Water Resources and the Land-Water Interface

Water resources in agricultural watersheds can be improved by effective multidisciplinary planning.

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Summary. Development and implementation of local and regional plans to control nonpoint sources of pollution from agricultural land are major mandates of section 208 of Public Law 92-500. Many planners tend to equate erosion control as measured by the universal soil loss equation with improvements in water quality. Others implement channel management practices which degrade rather than improve water quality and thereby decrease the effectiveness of other efforts to control nonpoint sources. Planners rarely recognize the importance of the land-water interface in regulating water quality in agricultural watersheds. More effective planning can result from the development of "best management systems" which incorporate theory from all relevant disciplines.

One major objective under the authority of section 208 of Public Law 92-500 (*1*) is to identify and plan for the control of nonpoint sources of pollution (NPS) from agricultural land. Local and regional planning authorities have been charged with the responsibility of developing and implementing plans to ensure "fishable and swimmable" waters by 1983. Because of the magnitude of such an effort in economic terms, it is essential that management decisions be founded on the broadest possible base of knowledge.

Implementation of such multidisciplinary planning is often slow, especially when it concerns management of stream channels. For example, between the initiation of a demonstration project (Black Creek Study) in Allen County, Indiana, in 1972 and late 1977, $519,000 was spent on cost-share programs for land treatment (*2*). Twenty-three percent of the expenditures were for land treatment activities, including crop residue management, grass waterways, terraces, and minimum tillage. Nearly twice as much (45 percent) was devoted to channel maintenance activities such as channelization, removal of nearstream vegetation, grade stabilization, and streambank protection (*3*). Black Creek project staff have continually updated their approach to NPS control; it is now recognized that much early channel maintenance had little direct relevance to water quality management. Consequently, actual per acre costs for water quality improvement are lower than reflected by total expenditures in Black Creek, because many of the subsidized practices there have had no bearing on improving water quality. Efforts to estimate nonpoint control costs by extrapolation to regional or statewide areas must be made cautiously (*4*).

Many channel management activities degrade rather than improve water quality and thereby decrease the effectiveness of nonpoint control programs. Our hypotheses are that (i) maintenance of more natural nearstream vegetation and channel morphology in agricultural watersheds can lead to significant improvements in water quality and stream biota, and (ii) the best management option for long-term benefit to society is an integrated effort involving sound management of the land surface and stream channels.

The approach used is a multidisciplinary synthesis. Specifically, we evaluate (i) existing data regarding the ability of nearstream vegetation to reduce nutrient and sediment transport from the terrestrial to the aquatic component of agricultural ecosystems, (ii) the effects of nearstream vegetation on water temperature and its implications for water quality, (iii) the effects of channel morphology on sediment loads, and (iv) the impact of nearstream vegetation and channel morphology on stream biota. With this information we judge the feasibility of using nearstream vegetation and channel morphology (*5*) to improve water quality and quality of stream biota. Finally, we propose a generalized model (*6*) which suggests that society should approach planning for control of nonpoint pollution in agricultural watersheds with a multidisciplinary synthesis of best management practices. Effective nonpoint control will depend on the concept of "best management systems."

Impact of Nearstream Vegetation and Channel Morphology on Water Quality

Effects of vegetation on nutrient and sediment transport. Most plant nutrients (especially phosphorus and to some extent nitrogen) in surface runoff from agricultural watersheds are attached to sediment particles (*7*). For brevity, we only mention sediment. The capacity of vegetation to reduce sediment transport to the aquatic environment changes with several variables, including water depth relative to vegetation height, length and slope of vegetated area, vegetation characteristics, size distribution of incoming sediments, application rate of water, slope, and slope length before water reaches the vegetation (*8*). When water depths are much less than grass height (overland flow), up to 54 percent reduction in sediment loads have been recorded (*9*).

Studies of sediment loads in shallow channel flow range from early descriptive work (*10*) to more quantitative field and laboratory studies (*11*) of real and simulated vegetation. These studies show: (i) efficiency at reducing sediment loads varies with the type of vegetation, with efficient species removing 50 percent of initial sediment concentration (5000 parts per million) in 300 feet (1 foot = 0.304 meter) and 99 percent in 1000 feet; (ii) an inverse relationship existing between particle size and vegetation length required to remove a given percentage of that particle size; (iii) the rate of sediment deposition in the vegetation is constant over a range of lower slopes, but after a critical slope is

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reached efficiency declines; and (iv) when vegetation is clipped or flow depth is high enough to submerge the vegetation, "filtering" efficiency ultimately declines to zero.

Little quantitative information is available on relations among these variables when vegetation is used to prevent sediment and nutrients from entering streams under runoff conditions normally encountered in agricultural watersheds. However, data from long-term (15 years) field studies in forested watersheds indicates that maintenance of natural vegetation along streams (buffer strips) leads to significant improvements in water quality in logged areas (Table 1) (*12*). Land use practices adjacent to streams in agricultural watersheds indicate that these relations should be investigated and the subject given more effective consideration in section 208 planning programs.

