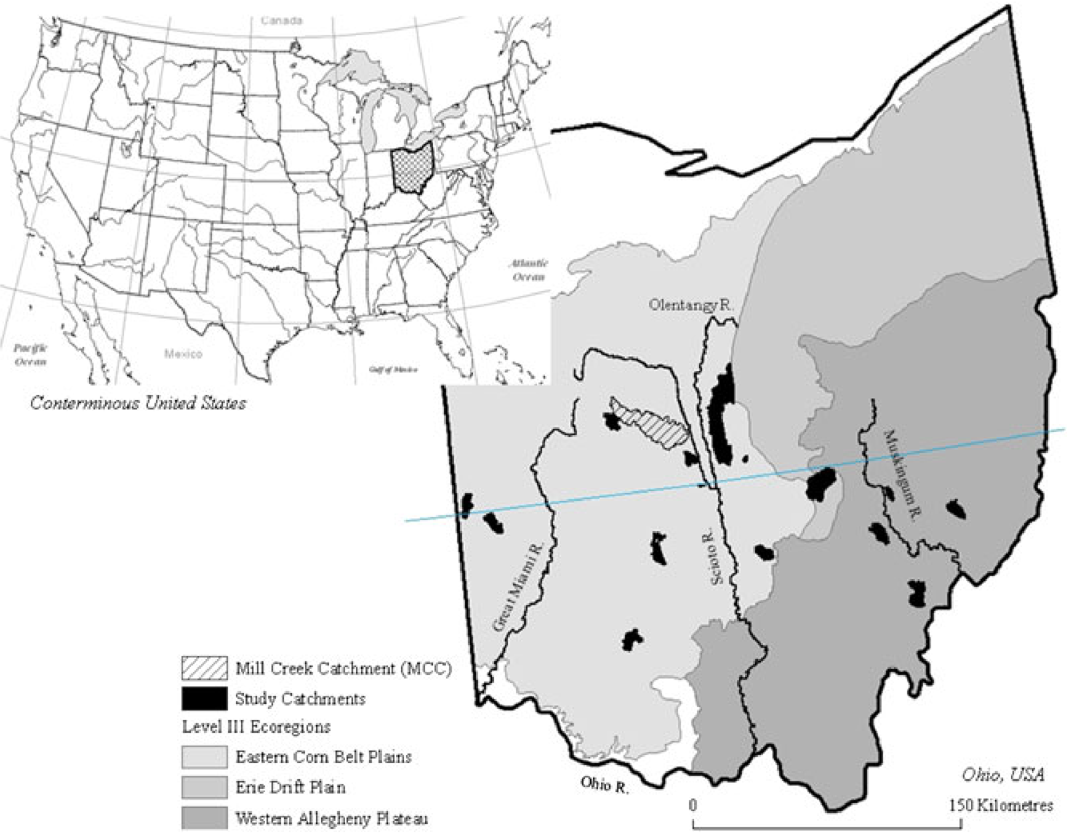

Figure 1. Locations of the 16 study catchments in Ohio, USA, along with major river systems and the catchment used for model calibration (Mill Creek – illustrated with diagonal hash marks). Shaded portions of the map illustrate the Level III Ecoregions (Omernik, 1987) in which study catchments are located.

catchment a representative stream reach (20X mean bankfull width (Kondolf and Micheli, 1995)) was selected and fish assemblages were surveyed, detailed reach-scale habitat and geomorphic assessments were performed, and water quality data were collected. Subsequently, SWAT was used to model catchment-scale hydrologic, sediment, and nutrient processes. Catchments varied in size from 4.3 km^2 to 372.5 km^2 (2nd–4th order streams (Strahler, 1957)) and represented a gradient of predominant OH land uses (i.e. development, agriculture, and forest).

Fish surveys

Fish assemblages were surveyed using a Smith-Root® LR-24 backpack electrofisher under normal flow conditions during the summer and early autumn of 2009. A 70% depletion of fish in the reach was necessary given the need for population-level data of species selected for subsequent use in an OH fish-based IBI. Because it would have been unlikely to achieve a 70% depletion for all species in the assemblage, either creek chubs (*Semotilus atromaculatus*) or bluntnose minnows (*Pimephales notatus*) were chosen to measure the depletion level in the field. Both of these species are common in OH streams and were present at all study sites. Three to four passes were typically required to achieve an acceptable level of depletion.

Fish-based indices of biotic integrity are a method by which key descriptors of assemblages are compiled to generate a numerical score that serves as an indicator of the overall biotic integrity of a stream (Karr, 1981). A fish-based IBI developed by the OH Environmental Protection Agency (OHEPA, 1987) was used in this study. Scoring criteria for the OH IBI follows the general framework introduced by Karr (1981) whereby key fish assemblage metrics (e.g. species richness, % insectivores, and others) are given scores of 1 (large deviation from reference), 3 (some deviation from reference), or 5 (reference). Twelve metrics are scored in this manner with total IBI scores ranging from 12 (all metrics deviate strongly from expected reference conditions) to 60 (all metrics represent reference conditions). OH IBI protocol distinguishes 'headwater' sites (drainage area $<52\,km^2$) from 'wading' sites (drainage area $>52\,km^2$), and a different set of scoring metrics is used for each (see Table 5 in 'Results' for metrics used in each category).

Reach-scale assessments

Stream geomorphology

At each reach, transects were established perpendicular to the stream channel where bankfull and wetted widths, bankfull depth, low bank height, and floodprone width were measured. From these measures, mean bankfull width and mean and maximum bankfull depths were calculated. Width-to-depth, entrenchment, and incision ratios following Rosgen (1994) were also calculated. Width-to-depth ratio (mean bankfull width ÷ mean bankfull depth) is a relative index of channel shape, with large values indicating channel overwidening. Entrenchment ratio (floodprone width ÷ bankfull width) describes the vertical containment of a stream within its valley. Incision ratio (low bank height ÷ maximum bankfull depth) is considered a more sensitive measure of bed degradation than entrenchment ratio, targeting early stage degradation. Substrate composition was characterized (mm, D_{50} and D_{95}) using pebble counts following Wolman (1954).

