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Researchers conducting water quality tests in the lower Pigeon River

ABSTRACT

The Pigeon River drains a 16,765-ha agricultural watershed in western Ottawa County, Michigan and discharges into south-central Lake Michigan. Extensive areas of wetlands in the upper watershed were drained in the 1920s, causing significantly altered hydrology characterized by flashy discharges during storms and periods of snowmelt. We studied stream chemistry and hydrology for a four-year period between September, 1996, and October, 2000, to determine water quality status, to estimate annual nutrient exports, and to evaluate the effects of different seasonal flow types. Results of our study confirmed that the upper reaches of the Pigeon River experience chronically degraded water quality, with contributions from both nonpoint and point sources. As a result, the watershed has high annual rates of nutrient export (approximately 10.8 kg ha^{-1} *inorganic N and 0.25 kg* ha^{-1} PO_4*-P). With the influx of groundwater, change in land use to forest, and development of natural stream channel characteristics in the lower mainstream, water quality at baseflow in this section of the Pigeon River improves to the point where coldwater fish populations should persist. Inputs of degraded water during high flows, however, produce periods of environmental stress and the fish population in the lower Pigeon includes only a low number of pollution-tolerant, warmwater species. Large summer storms are biologically stressful because of increased temperatures and reduced dissolved oxygen levels, while spring storms and snowmelt contribute substantially to total nutrient and suspended solids exports. Efforts to improve water quality in this and similar agricultural watersheds need to emphasize major reductions in nonpoint source inputs through substantial improvements in land and water management practices. Wetland restoration and implementation of other stormwater retention practices in such watersheds also are required to reverse the acute impacts of high stormwater discharges caused by past drainage and stream channelization.*

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INTRODUCTION

Agricultural nonpoint source pollution often is manifested both in the chronic degradation of water quality (Omernik 1976; 1977) and in the more acute biologically harmful effects that may occur during storm flows (Rimer et al. 1978; Graczyk and Sonzogni 1991; Greb and Graczyk 1995). Drainage and stream channelization in agricultural watersheds have increased peak discharges (Beaulac and Reckhow 1982), exacerbating these water quality problems. Water quality degradation not only adversely impacts stream biota (Karr et al. 1985), but also results in elevated export of nutrients and sediments to water bodies downstream (Gburek and Heald 1974; Beaulac and Reckhow 1982; David et al. 1997). For example, nutrient loading from tributaries draining agricultural watersheds has contributed to eutrophication in Delaware and Chesapeake Bays, Lake Okeechobee, the Everglades, and the Great Lakes (Daniel et al. 1998).

In the Great Lakes region, larger tributaries have been intensively sampled to determine nutrient export rates, whereas contaminant loadings from most small ungaged tributaries are unknown (Robertson 1997). One such small Great Lake tributary is the Pigeon River, which drains a 16,765-ha watershed in Ottawa County, Michigan, and discharges into Pigeon Lake just above its ultimate outlet to Lake Michigan (Figure 1). The Pigeon is a low-gradient stream (0.9 m km^{-1}), typical of most tributaries draining into the southern two-thirds of Lake Michigan (Robertson 1997). Presettlement ecosystems in this watershed included hardwood forests in the uplands surrounding large areas of wetlands in the lowlands (Comer et al. 1995). Following land clearing for agriculture, an extensive county drain network was constructed during the early 1920s to drain the major wetland areas of the watershed. Currently, approximately 49% of the watershed is agricultural, largely at the headwaters and in the central portion of the watershed. Another 36% of the watershed is forested, primarily in the western third of the watershed. As a result of drainage, less than 1% of the watershed is now occupied by wetlands.

The lower reaches of the Pigeon River are designated as a coldwater fishery by the Michigan Department of Natural Resources. As recently as 1969, stream surveys found a trout population comprising multiple year classes in the Pigeon River. By 1989, however, biological surveys of the river indicated that reduced water quality had severely impacted the biotic community of the Pigeon River. Water quality problems identified at this time included sedimentation, nutrient loading, elevated temperatures, low flows during the summer, and low dissolved oxygen levels (Pigeon River Watershed Advisory Committee 1997). Recent surveys have found only a low number of pollution-tolerant warmwater fish species, with a seasonal presence of migratory salmonids (Wiley and Seelbach 1998). Because of poor fish and macroinvertebrate communities, nutrient enrichment, and nuisance algae growths, the Pigeon River was placed on Michigan's Clean Water Act Section 303(d) list as a water body that will