Effects of streamside vegetation on water temperature and nutrient dynamics. Temperature is important in regulating physical and biotic characteristics of streams, and stream temperatures are greatly affected by nearstream vegetation. Weekly maximum temperatures of streams in cropland range 5.0° to 12.8°C (average 4.6°C) above a nearby forested stream (*13*). Temperatures of the forested stream during the coldest month (February) ranged as high as 3.9°C above the farm stream. Summer water temperatures for a stream inside a small woodlot (19°C) were much lower than in nearby unshaded areas (28°C) (*14*).

Net thermal radiation in relation to stream discharge is the primary determinant of stream temperature. Examination of temperature in various streams bordered by shrubs or trees indicates that angular canopy density (a measure of shading ability of the vegetation) is the only vegetation parameter correlated with temperature (*15*). Vegetation width is not important. Furthermore, buffer effectiveness decreases with increasing stream size. Small streams have greater temperature problems, but the inverse relations between temperature change and stream discharge for a given input of thermal radiation means that temperature problems are easier to control in small streams. Temperature control in the upper reaches of drainages will reduce temperature-associated problems in headwater and downstream areas, including small lakes and reservoirs.

The effects of temperature on water quality and biotic communities are numerous. As water temperature increases, its capacity to hold oxygen decreases. Therefore, at elevated temperatures the ability of streams to assimilate organic wastes without oxygen depletion is reduced. This exaggerates the impact on the system of each additional unit of waste. Temperature increases also increase the rate at which nutrients attached to suspended solids are converted to readily available (soluble) forms (*16*). Slight increases in temperature above 15°C produce substantial increases in the amount of phosphorus released because of the exponential increase in conversion rates with increasing temperature.

Table 1. Percentage of change in sediment and nitrate loads over a 15-year period under varying forestry practices (*12*).

Forestry practice	Suspended sediments	Nitrates
Clear-cut	205	400
Clear-cut with buffer strip along streams	54	0
Control	0.1	0

Streamside vegetation not only reduces sediment and nutrient transport from the terrestrial to aquatic environment. It also has potential for temperature control, for enhancement of the oxygen-carrying capacity of streams, and for reducing nutrient availability and utilization. Its impacts on stream energetics and biota are discussed later.

Channel morphology and sediment loads. The concept of unit stream power was developed to predict total suspended sediment concentration of a stream based on channel morphology (*17, 18*). The rate of sediment transfer is directly related to unit stream power (USP)—the rate of energy expenditure by a stream as it flows from a higher to a lower point (Fig. 1). It is defined as the time rate of potential energy expenditure per unit weight of water in an alluvial channel. Mathematically, USP is defined (*17–19*) in terms of average water velocity and, under uniform flow conditions, the surface slope of the water. In the Middle Fork of the Vermillion River in Illinois, USP was 23 to 26 percent lower in a pool and riffle stream during medium and low flow conditions than in an equivalent uniform channel similar to those formed by modern channelization practices (*17*). Pools and riffles served to reduce USP and therefore erosive energy and sediment transporting capability during low and medium flows. At high flows, pools and riffles were obscured and did not reduce USP. In another study (*14*) a similar reduction in suspended solids (28 percent) occurred in a section of wooded stream with meandering, pool-and-riffle topography relative to that in straight channel areas associated with agricultural land above and below the woodlot (Fig. 2). These results suggest the presence of a higher equilibrium sediment concentration in the straight channels associated with agriculture above and below the forest and a lower equilibrium sediment concentration in the meandering section of the channel in the forest. An increase in the roughness factor (*20*) in the woodlot is probably responsible for the decreased sediment loads, because the slopes are lower (0.25) above and below than in the woodlot (0.40) (*21*).

Research from agriculture, forestry, and hydrology suggests the following conclusions: (i) a more natural nearstream vegetation can reduce nutrient and sediment transport from the terrestrial to aquatic component of ecosystems; (ii) nearstream vegetation can be used to reduce temperature-associated water quality problems in agricultural watersheds; and (iii) allowing streams to maintain a natural morphology to reduce USP, bank erosion, and suspended sediment concentrations is a feasible management alternative for improving water quality.

Impact of Nearstream Vegetation and Channel Morphology on Stream Biota

When nearstream vegetation or channel morphology is modified, stream biota may be affected by elevated sediment loads, increased water temperature, disruption of aquatic food webs, and decreased habitat diversity.

Effects of sediment. Only very high concentrations of sediment (greater than 20,000 parts per million) cause mortality in adult fish, primarily by clogging the opercular cavity and gill filaments (*22*), and by preventing normal water circulation and aeration of the blood. Such high sediment levels are rarely encountered in streams. Indirect effects on adults may occur at much lower sediment concentrations, primarily by causing subtle changes in behavior (*23*).