A Rapid Geomorphic Assessment (RGA) protocol, modified for unconfined OH streams (VTDEC, 2003), was used to evaluate geomorphic condition based on current and historic channel adjustment processes. The RGA is designed to evaluate current channel adjustment and can be used to determine the stage of channel evolution based on field indicators (e.g. sediment accumulation, presence of mid-channel bars, bank erosion, bed scour, etc.) of four dominant geomorphic adjustment processes: degradation, aggradation, widening, and change in planform. In the RGA, the magnitude of each adjustment process is scored from 0 to 20, where 0 represents significant channel adjustment and a gross deviation from expected geomorphic conditions and 20 represents reference conditions where channel adjustment processes are in equilibrium and there is little indication of deviation from expected geomorphic condition. Total RGA scores range from 0 to 80.

Habitat

The OH QHEI protocol (Rankin, 2006) was used to evaluate the relative quality of instream, bank, and riparian habitat at the reach level. In general, higher total QHEI scores (0–100) indicate greater habitat quality and heterogeneity. The QHEI is composed of seven categories: substrate, instream cover, channel morphology, bank erosion/riparian zone, pool/glide quality, riffle/run quality, and gradient. Each category is scored individually and summed to obtain a total score. In addition to the QHEI, all pieces of large woody debris (LWD, $>0.1\,\mathrm{m} \times 1.0\,\mathrm{m}$) located within the bankfull channel (Montgomery *et al.*, 1995) were counted to evaluate further the availability of physical habitat for fish.

Water quality

Although water quality linked to pollutants, pesticides, and other noxious inputs are a concern for streams in the study area, a careful experimental design was used to limit these potential effects by excluding sites lacking a relatively intact, vegetated riparian buffer (defined for this study as a riparian shrub and/or forest buffer covering >50% of each bank and extending >10 m from channel) and/or contaminant point sources (e.g. sewage treatment plant outflow or recent construction activity) located within or directly upstream of the reach. Reaches were sampled for pH and conductivity using a YSI 650 MDS® with an attached 600R® sonde. Nine samples were obtained at each reach: three taken laterally across the channel (e.g. left bank, centre, and right bank) at the bottom, middle, and top of each reach. Conductivity and pH were selected as focal measures of water quality, as they have been shown to be particularly variable in the region and to account for influences of non-physical abiotic factors on fish assemblages (Fischer and Paukert, 2008; Sutela *et al.*, 2010). All water quality parameters were measured before electrofishing surveys.

SWAT modelling

The minimum, maximum, mean, and standard deviation (SD) of discharge ($m^3\ s^{-1}$), mean and maximum sediment yield ($t\ km^{-2}$), mean and maximum sediment concentrations ($mg\ L^{-1}$), mean total nitrogen yield ($kgN\ km^{-2}$), and mean total phosphorus yield ($kgP\ km^{-2}$) were modelled for each study catchment using SWAT. The model operates on a continuous daily time-step while simulating precipitation, infiltration, surface runoff, evapotranspiration, lateral flow, and percolation processes in a catchment (Neitsch *et al.*, 2004, 2005). The following data were downloaded for use in the SWAT-modelling procedure: a 30-m digital elevation model and National Land Cover Dataset from the United States Geological Survey (NLCD, 2001) and a state-specific soils database obtained from the

United States Department of Agriculture National Resource Conservation Service (STATSGO; http://soildatamart.nrcs.usda.gov). Detailed daily precipitation data from nearby weather stations operated by the OH Agricultural Research and Development Center (OARDC) were put into the SWAT weather generator to enhance the likelihood of accurate modelling results.

Basic parameterization and calibration of the SWAT model were performed using techniques outlined in Neitsch *et al*. (2002). Region-specific recommendations and results from a detailed SWAT-modelling study undertaken in a central OH catchment by Witter (2006) were used to further inform the parameterization and calibration of the model. Because none of the study catchments contained flow gauges, a centrally located, gauged catchment (Mill Creek Catchment, Figure 1) within the larger study area was chosen for use in calibrating the model. The model was calibrated only for hydrology; sediment and other water quality data were unavailable. Calibration of the model, only with respect to flow, is consistent with other ecological studies using SWAT (Cianfrani *et al*., 2010). Parameters modified for calibration purposes and their original (i.e. default) values are outlined in Table 1. The altered parameter values from the Mill Creek calibration were used to parameterize the model and guide simulations in all other study catchments.

Performance of the calibrated model was assessed by comparing mean daily stream flow for each month, simulated by SWAT, to observed stream flow from the USGS stream gauge located on Mill Creek (Figure 1). The time period of climate and stream-flow data utilized during calibration runs was a 6-year period from 1 January 2001 to 31 December 2006. The initial year (2001) in the modelling procedure was used as a warm-up to allow for model stabilization. To assess overall model performance (1) the coefficient of determination (R^2) from a simple linear regression of measured monthly stream flow on SWAT-predicted flow, (2) Nash–Sutcliffe coefficient of efficiency (NSE) (Equation (1)), and (3) per cent bias (PBIAS) were used. The NSE is a goodness-of-fit method that assesses how well observed and predicted stream discharge data fit a 1:1 line with slope of 1 and intercept 0 (Nash and Sutcliffe, 1970). Values closer to 1 indicate better fit with the 1:1 line. Per cent bias is a measure of the tendency for simulated values, in this case SWAT-modelled discharge, to be larger or smaller than the observed values (Gupta *et al*., 1999). Both NSE and PBIAS were calculated using the hydroGOF package in R (R Development Core Team, 2008).

Table 1. Soil and Water Assessment Tool (SWAT) input parameters that were modified for model calibration using Mill Creek Catchment, Ohio, USA. The SCS (Soil Conservation Service) curve number is a model parameter that estimates surface runoff based on soil and land-use characteristics. The baseflow alpha factor is a model parameter that estimates the change in groundwater flow in response to recharge

Calibration variable	Original/ default value	Calibrated value
Surface runoff lag coefficient	4	2
Manning's n for tributary channels	0.014	0.044
Manning's n for main channel	0.014	0.050
SCS curve number	default	± 5-10%
Baseflow alpha factor	0.048	0.020

Statistical approach

Given the strong species–area relationships found in stream ecosystems (Angermeier and Schlosser, 1989) coupled with the differences in stream sizes, fish descriptors consisting of counts (e.g. richness, number of darter species, and number of intolerant species) were adjusted following the species–area equation developed by Preston (1960). Where necessary, variables were transformed before analysis to satisfy multivariate assumptions.