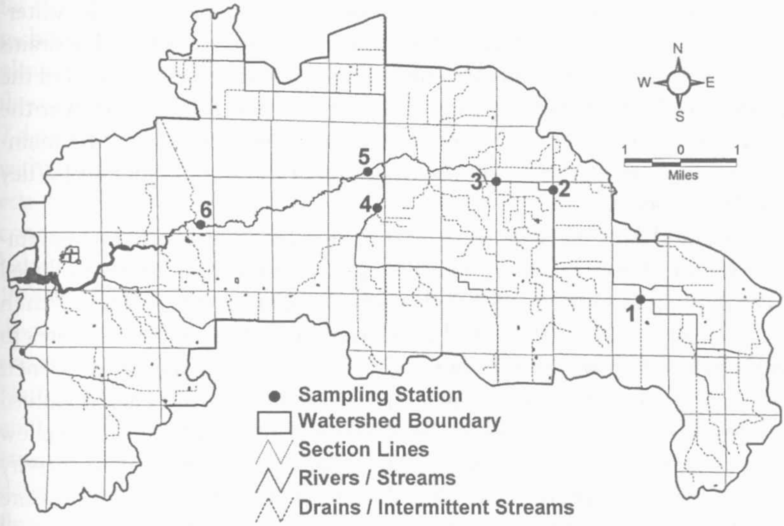


FIGURE 1. Pigeon River watershed in Ottawa County, Michigan. Stations 1, 2, 3, and 4 are located on the channelized drains of the headwaters and tributaries, and Stations 5 and 6 are located in the intact forested floodplain where the lower mainstream is designated as a coldwater fishery section.

not attain water quality standards with technology-based controls (Creal and Wuycheck 1998).

Beginning in September, 1996, we undertook a water quality study of the Pigeon River in support of the planning and implementation phases of the Pigeon River Watershed Project. While there was a general understanding of water quality problems in the Pigeon River based on the results of previous biological surveys and intermittent monitoring studies, there was a lack of consistent and continuous water quality data to identify specific problem areas within the watershed, and to provide a focus for proposed watershed restoration and management efforts. The objectives of our study were to quantify the spatial and seasonal water quality conditions in the watershed, to estimate annual nutrient and suspended solids exports from the watershed, and to identify critical periods when acute water quality problems might occur that would hinder the maintenance of coldwater fish populations in the Pigeon River.

METHODS

We established sampling stations at six locations within the Pigeon River watershed (Figure 1). Stations 1, 2, and 3 are located on county drains that now form the headwaters of the Pigeon River. Station 3 also is downstream from a major point source discharge of food-processing wastewater within the watershed. Station 4 is located on Sawyer Creek, a channelized tributary that drains an intensively agricultural subwatershed. Station 5 is at the upper end of the designated coldwater fishery section of the stream, and Station 6 is near the lower end of this section above Lake Michigan. Below Station 3, the mainstream enters a well-defined valley with an intact forested floodplain (Wiley and Seelbach 1998).

We collected data and samples at least once each month between September, 1996 and October, 2000. The first year's monitoring efforts included weekly sampling from May 7, 1997 through October 13, 1997. From March through August in 1998, 1999, and 2000, we sampled on additional dates to target high flows following a minimum 2.5-cm, 24-h rainfall or major snowmelt period. On all sampling dates, we measured water temperatures and dissolved oxygen levels using a YSI Model 55 dissolved oxygen meter (YSI, Inc., Yellow Springs, OH), and collected duplicate 125-mL samples for pH and conductivity analyses. We also collected one 300-mL sample at each station to measure dissolved oxygen levels using the Winkler titration method. We determined discharge by measuring stream velocities (at 60% depth) at intervals across the stream using a Teledyne Gurley Model 625 Pygmy water current meter (Teledyne Gurley, Troy, NY). We also recorded stage heights from staff gages and permanent reference points, and used these data to estimate discharge during large storms from rating curves.

We performed conductivity and pH analyses and dissolved oxygen titrations immediately upon return from the field. We measured conductivity with a YSI Model 35 conductance meter (YSI, Inc., Yellow Springs, OH), determined pH with a Cole-Parmer Series 5986 pH meter (Cole-Parmer Instrument Co., Vernon Hills, IL), and completed titrations with a Hach digital titrator (Hach Co., Loveland CO). Mean values for each sample were based on a minimum of two determinations. Repeated measurements errors, based on 100% replication, were 0.7% for conductivity, 0.8% for pH, and 1.1% for dissolved oxygen. At least once each month, and for all sampled storm events, we collected a one-liter water sample at each station for constituent analyses (NH_4-N, NO_3-N, PO_4-P, total suspended solids). We used the following standard protocols (APHA 1992) for these analyses: NO_3-N (4110-ion chromatography), NH_4-N (4500-NH3(F)-ion selective electrode), PO_4-P (soluble reactive phosphate, 4500-P(E)-ascorbic acid), and suspended solids (2540(D)-gravimetric). We followed a standard laboratory quality assurance program for this project which included the analysis of one matrix spike and matrix-spiked duplicate for each sampling event in addition to the daily analysis of blanks and calibration standards. Quality assurance acceptance criteria were ± 20% for precision and accuracy for project samples and ± 10% for calibration standards.

Data were manipulated and analyzed using microcomputer software packages (RBASE, EXCEL, SYSTAT). We estimated annual constituent exports for the watershed with data from Station 6. We used a modified integration technique (Preston et al. 1989) by subjectively weighting each discrete sampling period by an appropriate number of days based on our observations of high flow durations in this watershed. Snowmelt periods were assigned a weight of 7 days each, spring and summer storms were assigned a weight of 3 days each, with intervening periods of normal flows weighted accordingly. We also estimated constituent exports using discharge x time-weighted mean annual concentrations and annual runoff estimates from the Thornthwaite water balance equation (Mather 1978). This averaging technique (Preston et al. 1989) should be less subject to bias that could occur with integration of discontinuous discharge measurements. Mean monthly temperature and precipitation data for the Thornthwaite calculations were obtained from the National Weather Service station in Grand Rapids, Michigan. Among-station analyses of variance were conducted with sampling stations considered a fixed effect and by treating sampling dates as a block effect. We treated sampling dates as replications for within-station analyses of variance comparing seasonal flow types. We used Tukey's multiple comparison test to judge significant differences among sample means (Steel and Torrie 1980).

RESULTS AND DISCUSSION

Spatial Trends in Water Quality

Noticeable trends in water quality were evident from Station 1 in the headwaters to Station 6 in the lower reaches of the watershed (Table 1). Nitrate, NH_4-N, PO_4-P, and suspended solids concentrations at Stations 1, 2 and 4 were related to agricultural nonpoint sources in the upper watershed (e.g., Beaulac and Reckhow 1982), along with nonpoint inputs from residential areas and small villages in the watershed (e.g., Johnson et al. 1976). Mean PO_4-P and inorganic N concentrations in the Pigeon River exceeded those reported by Omernik (1976, 1977) for other North American agricultural watersheds (0.03–0.06 mg PO_4-P L^{-1}; 1.0–3.2 mg NO_3+NH_4-N L^{-1}). Mean PO_4-P concentrations also exceeded the USEPA standard for streams (0.05 mg PL^{-1}, Pionke et al. 1996) and greatly exceeded the 0.01 mg P L^{-1} suggested as a threshold for environmental concern (Sims et al. 1998). Confined animal operations, lack of conservation practices, tile drainage, and propensity to generate surface runoff are characteristics of the upper part of the Pigeon River watershed, and all have been identified as factors contributing to nonpoint source pollution potential in agricultural watersheds (Brenner and Mondok 1995; David et al. 1997; Gburek and Sharpley 1998). Significant subsurface phosphorus losses also can occur from sandy or high organic matter soils, and from soils with high phosphorus levels from over-fertilization or application of livestock waste (Sims et al. 1998). These factors also are present in the upper Pigeon River watershed and contribute to the elevated stream PO_4-P concentrations observed in this study.

TABLE 1. Trends in water quality means at six stations in the Pigeon River watershed, Ottawa County, Michigan (September, 1996–October, 2000).

	Station+						
Variable	**1**	**2**	**3**	**4**	**5**	**6**	**P¶**
Temperature °C	11.8c	12.1c	13.7a	12.8b	12.0c	12.2c	<0.001
Dissolved oxygen mg L^{-1}	8.3b	8.3b	8.2bc	6.9d	7.8c	8.8a	<0.001
Oxygen deficit mg L^{-1}	–2.8bc	–2.7c	–2.4cd	–3.9a	–3.2b	–2.1d	<0.001
Conductivity mS m^{-1}	47.6c	52.1c	138.1a	45.5c	78.3b	56.2c	<0.001
pH	7.52bc	7.55bc	7.54bc	7.50c	7.56b	7.63a	<0.001
PO_4–P, mg L^{-1}	0.10b	0.09b	0.22a	0.13b	0.14b	0.08b	<0.001
NO_3–N, mg L^{-1}	1.9c	3.4bc	8.7a	4.5b	4.9b	3.9b	<0.001
NH_4–N, mg L^{-1}	0.13b	0.14ab	0.25a	0.13ab	0.12b	0.04b	<0.001
Suspended solids mg L^{-1}	13.5cd	17.5bc	24.9ab	35.5a	13.9cd	9.0d	<0.001

+ Station locations as follows: 1 at 84th Avenue and Tyler Street, 2 at 96th Avenue, 3 at 104th Avenue, 4 at Sawyer Creek (Croswell Street), 5 at Pigeon Creek Park, 6 at West Olive Road.

¶ Significance probability of one–way analysis of variance, with sampling dates treated as blocks ($n = 80$ for all variables except PO_4–P, NO_3–N, NH_4–N, and suspended solids, where $n = 63$). Means without common letters differ significantly; letters compare means across stations within a single variable.

Significant increases in conductivity, NO_3-N, PO_4-P, suspended solids, and temperature at Station 3 represent effects of the point source discharge that occurs between Stations 2 and 3 (Table 1). Similar effects of a point source discharge on water chemistry were noted by Johnson et al. (1976) in a rural watershed in New York. This discharge can greatly influence water quality in the upper Pigeon during summer baseflow when the discharge from this source may equal or exceed 15% of the total flow at Station 3 (C. Veldkamp, MDEQ, personal communication, 1999). We observed significantly lower dissolved oxygen levels and higher oxygen deficits (dissolved oxygen at saturation minus measured dissolved oxygen) at both Stations 4 and 5 (Table 1). Mean concentrations of dissolved oxygen in the mainstream were least at Station 5 as a result of the influx of poor quality water from Sawyer Creek (Station 4). Decreasing concentrations of nutrients and suspended solids from Station 5 downstream represent the combined effects of dilution by groundwater, adsorption by bottom sediments (e.g., Johnson et al. 1976), chemical precipitation, sedimentation, biodegradation, and microbial transformation. The lower mainstream is characterized by abundant meanders, pools, and woody debris, all of which increase residence time and encourage improvement in water quality. These natural water quality improvement processes between Stations 5 and 6 result in significantly increased dissolved oxygen levels and reduced oxygen deficits in the lower Pigeon (Table 1).