Principal component analysis (PCA) was used on (1) reach-scale environmental variables and (2) SWAT-modelled variables to generate two reduced sets of uncorrelated variables (Rencher, 1995). Those PCA axes that cumulatively explained 80% of the total variation were retained and subsequently used as predictor variables in multiple regression model building (Rencher, 1995). The total IBI scores and each of the suite of individual metrics (e.g. those representing species richness, assemblage composition, density, and fish condition) assessed within the IBI framework were used as response variables. Regression models were run using a mixed (e.g. forward and backward) stepwise linear regression procedure; a P-value threshold of 0.05 was used for addition and removal of explanatory variables during model building. Following model-building, a sequential Bonferroni correction for multiple tests was run (Holm, 1979; Rice, 1989). All statistical procedures were conducted using JMP 9.0 (SAS Industries, Cary, NC).

RESULTS

Fish assemblages and IBI

IBI scores for headwater sites ranged from 20–48 whereas scores for wading sites ranged from 32–48

(Table 2). In general, headwater streams from developed catchments received the lowest IBI scores, streams from forested catchments received slightly higher scores, and agricultural streams received the highest IBI scores. Stream reaches in more highly developed catchments were characterized by relatively few darter species, headwater species, sensitive species, and lithophilic species, and a dominance of tolerant fishes (Table 2). A relatively small proportion of piscivorous fish across 'wading' reaches contributed to low IBI scores as well. A high percentage of deformities, eroded fins, lesions, and tumours (DELT) among fish was also an influential parameter in low IBI scores in some cases.

Reach-scale assessments

Physical, habitat, and geomorphic conditions varied across study reaches (Table 3). Benthic sediment size distributions ranged from stream beds dominated by fine sediments ($D_{50} = 0.5$ mm; $D_{95} = 11$ mm) to reaches with large, irregular shaped rocks and small boulders ($D_{50} = 67$ mm; $D_{95} = 287$ mm). LWD was present in varying densities with the highest densities (0.18 and 0.17 pieces m^{-2}) found in small streams from agricultural catchments with forested, although laterally constricted, riparian zones. Conductivity ranged from 224 μS m^{-2} to 1368 μS m^{-2} and pH from 7.9 to 8.9. Both water quality parameters followed a general trend linked to land use; low values in forested reaches ranging to higher values in developed reaches.

Many of the reaches in more developed landscapes were undergoing (or had recently undergone) active geomorphic adjustment linked to channel degradation, channel widening, and

Table 2. Ohio fish-based Index of Biotic Integrity (IBI) metrics and scores (in parentheses) for the 16 study reaches in Ohio, USA. DELT anomalies are deformities, eroded fins, lesions, or tumours. Study streams are: INDR (Indian Run), SLTR (Slate Run), RSER (Rose Run), MFDC (Middle Fork Duck Creek), MNNF (Mann's Fork), SFBC (South Fork Bradford Creek), WFGC (West Fork Greenville Creek), MADR (Mad River), MLRF (Miller's Fork), WLHR (West Branch Little Hocking River), CLRC (Clear Creek), EFLM (East Fork Little Miami River), WWFC (West Wolf Creek), EFPC (East Fork Paint Creek), JONC (Jonathon Creek), and ALMC (Alum Creek)

	Reaches designated as 'headwater sites' under OH IBI protocol										
	INDR	SLTR	RSER	MFDC	MNNF	SFBC	WFGC	MADR	MLRF	*Mean*	*Standard deviation*
Drainage area (km^2)	39.2	6.0	4.3	51.0	20.5	17.0	48.2	29.0	51.2	29.6	18.7
Spp. richness	11 (3)	4 (1)	7 (3)	13 (3)	17 (5)	14 (5)	16 (3)	13 (3)	15 (3)	12.2	4.3
No. darter spp.	0 (1)	0 (1)	1 (3)	3 (3)	4 (5)	5 (5)	5 (5)	3 (3)	5 (5)	2.9	2.1
No. of headwater spp.	1 (1)	0 (1)	0 (1)	1(1)	2 (3)	1 (1)	2 (3)	4 (5)	2 (3)	1.6	1.3
No. of minnow spp.	5 (3)	2 (1)	3 (3)	3(1)	6 (3)	4 (3)	5 (3)	7 (5)	3 x(1)	3.8	2.2
No. of sensitive spp.	1 (1)	0 (1)	0 (1)	3(3)	2 (1)	3 (3)	5 (3)	3 (3)	3 (3)	2.2	1.6
% tolerant	71% (1)	71% (1)	46% (3)	54% (1)	48% (3)	47% (3)	52% (1)	28% (5)	13% (5)	47.8%	18.5%
% omnivores	27% (3)	2% (5)	24% (1)	7% (5)	20% (3)	17% (3)	10% (5)	13% (3)	1% (5)	13.4%	9.3%
% insectivores	7% (1)	30% (5)	47% (5)	35% (5)	43% (5)	39% (5)	50% (5)	61% (5)	86% (5)	44.2%	21.7%
% pioneering	60% (1)	70% (1)	86% (1)	54%(1)	43% (3)	38% (3)	26% (5)	38% (3)	12%(5)	47.4%	22.7%
No. of individuals 300 m^{-1}	292 (3)	478 (5)	1311 (5)	391 (3)	840 (5)	669 (5)	376 (3)	994 (5)	1194 (5)	727.2	376.5
No. of simple lithophilous spp.	2 (1)	1 (1)	1 (1)	5(3)	5 (3)	7 (5)	9 (5)	7 (5)	4(3)	4.6	2.8
% DELT anomalies	1.6% (1)	1.3% (1)	0% (5)	0% (5)	0.6% (3)	7.7% (1)	0.5% (3)	0.8% (3)	0% (5)	1.4%	2.4%
TOTAL IBI SCORE	20	24	32	34	42	42	44	48	48	37.6	10.6