Nutrient Export

Thornthwaite estimates of mean annual runoff from the Pigeon River watershed for the period September, 1996 to August, 2000 averaged 36.6% of the total mean annual precipitation (Table 2), similar to annual rates of runoff reported for agricultural watersheds in the Chesapeake Bay piedmont region (36–37% of total precipitation, Jordan et al. 1997b). In comparison, runoff estimates determined using the integration method were lower (31.7% of total precipitation, Table 2). In comparison to other North American watersheds (Omernik 1976; 1977; Castillo et al. 2000), the Pigeon River is at the high end of PO_4-P and inorganic nitrogen export. Omernik (1976, 1977) reported annual inorganic nitrogen export from agricultural watersheds ranging from 2.9 to 7.8 kg N ha^{-1}, as compared to the 9.4 to 10.8 kg inorganic N ha^{-1} estimated for the Pigeon River watershed (Table 2). Similarly, Omernik (1976, 1977) reported annual PO_4-P exports ranging from 0.09 to 0.12 kg P ha^{-1}, as compared to the 0.22 to 0.25 kg P ha^{-1} estimated for the Pigeon River watershed (Table 2). Reasons for high export rates from the Pigeon River watershed include high livestock densities and substantial annual point source inputs of NO_3-N (~2.8 kg ha^{-1}) and PO_4-P (~0.04 kg ha^{-1}).

Reliable estimates of nutrient loading into the Great Lakes are needed for individual tributaries, but constituent loadings from most tributaries are unknown (Robertson 1997). For example, Robertson (1997) used an estimate of total phosphorus export of 0.31 kg P ha^{-1} yr^{-1} for a 325-km^2 area in western Ottawa County including the Pigeon River watershed. In comparison, our estimates of 0.22 to 0.25 kg PO_4-P ha^{-1} yr^{-1} (Table 2) represent an annual export of approximately 0.55 to 0.62 kg total P ha^{-1} (PO_4-P x 2.5). Nutrient exports from the Pigeon River watershed appear to be elevated because of high inputs from nonpoint sources combined with additional nitrogen and phosphorus inputs from a point source discharge. Elevated stream nutrient concentrations support this interpretation, and Robertson (1997) notes that his method may have underestimated loads from tributaries with large point-source contributions.

In contrast to phosphorus export, our estimates of total suspended solids export are at the low end of the range for similar watersheds (Correll et al. 1999). Robertson (1997) used a suspended sediment export of 107 kg ha^{-1} yr^{-1} to estimate outputs from the Pigeon River watershed, compared to our estimates of 20 to 23 kg ha^{-1} yr^{-1} suspended solids export at Station 6. While our values may be underestimated for a variety of reasons discussed below, there are other explanations for relatively low suspended solids export from the Pigeon River. The Pigeon River has a low gradient, and this is associated with reduced exports of suspended solids (Robertson 1997). Suspended solids concentrations in the upper watershed are fairly high (Table 1), and estimated mean annual export rates for the watershed above Station 3 range from 73 to 76 kg ha^{-1}. In the lower mainstream, stormwaters are held in the floodplain during high flows, and substantial reductions in suspended solids occur above Station 6. Further reductions in suspended solids exports to Lake Michigan may occur as a result of retention in Pigeon Lake.

TABLE 2. Mean annual precipitation, runoff, nutrient export, and suspended solids export estimates for the Pigeon River watershed, Ottawa County, Michigan for the period September, 1996–August, 2000.

Variable	Units	Integration Method Mean ± SD+	Averaging Method Mean ± SD
Precipitation¶	cm		83.7 ± 7.3
Runoff	cm	26.5 ± 6.6	30.6 ± 2.7§
NO_3–N	mg L^{-1}	NA#	3.47 ± 0.34
	kg ha^{-1}	9.25 ± 2.64	10.65 ± 1.90
NH_4–N,	mg L^{-1}	NA	0.040 ± 0.025
	kg ha^{-1}	0.11 ± 0.09	0.12 ± 0.08
PO_4–P	mg L^{-1}	NA	0.083 ± 0.027
	kg ha^{-1}	0.22 ± 0.09	0.25 ± 0.07
Suspended Solids	mg L^{-1}	NA	7.56 ± 4.08
	kg ha^{-1}	19.6 ± 11.8	23.1 ± 12.7

[+] Mean ± standard deviation, from annual estimates for 9/96–8/97, 9/97–8/98, 9/98–8/99, and 9/99–8/00 using integration and averaging methods to estimate nutrient and suspended solids exports. Discharge x time–weighted concentrations in mg L^{-1} and estimates of annual nutrient export rates in kg ha^{-1}, calculated from data for Station 6 on the lower mainstream.

[¶] Precipitation as measured by the National Weather Service at Gerald R. Ford International Airport, Grand Rapids, Michigan.

[§] Runoff for averaging method calculated using the Thornthwaite water balance equation (Mather 1978) using mean monthly temperature and precipitation as measured by the National Weather Service at Gerald R. Ford International Airport, Grand Rapids, Michigan.

[#] NA = not applicable, weighted mean concentrations not used directly in integration method.