	Reaches designated as 'wading sites' under OH IBI protocol								
	WLHR	CLRC	EFLM	WWFC	EFPC	JONC	ALMC	*Mean*	*Standard deviation*
Drainage area (km^2)	86.5	57.3	60.3	64.4	53.5	160.6	372.5	122.2	116.5
Spp. richness	17 (3)	21 (5)	21 (5)	15 (3)	20 (5)	20 (3)	27 (5)	20.4	3.4
No. darter spp.	3 (3)	3 (3)	4 (3)	5 (5)	3 (3)	4 (3)	4 (3)	3.7	0.8
No. of sunfish spp.	4 (5)	2 (3)	5 (5)	1 (1)	5 (5)	5 (5)	7 (5)	4.1	2.0
No. of sucker spp.	2 (3)	2 (3)	3 (5)	2 (3)	2 (3)	3 (3)	3 (3)	2.4	0.5
No. of intolerant spp.	2 (1)	7 (5)	5 (5)	2 (3)	4 (5)	5 (5)	6 (5)	4.4	1.9
% tolerant	56% (1)	11% (5)	43% (1)	22% (5)	46% (1)	18% (5)	35% (3)	32.9%	16.6%
% omnivores	19% (3)	4% (3)	21% (3)	12% (3)	33% (1)	13% (5)	12% (5)	16.2%	9.3%
% insectivores	69% (5)	64% (5)	34% (3)	78% (5)	62% (5)	43% (3)	61% (5)	58.7%	15.4%
% top carnivores	2.5% (3)	0.8% (1)	0.7% (1)	0% (1)	0.7% (1)	0.5% (1)	2.2% (3)	1.1%	0.9%
No. of individuals 300 m^{-1}	162 (1)	309 (3)	1176 (5)	669 (5)	523 (3)	830 (5)	376 (3)	577.9	346.1
% simple lithophilous	10% (1)	31% (3)	23% (3)	31% (3)	11% (1)	35% (5)	43% (5)	26.1%	12.4%
% DELT anomalies	0.6% (3)	4% (1)	15% (1)	0% (5)	0.2% (3)	0% (5)	1% (3)	3.0%	5.4%
TOTAL IBI SCORE	32	40	40	42	46	48	48	42.3	5.7

Table 3. Descriptive statistics for reach-scale environmental variables and SWAT-modelled catchment-scale variables from the 16 study reaches in Ohio, USA. Catchment-scale variables were derived from mean monthly values from SWAT simulations (2002–2006). Entrenchment, width-to-depth, and incision ratios are measures of floodplain connectivity. A Rapid Geomorphic Assessment (RGA) was used to evaluate reach geomorphic condition and the Ohio Qualitative Habitat Evaluation Index (QHEI) was used to evaluate instream, bank, and riparian habitat quality. LWD is large woody debris (>1 m × 0.1 m)

	Minimum	Median	Maximum	Mean	SD
Reach-scale environmental variables					
Mean bankfull depth (m)	0.25	0.38	0.59	0.40	0.09
Max bankfull depth (m)	0.61	1.43	1.73	1.27	0.34
Entrenchment ratio*	1.10	2.25	16.60	4.00	4.20
Width-to-depth ratio**	15.50	22.75	40.00	25.03	6.97
Incision ratio***	1.20	1.50	2.70	1.60	0.40
D_{50} (mm)	0.50	25.50	67.00	24.53	14.73
D_{95} (mm)	11.00	81.00	287.00	105.60	79.10
LWD (no. m^{-2})	0.02	0.08	0.18	0.08	0.04
pH	7.90	8.30	8.90	8.30	0.30
Conductivity (μS m^{-2})	224.00	650.00	1368.00	721.30	299.90
RGA score (out of 80)	42.00	55.50	66.00	55.50	6.40
QHEI score (out of 100)	51.00	67.25	84.00	68.80	9.30
SWAT-modelled watershed processes					
FLOW (m^3 s^{-1})	0.05	0.80	4.25	1.06	1.12
MAX_FLOW (m^3 s^{-1})	0.07	1.17	5.59	1.55	1.55
MIN_FLOW (m^3 s^{-1})	0.02	0.31	2.51	0.52	0.68
SD_FLOW (m^3 s^{-1})	0.03	0.64	3.29	0.79	0.81
SED_YLD (t km^{-2})	0.84	13.72	63.55	14.78	15.18
MAX_YLD (t km^{-2})	1.80	21.19	128.21	26.37	30.87
SED_CONC (mg L^{-1})	6.20	136.94	551.93	137.77	134.66
MAX_CONC (mg L^{-1})	9.83	188.26	784.75	209.14	210.83
TOTAL_N (kg km^{-2})	38.77	240.34	341.29	210.78	96.69
TOTAL_P (kg km^{-2})	1.35	13.34	38.94	15.53	10.78

*Entrenchment ratios <1.4 indicate highly entrenched streams with little or no floodplain development, 1.4–2.2 indicate moderate degree of entrenchment, and >2.2 indicate little or no entrenchment with well-developed floodplains.
**Width-to-depth ratio is a measure independent of stream size, with larger values typically corresponding to increasing levels of disturbance.
***Incision ratios ~1 indicate channels that are not incised and are actively connected to their floodplains; values >1 indicate increasing levels of channel degradation and decreasing floodplain connectivity.

planform change. The magnitude of these adjustment processes was reflected in lower RGA scores for streams in developed catchments. Aggradation and change in planform dominated adjustment processes and drove geomorphic condition scores at reaches in agricultural catchments. Although several reaches were severely entrenched (entrenchment ratio <1.4), in general study streams showed little entrenchment.

The lowest QHEI score (MADR, 51) was based largely on low scores for substrate characteristics (e.g. dominated by smaller sediment sizes), lack of functional habitat (e.g. few large boulders in riffles or pieces of LWD in pools), and poor pool–riffle development. The highest QHEI score (MLRF, 84) was due in large part to a heterogeneous mixture of large and small substrates, deep pools with functional habitat, and well-developed flow habitats (e.g. pools, riffles, runs).