Our constituent export estimates are subject to errors related to the inherent limitations of the methods used to make them (Cohn et al. 1989; Preston et al. 1989). In this study, the most likely sources of errors include the lack of continuous flow data for this ungaged stream, relatively small sample sizes (n = 15 to 18 samples yr^{-1}), and bias introduced by sampling strategy (Robertson and Roerish 1999). We employed a storm-chasing approach that could underestimate storm flow concentrations in small flashy streams like the Pigeon (Robertson and Roerish 1999), and we did not attempt to sample all storm flows during the year. The integration method we employed would not account for increases in streamflow and constituent concentrations during unmeasured high flows, and such load estimates could be greatly underestimated (Robertson and Roerish 1999). We did not use a log linear rating curve approach (Cohn et al. 1989) because of relatively weak relationships between discharge and nutrient concentrations in this watershed (r^2 values < 0.35). Our general sampling approach, however, was appropriate for short-duration studies in small watersheds (Robertson and Roerish 1999), and results are consistent with relatively higher rates of nutrient export and lower rates of suspended solids export from this watershed as compared to previous estimates.

Effects of Seasonal Flows

Discharge varied during the four-year study according to season and occurrence of storm flows (Figure 2a). Discharge followed a typical seasonal pattern of higher flows in the winter and spring months, followed by much lower flows in the summer. The watershed produced large flows after major storms or during snowmelt that were rapidly transmitted downstream as a direct result of drainage and channelization in the upper watershed. This propensity to generate rapidly peaking flows after storms is reflected in a relatively high flashiness index of 30.8 for the Pigeon River at Station 6 (ratio of 95th percentile flow to 5th percentile flow, Robertson and Roerish 1999). During low flows, inputs of groundwater below Station 3 (26 to 45 $m^3\ h^{-1}\ km^{-2}$) maintained fairly stable baseflows in the lower Pigeon (Wiley and Seelbach 1998).

Based on previously reported causes of reduced water quality, we expected that temperature and dissolved oxygen levels would reach critical levels sometime during the months of May to September during low flows. Results of this study indicated that critical periods could occur during summer, but they were associated with high summer storm flows in June and July of 1997 (Figure 2a) in response to unusually heavy rains in the watershed. High discharges at this time were accompanied by elevated temperatures (> 20 °C, Figure 2b) and low dissolved oxygen levels (< 3 mg L^{-1}, Figure 2c). In contrast, dissolved oxygen and temperature during summer low flows in the lower mainstream were within the limits required to sustain trout (Wiley and Seelbach 1998).

Small summer storm flows (≤ 5-year events) tended to have higher temperatures, lower dissolved oxygen levels, and higher oxygen deficits than summer

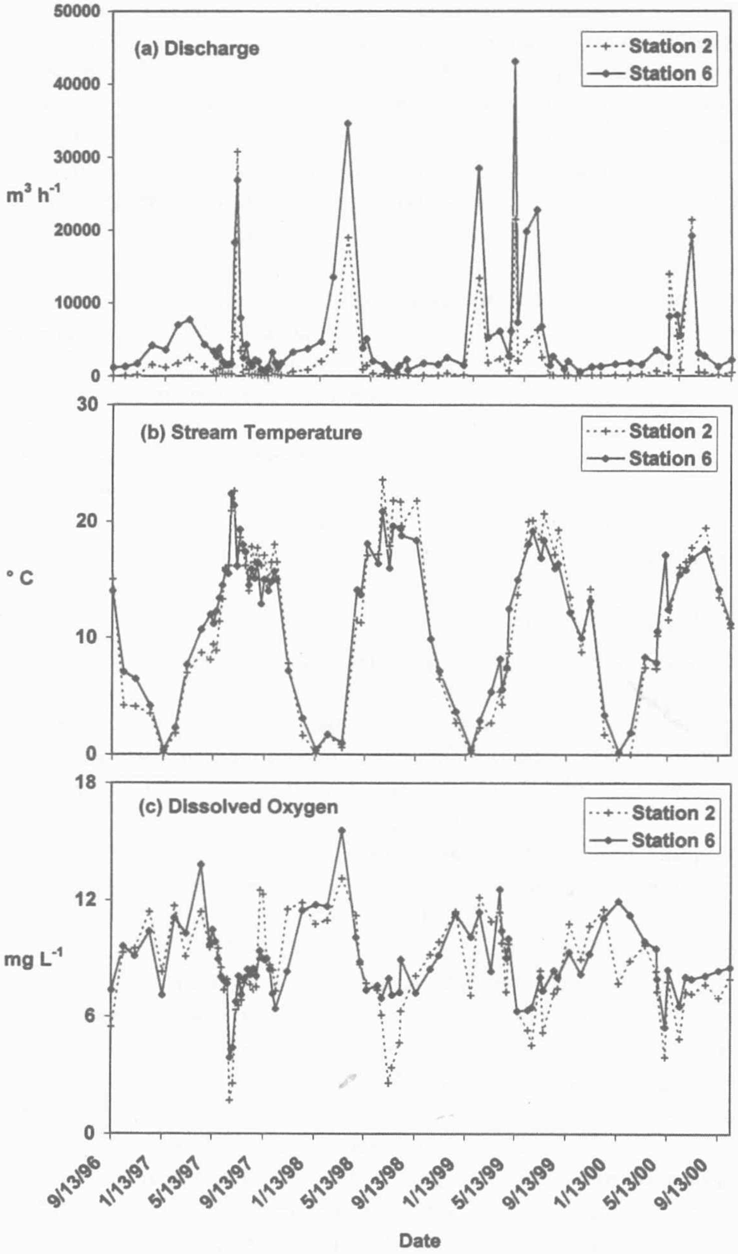


FIGURE 2. Observed variations in (a) discharge, (b) temperature, and (c) dissolved oxygen concentrations at two stations on the Pigeon River. Station 2 is located on a channelized stretch of the mainstream in the upper watershed, while Station 6 is in the forested floodplain of the lower mainstream.