SWAT modelling

Calibration of the SWAT model for Mill Creek Catchment (MCC) reached acceptable levels of accuracy according to model performance criteria. A linear regression of predicted mean discharge for each month against observed mean monthly discharge from 1 January 2002–31 December 2006 resulted in a relatively strong fit ($R^2 = 0.71$). The Nash–Sutcliffe Coefficient of Efficiency also indicated a close agreement between observed and predicted discharge for MCC over this same timeframe (NSE = 0.77). The PBIAS estimate was +6.8, indicating that the model only slightly underestimated mean monthly stream discharge when compared with observed data over the simulation period (Figure 2). The values for all model performance criteria compared favourably with the results reported in a range of other SWAT studies and fell within the 'very good' range according to the model performance ratings outlined in Moriasi *et al.* (2007).

Following calibration, simulations were run for each catchment using the calibrated model parameters. Modelling results illustrated several key elements regarding contemporary catchment-scale processes across the study area. In general, mean and maximum discharges were linked to stream size and drainage area. Across all catchments, peak

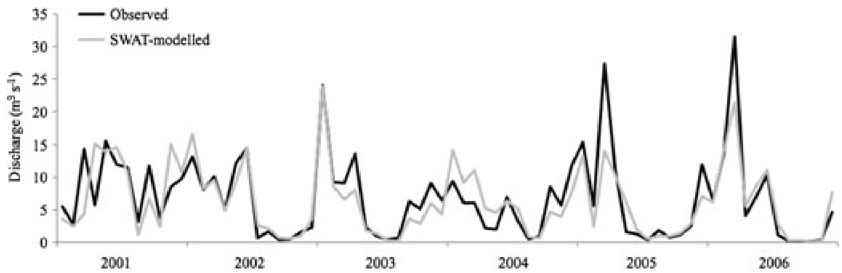

Figure 2. Hydrographs for observed and modelled (Soil and Water Assessment Tool – SWAT) mean monthly discharge (2001–2006) for Mill Creek Catchment (MCC). The year 2001 was used as a 'warm-up' during the calibration procedure.

flows occurred during the spring and early summer with a second, smaller peak during winter, and low flows occurred during late summer and autumn.

Sediment and nutrient outputs were variable (Table 3). Sediment yields were generally higher from predominantly agricultural catchments, especially from those located in areas with steep topography. Mean sediment concentration in streams was highly variable but showed a trend toward elevated concentrations in streams from agricultural landscapes. Total nitrogen inputs were substantially greater in agricultural catchments. In contrast, model results from developed catchments and heavily forested catchments showed reduced nitrogen yields. Similar to nitrogen, the magnitude of phosphorus yields was highest in agricultural landscapes, intermediate in developed catchments, and lowest in heavily forested areas.

PCA and regression analysis

In total, 23 environmental variables from reach-scale field measurements ($n = 13$) and catchment-modelling results ($n = 10$) were included in the PCA analysis. The first four axes from the reach dataset (REACHPC1 – REACHPC4) were retained. These axes cumulatively explained 82% of the variation and demonstrated the major patterns and gradients of environmental variation in reach-scale factors across study sites (Table 4(a)). The first two axes from the SWAT dataset (SWATPC1 and SWATPC2) were retained as they cumulatively accounted for over 85% of the variance in the SWAT dataset. We also elected to retain SWATPC3 (eigenvalue = 0.86) as it represented nutrient yield variables that were not influential in the other PCs (Table 4(b)).

The four retained REACHPC axes accounted for 37% (REACHPC1), 25% (REACHPC2), 11.5% (REACHPC3), and 9.2% (REACHPC4) of the variance in the reach-scale environmental data matrix. The first PC included a mix of positive and negative loadings with D_{95} ($r^2 = 0.18$; + relationship), conductivity ($r^2 = 0.14$; +), maximum bankfull depth ($r^2 = 0.15$; –), mean bankfull depth ($r^2 = 0.13$; –), and RGA ($r^2 = 0.13$; –) loading heavily on the axis. Positive loadings of QHEI ($r^2 = 0.23$) and entrenchment ratio ($r^2 = 0.22$), and a negative loading of incision ratio ($r^2 = 0.25$) influenced REACHPC2. The third PCA axis from the reach dataset was largely represented by LWD, which loaded negatively and was highly correlated with the axis ($r^2 = 0.58$). The fourth reach-scale PCA axis was positively correlated with width-to-depth ratio ($r^2 = 0.22$) and negatively with pH ($r^2 = 0.20$). REACHPC5 through REACHPC8, though not included in analysis, combined to account for almost 15% of the remaining variance in the dataset.

The three retained SWATPC axes accounted for 51.6% (SWATPC1), 34.1% (SWATPC2), and 8.6% (SWATPC3) of the variance in the SWAT-modelled catchment-scale sediment, nutrient, and stream-flow variables. SWATPC1 consisted of all positive loadings with sediment yield and sediment concentration variables being the most influential variables on this axis. Stream-flow variables loaded positively onto SWATPC2 and were the most highly influential variables on that axis (Table 4(b)). Although the first two SWATPC axes accounted for over 85% of the variance in the SWAT dataset, we decided to retain SWATPC3 because it represented nutrient processes (nitrogen ($r^2 = 0.54$) and phosphorus ($r^2 = 0.21$) input variables were highly correlated with this axis), which were largely unaccounted for in the other PCs.