baseflows (Table 3). While these effects were not statistically significant, small summer storm flows may limit the suitability for sensitive invertebrate and fish species in the upper reaches of the mainstream by reducing dissolved oxygen levels below 6 mg L^{-1} for periods of time. In contrast, we observed dramatic reductions in oxygen concentrations only during the large summer storm flows in 1997 (>100-year events). Spring storms ($\leq$ 5-year events) had higher oxygen deficits than normal spring flows, but dissolved oxygen levels remained higher because of cool stream temperatures (Table 3). While typical spring and summer storms ($\leq$ 5-year return period) did not produce critical declines in dissolved oxygen in the Pigeon River, they were associated with other indications of degraded water quality such as elevated suspended solids concentrations. Similar reductions in dissolved oxygen during floods have been reported in other watersheds (Rimer et al. 1978; Graczyk and Sonzogni 1991; Greb and Graczyk 1995), and may stress fish populations or cause fish kills (Graczyk and Sonzogni 1991). Low dissolved oxygen levels during flooding can be the result of increased stream temperatures, influx or resuspension of oxygen-demanding materials, rapid movement of anoxic surface- or groundwater into the stream, or reduced photosynthetic activity during high flows (Graczyk and Sonzogni 1991).

Large summer storms, spring storms, and snowmelt produced peak discharges on the order of 20,000 $m^3 h^{-1}$ in the lower mainstream, with the upper watershed producing a substantial amount of the total runoff under these conditions (Table 3). During high flows both pH and conductivity in the river dropped significantly as a result of the influx of large quantities of surface runoff from precipitation or melting snow (Table 3). Stream pH was negatively correlated with ln(discharge) at all stations ($r = -0.61$ to -0.79, $P<0.001$), with higher pH levels (>7.6) typifying baseflow periods and much lower pH levels (<7.2) occurring during storm flows. Precipitation pH in Ottawa County averages around 4.35 (MacDonald and Ducsay 1997), so that as more surface runoff enters, stream pH levels are reduced below the range typical of baseflow periods.

Suspended solids and NH_4-N (Figure 3a,b) concentrations were noticeably elevated during spring storms, related to surface runoff from cropland (Jordan et al. 1997a; Correll et al. 1999; McFarland and Hauck 1999). In contrast, NO_3-N (Figure 3c) concentrations tended to decrease during snowmelt and spring storms as a result of dilution effects (David et al. 1997; Jaynes et al. 1999). Soluble reactive phosphate concentrations (Figure 3d) were most noticeably increased during snowmelt, possibly because of influx of manure-contaminated runoff (Johnson et al. 1976; Brenner and Mondok 1995; McFarland and Hauck 1999) or high input of soluble P in subsurface drainage waters (Sims et al. 1998). The single large summer storm sampled for constituent analyses (not shown in Figure 3) also had elevated NH_4-N (0.20 mg L^{-1}) and PO_4-P (0.27 mg L^{-1}) concentrations.

TABLE 3. Seasonal flow types and water quality at two stations in the Pigeon River watershed, Ottawa County, Michigan (September, 1996–October, 2000).

Variable	Station	Seasonal Flow Type								P^+
		Summer Flows			Fall Flows	Winter Flows		Spring Flows		
		Base	1–5 yr.	>100 yr.	Normal	Normal	Snowmelt	Normal	1–5 yr.	
Discharge	2	194d	1111bc	18036a	346cd	1284b	9579a	764bc	10801a	<0.001
$m^3 h^{-1}$	6	1600c	3842b	22622a	2028bc	4361b	20686a	3322bc	18240a	<0.001
Temperature	2	17.9ab	18.6a	21.8a	9.0c	2.4d	1.3d	11.1bc	12.7abc	<0.001
°C	6	16.6ab	17.6ab	21.9a	9.2bc	3.0d	2.1d	12.9bc	12.8bc	<0.001
DO[¶]	2	7.5abc	5.7c	2.1d	10.0a	9.8a	10.5a	9.3ab	6.4bc	<0.001
$mg L^{-1}$	6	8.1ab	7.3b	4.2c	9.2ab	10.6a	11.4a	9.5ab	7.5b	<0.001
DO deficit	2	–2.0ab	–3.6ab	–6.6c	–1.8a	–3.9abc	–3.6ab	–1.8a	–4.4b	<0.001
$mg L^{-1}$	6	–1.7ab	–2.2ab	–4.6c	–2.5ab	–2.9abc	–2.4ab	–1.1a	–3.2bc	<0.001
Conductivity	2	61.2a	53.1a	29.2b	57.6a	48.5a	27.8b	53.1a	33.7b	<0.001
$mS m^{-1}$	6	66.8a	58.7ab	27.8c	64.0a	47.9b	31.1c	56.7ab	35.1c	<0.001
pH	2	7.72a	7.54ab	7.06d	7.68a	7.39bc	7.12d	7.60ab	7.24cd	<0.001
	6	7.77a	7.68a	7.24b	7.63a	7.60a	7.22b	7.73a	7.36b	<0.001
n (80 total)		20	7	2	17	8	4	15	7	

+Significance probability of one–way analysis of variance, based on replications of flow types. Means without common letters differ significantly; letters compare means across seasonal flow types within a single variable and station.