Using the retained principal components as predictor variables and (1) the individual IBI scoring metrics and (2) the total IBI score as response variables, six significant models were generated, of which four were retained after a sequential Bonferroni adjustment (Table 5). SWATPC2 drove the majority of significant models (three of four), where it explained 60–63% of the variation in total T5

Table 4. Principal components (PCs) retained for use in regression models, including eigenvalues and percentage variance captured by the principal components, along with each component's loading and the proportion of variance (r^2) each variable shared with its respective PCA axis. (a) PCs from reach-scale environmental variables and (b) PCs from SWAT-modelled catchment-scale process variables

(a)

REACHPC1	Loading	r^2	**REACHPC2**	Loading	r^2	**REACHPC3**	Loading	r^2	**REACHPC4**	Loading	r^2
D_{95} (mm)	0.89	0.18	QHEI	0.82	0.23	Mean bankfull depth (m)	0.40	0.11	Width:Depth ratio	0.50	0.22
Conductivity (μS m^{-2})	0.79	0.14	Entrenchment ratio	0.81	0.22	Max bankfull depth (m)	0.32	0.08	QHEI	0.39	0.14
pH	0.63	0.09	D_{50} (mm)	0.62	0.13	D_{50} (mm)	0.30	0.07	Incision ratio	0.33	0.10
D_{50} (mm)	0.58	0.08	RGA	0.38	0.05	Width:Depth ratio	0.26	0.05	D_{95} (mm)	0.30	0.08
Width:Depth ratio	0.49	0.05	pH	0.36	0.04	D_{95} (mm)	0.21	0.03	RGA	0.27	0.07
LWD (no. m^{-2})	−0.03	0.00	Max bankfull depth (m)	0.34	0.04	QHEI	0.06	0.00	LWD (no. m^{-2})	0.23	0.05
Incision ratio	−0.10	0.00	Conductivity (μS m^{-2})	0.25	0.02	Conductivity (μS m^{-2})	−0.06	0.00	D_{50} (mm)	0.17	0.03
QHEI	−0.21	0.01	D_{95} (mm)	0.14	0.01	Incision ratio	−0.06	0.00	Max bankfull depth (m)	0.03	0.00
Entrenchment ratio	−0.40	0.04	LWD (no. m^{-2})	0.13	0.01	Entrenchment ratio	−0.10	0.01	Entrenchment ratio	−0.13	0.01
RGA	−0.76	0.13	Width:Depth ratio	−0.04	0.00	pH	−0.18	0.02	Mean bankfull depth (m)	−0.24	0.05
Mean bankfull depth (m)	−0.77	0.13	Mean bankfull depth (m)	−0.13	0.01	RGA	−0.24	0.04	Conductivity (μS m^{-2})	−0.25	0.06
Max bankfull depth (m)	−0.81	0.15	Incision ratio	−0.86	0.25	LWD (no. m^{-2})	−0.90	0.58	pH	−0.47	0.20
Eigenvalue	4.43			2.95			1.38			1.10	
Variance explained	36.9%			24.6%			11.5%			9.2%	

(b)

SWATPC1	Loading	r^2	**SWATPC2**	Loading	r^2	**SWATPC3**	Loading	r^2
MAX SED_YLD (t km^{-2})	0.87	0.15	MIN_FLOW (m^3 s^{-1})	0.82	0.20	TOTAL_N (kg km^{-2})	0.68	0.54
SED_YLD (t km^{-2})	0.86	0.14	FLOW (m^3 s^{-1})	0.76	0.17	TOTAL_P (kg km^{-2})	0.42	0.21
SED_CONC (mg L^{-1})	0.85	0.14	MAX_FLOW (m^3 s^{-1})	0.72	0.15	SD_FLOW (m^3 s^{-1})	0.08	0.01
MAX SED_CONC (mg L^{-1})	0.84	0.14	SD_FLOW (m^3 s^{-1})	0.69	0.14	FLOW (m^3 s^{-1})	0.08	0.01
SD_FLOW (m^3 s^{-1})	0.71	0.10	SED_CONC (mg L^{-1})	−0.35	0.04	MAX_FLOW (m^3 s^{-1})	0.06	0.00
MAX_FLOW (m^3 s^{-1})	0.68	0.09	MAX SED_YLD (t km^{-2})	−0.42	0.05	MIN_FLOW (m^3 s^{-1})	0.03	0.00
FLOW (m^3 s^{-1})	0.65	0.08	MAX SED_CONC (mg L^{-1})	−0.46	0.06	MAX SED_YLD (t km^{-2})	−0.15	0.02
TOTAL_P (kg km^{-2})	0.58	0.06	SED_YLD (t km^{-2})	−0.46	0.06	SED_YLD (t km^{-2})	−0.15	0.03
MIN_FLOW (m^3 s^{-1})	0.56	0.06	TOTAL_N (kg km^{-2})	−0.47	0.06	MAX SED_CONC (mg L^{-1})	−0.20	0.04
TOTAL_N (kg km^{-2})	0.42	0.03	TOTAL_P (kg km^{-2})	−0.49	0.07	SED_CONC (mg L^{-1})	−0.34	0.13
Eigenvalue	5.16			3.41			0.86	
Variance explained	51.6%			34.1%			8.6%	

Table 5. Regression models generated from REACH and SWAT principal component predictor variables and fish Index of Biotic Integrity (IBI) response variables. All models significant at $\alpha = 0.05$ following sequential Bonferroni corrections

Assemblage metric	Variable	Coefficient	R^2	F
Species richness	Intercept	15.01	0.75	17.64
	SWATPC2	1.58	0.63	-
	REACHPC3	1.23	0.12	-
No. of sensitive or intolerant spp.	Intercept	2.83	0.74	16.81
	SWATPC2	0.17	0.61	-
	REACHPC3	0.15	0.13	-
No. of darter spp.	Intercept	2.90	0.74	16.64
	SWATPC2	0.16	0.60	-
	REACHPC3	0.14	0.14	-
IBI score	Intercept	70451.5	0.57	8.67
	SWATPC1	9395.5	0.34	-
	SWATPC3	18670.0	0.23	-

species richness and assemblage composition (e.g. species richness for darters and for sensitive/intolerant species). In these models, REACHPC3 accounted for 12–14% additional variation. SWATPC1 and SWATPC3 were the explanatory variables in the model that best predicted overall IBI scores.

DISCUSSION

In this study, a process-based catchment-modelling approach using SWAT emerged as a significant predictor of fish assemblage richness and composition in streams draining catchments with diverse land cover and a gradient of human disturbance on the landscape. The relative importance of dynamic broad-scale environmental factors, represented in this study by SWAT-modelled hydrology, sediment, and nutrient parameters, corroborates findings from other studies that have also suggested that catchment-scale environmental factors may have greater influence than local-scale factors on stream fish assemblages, especially in human-dominated landscapes (Wang *et al.*, 2000; Snyder *et al.*, 2003; Kautza and Sullivan, unpublished data). The relative importance of broad-scale catchment processes in this study support the use of SWAT as a potential tool to enhance field-based assessments of stream condition in relation to fish assemblages. Given that catchment processes regulate stream physicochemical properties, the strength of the results also suggests that SWAT may be a useful tool for stream fish conservation applications.

Reach-scale environmental factors

Reach-scale environmental features represent a high-resolution profile of the quantity, quality, and complexity of physical habitat and chemical conditions in a stream. These localized characteristics can be important influences on fish assemblage structure and composition (Berkman and Rabeni, 1987; Hrodey *et al.*, 2009).

REACHPCs explained relatively small amounts of variation in the environment–fish models. REACHPC3 accounted for some variation in species richness ($R^2 = 0.12$), richness of darters ($R^2 = 0.14$), and sensitive or intolerant species richness ($R^2 = 0.13$). Density of LWD was the most influential variable in REACHPC3. Wood is an important contribution of allochthonous energy to streams and is a critical habitat feature for fish and other aquatic biota, largely because it contributes to habitat complexity (Dolloff and Warren, 2003; Gurnell *et al.*, 2005). Wood may be particularly important in enhancing habitat heterogeneity in low-gradient streams and in those with a predominance of fine sediments (Wallace and Benke, 1984), such as many streams found in the study area (D_{50}, $\bar{x} = 24.5$ mm). Furthermore, because of the large size (relative to other coarse particulate matter) and slow rate of decomposition, LWD traps and retains other forms of organic matter and inorganic sediments (Bilby and Ward, 1991), potentially affecting fish assemblages. Shields *et al.* (2008), for instance, observed a negative relationship between the amount of organic carbon sources present in a reach (e.g. organic detritus trapped in LWD) and a fish IBI.

The links between water quality and fish are also known relative to both individual fish physiological responses (Bonga, 1997) and assemblage composition (Taylor *et al.*, 1993; Maret *et al.*, 1997; Miserendino *et al.*, 2011). For instance, episodes of low pH (<5) caused extensive mortality of acid insensitive species (e.g. blacknose dace *Rhinichthys obtusus*) in Pennsylvania streams (Baker *et al.*, 1996). Conductivity can be correlated with assemblage composition and usually leads to decreases in richness and assemblage density at high levels of specific conductance (Kimmel and Argent, 2010). However, in this study, conductivity and pH did not emerge as influential variables on fish assemblage characteristics. Because only a narrow range of pH was observed across study reaches (7.9–8.9), this parameter was expected to have minimal influences on fish assemblages. Although a greater range in conductivity was found across study sites (224–1368 μS m^{-2}), Kimmel and Argent (2010) found no substantial assemblage impairment until conductivity reached 3000 μS m^{-2}.

Stream rapid assessment protocols are aimed at capturing habitat heterogeneity across a reach (Barbour *et al*., 1999) and fish assemblage characteristics are often highly correlated with the results of these assessments (Sullivan and Watzin, 2008; D'Ambrosio *et al*., 2009). In particular, some investigators have observed a positive relationship between a QHEI and fish IBI scores in streams in the Midwest, USA (Sullivan *et al*., 2004; Hrodey *et al*., 2009). However, other studies have found that reach-level physical habitat characteristics do not explain substantial variation in IBI scores (Shields *et al*., 1995). Although the QHEI scores in the present study were not influential either for overall IBI score or for other fish descriptors, we anticipate that had the reaches spanned a greater range of scores (<51 to >84), their relative importance to the fish models would probably have been greater. In addition, many studies that have observed strong relationships between fish and reach-scale factors have focused on streams in agricultural catchments (Sullivan *et al*., 2004; Rowe *et al*., 2009) or in relatively undisturbed landscapes (Wang *et al*., 2003), whereas the catchments used in this study spanned a range of land-use types, including highly developed catchments and those containing a complex mixture of land-cover classes.

Geomorphic factors, such as substrate composition (Berkman and Rabeni, 1987; Walters *et al*., 2003b), geomorphic adjustment processes (Sullivan *et al*., 2006), and channel morphology (Rowe *et al*., 2009) have been found to influence stream fish assemblage structure and composition. In contrast, Chessman *et al*. (2006) found no significant relationship between geomorphic condition and local assemblage composition. Although in the current study, geomorphic characteristics measured at the reach scale had only minimal influence on fish assemblage characteristics, nonetheless we are confident that geomorphic–fish relationships exist. Kautza and Sullivan (unpublished data) found that RGA scores and median sediment diameter were relatively strong predictors of assemblage richness and diversity in streams of the same region. In the present study, it is likely that reach-scale geomorphic influences were overshadowed by SWAT-modelled variables related to hydrology and sediment, which provide the mechanism by which local-scale features are linked to broader-scale processes.

SWAT-modelled catchment-scale processes

Catchment-scale environmental processes are the product of physical factors (e.g. geology and topography), climate, and land cover that act in concert to shape hydrological and sediment regimes (Montgomery, 1999). Given the hierarchical spatial relationships thought to exist in catchments, broad, catchment-scale processes are linked to smaller-scale factors and constrain habitat, geomorphic, and water quality characteristics at the reach scale (Frissell *et al*., 1986; Poff, 1997; Burcher *et al*., 2007).

Changes in land use and land cover within a catchment can significantly alter catchment-scale processes (Allan, 2004). For example, sediment yields from forested landscapes are generally a fraction of those from landscapes exhibiting greater degrees of human disturbance (Sutherland *et al*., 2002), which was a pattern also observed in the present study. Hydrological regimes and stream flow are commonly altered through stream channelization, routing of storm runoff, and creation of impervious surfaces (Konrad and Booth, 2005; Lau *et al*., 2006; Blann *et al*., 2009). Alterations in hydrology and sediment can have profound changes in channel morphology (Rosgen, 1994), which can trigger a series of channel geomorphic adjustments (Schumm *et al*., 1984).