[¶] DO = dissolved oxygen. Station 2 is on the main county drain at 96th Avenue and Station 6 is in the designated coldwater section of the lower Pigeon at West Olive Road.

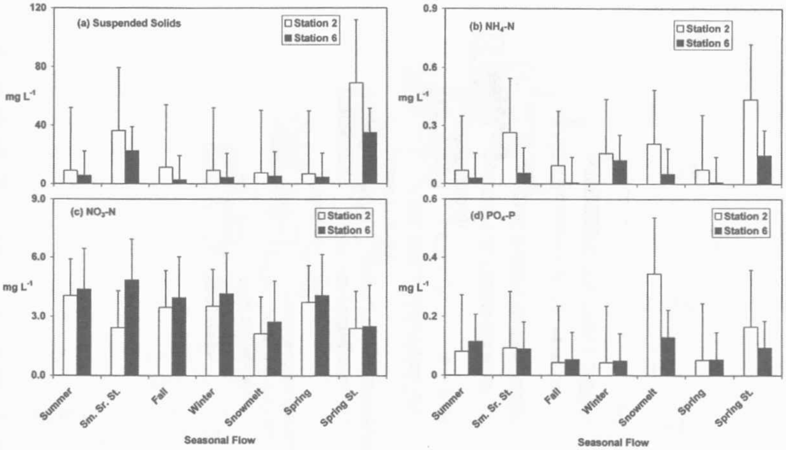


FIGURE 3. Effects of seasonal flows on concentrations of (a) suspended solids, (b) NH_4-N, (c) NO_3-N, and (d) PO_4-P. Sm. Sr. St. = small summer storms (≤5-yr), Spring St. = spring storms (≤5-yr), large summer storms not shown because of limited sampling dates for laboratory analyses (n=1). Error bars represent Tukey's critical value (w 0.05) for determining significant differences among means within each station. Station 2 is located on a channelized stretch of the mainstream in the upper watershed, while Station 6 is in the forested floodplain of the lower mainstream.

As a result of high discharge, alone or in combination with increased nutrient concentrations, storm flows contribute a substantial amount of annual nutrient and suspended solids exports from this and other agricultural watersheds (Gburek and Heald 1974; Johnson et al. 1976; Pionke et al. 1996; David et al. 1997; Castillo et al. 2000). We calculated flashiness indices (Robertson 1997) for constituent exports at Station 6 as the ratio of the mean export rate for a seasonal flow type (kg h^{-1}) divided by the four-year average export rate calculated from mean annual concentrations (Table 2) and the mean discharge of 3622 m^3 h^{-1}. Flashiness indices can be interpreted as the number of days of average flow required to equal the nutrient or suspended solids export of one day of storm flow (Robertson 1997). In the Pigeon River, flashiness indices were highest for NO_3-N (3.6), NH_4-N (19.0), and suspended solids (23.4) during spring storms. Flashiness indices for PO_4-P were highest during snowmelt (11.2) and large summer storms (17.9 in the one event sampled). The magnitudes of our maximum seasonal flow indices are in the range of those reported by Robertson (1997) for 10-year events in other Lake Michigan tributaries. In terms of impacts on stream ecosystems, spring storms and snowmelt contribute substantially to total constituent exports, but large sum-