The composite suite of stream discharge variables expressed in SWATPC2 was the single best predictor for three of the significant environment–fish models (Figure 3). In undisturbed systems, stream flow and discharge regimes (i.e. minimum, mean, and maximum discharge) reflect physical constructs of the stream ecosystem, including drainage area,

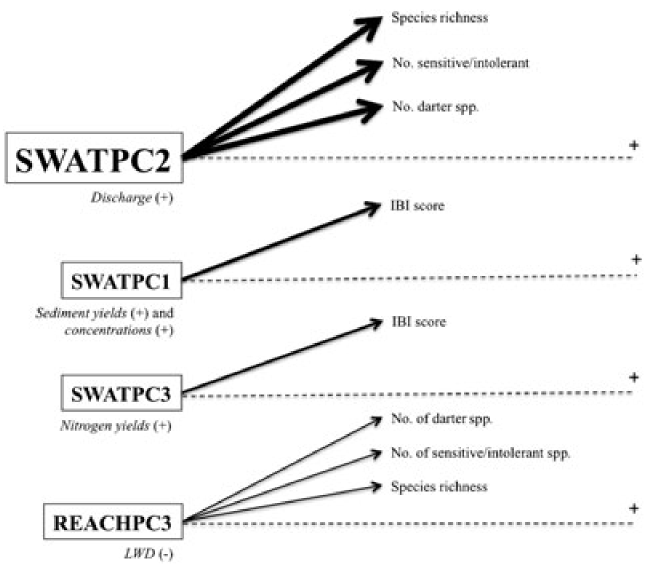

Figure 3. Key environment–fish assemblage relationships from principal component analyses (PCA) and regression models. Thicker arrows represent greater R^2 values. '+' or '-' represents direction of relationship.

stream order, and other correlates of stream size, such as depth and width (Hirsch, 1982). Many researchers have found a positive relationship between drainage area and discharge with fish species richness (Oberdorff *et al*., 1995; Matthews and Robison, 1998). Consistent with these results, a positive relationship between species richness and SWAT-modelled discharge characteristics was observed in this study (Figure 3). In addition, stream discharge regimes have been associated with presence/absence of various fish species based on their adaptations to specific flow patterns (Poff and Allan, 1995). Taxon-specific flow relationships may account for the positive correlations between discharge and darter species richness as well as richness of sensitive/intolerant species (e.g. redside dace (*Clinostomus elongates*); roseyface shiner (*Notropis rubellus*); and brindled madtom (*Noturus miurus*)) observed in this study.

Over half of the variation in fish IBI scores across the study reaches was accounted for by the combined influence of SWATPC1 ($R^2 = 0.34$) and SWATPC3 ($R^2 = 0.23$), indicating that sediment yield, sediment concentration, and nitrogen input all influenced IBI scores. Elevated sediment yields to streams and subsequent downstream transport can have substantial effects on geomorphic processes (e.g. aggradation), benthic habitat heterogeneity (e.g. embeddedness), and turbidity, with concurrent effects on fish (Berkman and Rabeni, 1987; Lenat and Crawford, 1994; Sullivan and Watzin, 2010). Sutherland *et al*. (2002) found evidence that sediment was linked to fish assemblage structure, particularly the relative abundances of lithophilic spawners, which were adversely influenced by high magnitudes of fine sediment. Marshall *et al*. (2008) found that as agricultural practices in a catchment changed, and land was taken out of row-crop production, tolerant fishes became less prevalent and overall IBI scores increased. In contrast, the results from the present study showed that sediment yields were positively correlated with IBI, a result potentially explained by the history of channelization in the region that led to sediment-limited streams that are now aggrading, restabilizing, and redeveloping the benthic habitat heterogeneity necessary to support a diversity of fish spawning and feeding guilds.

Nutrient additions to streams from across the landscape can have localized effects as well, from elevated instream primary productivity to eutrophication of receiving water bodies (Carpenter *et al*., 1998; Black *et al*., 2011). Results from the present study indicated that nitrogen inputs from the catchment had a positive effect on fish IBI. Elevated instream primary productivity from nitrogen inputs may create a bottom-up effect by promoting secondary production of benthic macroinvertebrates (Power, 1992), which in turn provide food sources for many stream fishes. Excessive nutrients, particularly nitrogen, can have negative consequences for lotic ecosystems by homogenizing periphyton communities leading to declines in consumer biodiversity (Griffith *et al*., 2009). However, the SWAT-modelled nitrogen values were not considered excessive as they fell within the range observed in other OH catchments (Reutter, 2003).

CONSERVATION IMPLICATIONS

Although the QHEI and other local-scale influences did not emerge as particularly significant in this study, links between field-based assessments and fish assemblages are widely documented. Given the observed strength of landscape–fish relationships, coupled with the growing understanding of the importance of broad-scale variables to aquatic biota (Allan, 2004; Johnson *et al*., 2007; Johnson and Host, 2010), SWAT may represent a method to enhance the predictive power of reach-level, field-based stream assessments. The incorporation of catchment modelling into stream assessment protocols may also help to explain additional variation in fish assemblage patterns not fully accounted for by field-based evaluations, as suggested by Cianfrani *et al*. (2010) and supported by findings in this study.

Additional advantages of modelling techniques include relatively low cost, easy access to available spatial data, and minimal practical constraints (e.g. no field crew, travel, or field equipment). Catchment modelling approaches could also be used as a screening tool to target streams or stream segments for subsequent field surveys or to aid in predicting critical areas for species of special concern (Dauwalter and Rahel, 2008). This application could be particularly useful for highly sensitive areas, inaccessible catchments, and biodiversity hotspots. Ultimately, we expect that long-term conservation of stream fishes will be more successful with incorporation of models such as SWAT that can accommodate changes in the catchment, including climate and hydrological shifts as well as disturbance-propagated erosion and runoff. For example, altering the proportions and characteristics of land-use and land-cover inputs in SWAT permits simulating changes to catchment-scale processes (e.g. stream flow and sediment and nutrient yields) under future scenarios (e.g. a downward trend of fish species richness and overall IBI scores in catchments predicted to undergo increasing urban development). Overall, these results suggest that SWAT may increase ecological understanding of process-based impacts and their net cumulative effects on stream biota and provide a powerful tool to enhance current stream assessments and to aid in monitoring, managing, and conserving stream fish assemblages.

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