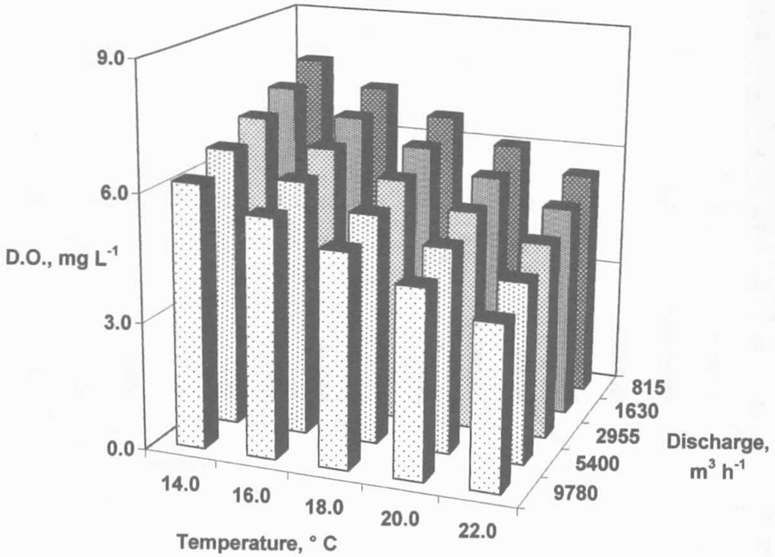


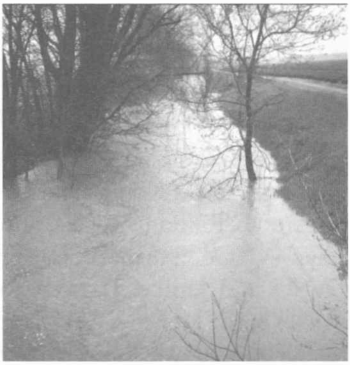
FIGURE 4. Combined effects of stream temperature and increasing surface runoff on dissolved oxygen (D.O.) levels at Station 5 on the mainstream of the Pigeon River. Discharge of 815 $m^3 h^{-1}$ represents normal summer baseflow, with a discharge of 1630 $m^3 h^{-1}$ occurring during smaller summer storm flows. Higher flows caused by influx of surface runoff during storms increase stream temperatures and introduce oxygen-demanding substances into the river, resulting in decreased dissolved oxygen concentrations. The discharge of 9780 $m^3 h^{-1}$ represents a flow resulting from a ≥ 100-yr 24-hr rainfall. Station 5 is in the forested floodplain of the Pigeon River near the upper end of the coldwater fishery section.

mer storms are biologically stressful because of increased temperatures and reduced dissolved oxygen levels.

The combined effects of increasing stream temperature and influx of oxygen-demanding materials in surface runoff on dissolved oxygen concentrations in the Pigeon River can be dramatic. At Station 5, seasonal effects of stream temperatures on dissolved oxygen levels are apparent, with lowest dissolved oxygen concentrations experienced during warm weather (Figure 4). High discharges during periods when stream temperatures are low (≤ 14 °C, fall, winter, spring) appear to have less potential biological impact than summer storms because dissolved oxygen concentrations typically remain above 6 $mg L^{-1}$ even during high flows. High discharges during the summer when stream temperatures approach or exceed 20 °C, however, can reduce dissolved oxygen to critical levels. Because of this sensitivity, summer storms that produce large amounts of surface runoff are a major ecological stress in this system and are one of the factors keeping its fish population depauperate (Wiley and Seelbach 1998). In the Raisin River watershed of southeastern Michigan, Roth et al. (1996) found that stream reaches whose upstream catchments were dominated by agriculture also ranked low in biotic integrity. They attributed this to habitat degradation related to altered flow regime, increased sediment inputs, and decreased organic matter inputs. Out results suggest that acute water quality degradation during storm flows in such streams also is implicated in the observed reduced biotic integrity.

Summary and Management Implications

This study confirmed that the Pigeon River contains high levels of inorganic pollutants associated with both point and nonpoint sources in the watershed, and is a source of elevated nutrient export to Pigeon Lake and Lake Michigan. This study also has shown that temperatures and dissolved oxygen levels in the lower mainstream of the Pigeon River typically remain in the range inhabitable by coldwater species such as trout even given the stream's existing pollution problems. Inputs of degraded water from upstream sources during high flows, however, produce periods of environmental stress in this section of the stream. As a result, the fish population in the lower Pigeon includes only a low number of pollution-tolerant, warmwater species. Continued efforts to implement effective nonpoint source controls (use of cover crops, residue management, waterways, vegetated buffers, animal waste management practices, etc.) are needed to reduce nonpoint source pollutant loads in the Pigeon River. Restoration of more natural stream channel characteristics (e.g., Riley 1998) and shading by vegetation in the drains of the upper watershed would increase in-channel residence time during low flow periods, help buffer temperature extremes, and encourage natural water quality improvement before these waters enter the lower Pigeon. The lower mainstream retains its natural channel morphology together with an intact floodplain, and should be preserved in its current state (Wiley and Seelbach 1998).



The Pigeon River at 104th Avenue, Station 3, at flood stage

Large summer storms can temporarily reduce dissolved oxygen concentrations to critical levels throughout the mainstream of the Pigeon River. High flows following snowmelt and spring storms contribute substantially to the high annual nutrient exports from this watershed. Both of these negative impacts have been exacerbated by extensive drainage and channelization of tributaries in the upper watershed. The effects of these sporadic high discharges need to be controlled by restoration of wetlands or creation of similar flood retention areas at strategic locations in the upper watershed (e.g., Roth et al. 1996; Middleton 1999; Richardson and Gatti 1999). Such wetland systems would serve to diminish the magnitude of storm discharges and to reduce pollutant loads in the detained water before it is released to the system, allowed to recharge the local groundwater, or permitted to evaporate in place (Hunt et al. 1999; Kovacic et al. 2000). Preliminary estimates of retention volumes required to reduce storm flows to acceptable levels in the Pigeon River watershed ($\leq 189\ m^3\ h^{-1}\ km^{-2}$) increase from 55 ha-m for a 2-year event (6.6 cm in 24 h) to 467 ha-m for a 100-year event (14.2 cm in 24 h, D. Fongers, MDEQ, personal communication, 2000). The same chronic and acute water quality problems observed in the Pigeon River watershed are common to many agricultural watersheds, and substantial efforts to change current land and water management practices will be required to accomplish necessary improvements in water quality and to reinstate natural hydrologic controls in these systems.

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