The major effect of sediment on fish populations is disruption of normal reproduction (*24*). When sediments settle they cover essential spawning grounds or eggs, or prevent emergence of recently hatched fry (*25*). These effects have been one of the major factors decreasing the quality of fisheries throughout the United States and has prompted some to suggest that changes in bottom type determine fish diversity (*26*). As bottom type is simplified by deposition of sediment, species diversity decreases (*27*).

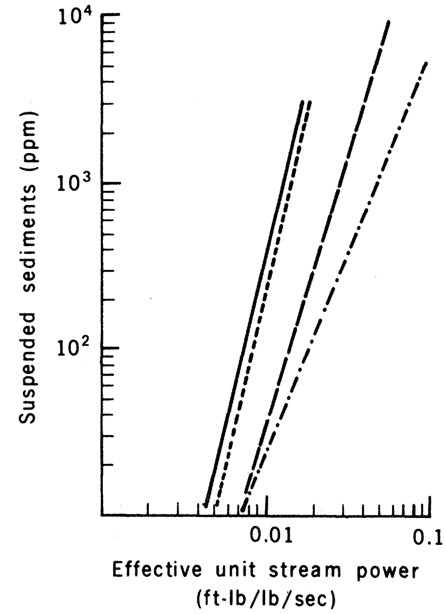

Fig. 1. Relation between effective unit stream power and measured suspended sediment concentrations for four streams (*18*).

However, a low correlation coefficient between substrate diversity and fish species diversity (r = .42) suggests other factors are also important in determining species distributions. Correlations between habitat diversity and biotic diversity are known for several groups of organisms, including both plants and animals (*21, 28*).

Sedimentation also commonly results in declining productivity in aquatic ecosystems across all trophic levels. A comprehensive study of the energetics of Red Cedar River in Michigan showed that stream productivity declined significantly following siltation (*29*). Increasing turbidity resulted in declines in aufwuchs (*30*) production of 68 percent and heterotrophic energy consumption of 58 percent.

Clearly, sediments alter the structure and productivities of plant, invertebrate, and vertebrate communities. Therefore, reductions in sediment loadings will have a beneficial effect on stream biotas. However, efforts to reduce sediment loads must be accompanied by more informed management of other stream characteristics for optimal effects on water quality and stream biota.

Effects of temperature on biota. Regardless of other physicochemical changes, temperature changes may cause shifts in the structure of aquatic communities (*31, 32*).

When vegetation is removed from along streambanks and water temperatures increase 6° to 9°C (*33*), it may become energetically impossible for species with lower temperature optimums to continue living in the area, regardless of changes in sediment loads, habitat structure, or other environmental conditions. A shift in community structure may occur with resident species being replaced by species less desirable but more tolerant of increased temperatures. All of these characteristics of streams must be improved simultaneously if "fishability" is a major goal of programs to reduce nonpoint pollution in agricultural watersheds.

Effects on stream energetics. We have emphasized the indirect impact of nearstream vegetation on stream biota by means of its effect on sediment and nutrient inputs and temperature fluctuations. An important direct effect of removing this vegetation is disruption of aquatic food webs, especially in areas where terrestrial inputs are major sources of energy for streams.

Headwater streams represent the maximum interface between terrestrial and aquatic environments, where most sediment enters streams and extensive channelization and removal of near stream vegetation is occurring. They are also important spawning and nursery grounds for commercial and sport species which spend their adult life in lakes or large rivers (*14, 34*). In these areas most energy utilized by the aquatic invertebrates and fish is terrestrial in origin (*35*). Once coarse particulate organic matter, such as leaves and twigs, is in the stream, either dissolved organics leached from it are utilized or the matter is directly ingested by invertebrates which shred the organic matter and digest the microorganisms growing on it. These organisms then egest a fine particulate organic matter which is utilized by other invertebrates. At the top of this food web are fish predators (*35*).

Removal of nearstream vegetation in upstream areas will result in significant reductions in invertebrate and fish production as a result of loss of allocthonous (terrestrial) energy inputs. Areas lacking deciduous vegetation commonly have low diversity and numbers of invertebrates (*36*). Maintenance of productive fisheries in streams depends on suitable instream habitat, water quantity and quality, and preservation of terrestrial sources of energy on which both invertebrates and vertebrates depend.

Effects of stream channelization. The primary goals of channelization are to prevent flooding of crops and increase the amount of tillable agricultural land by allowing rapid drainage. Historically, little attention has been paid to the detrimental effects of channelization on water quality, fisheries resources, and the recreational potential of streams. Included among its effects are (Fig. 3) (*37*) increased stream temperatures (*38*), bank erosion (*39*), downstream flooding (*40*), and reduction in habitat complexity (*27*).

The synergistic action of these effects on the physical environment is a reduction in both fish (up to 98 percent by standing crop) and invertebrate populations and shifts in fish to smaller-sized individuals and less desirable species (*41*). Although much is known about the effects of channelization on biota, few studies have tried to identify and quantify the environmental variables that are altered by channelization and which affect the distribution and abundance of organisms. Since the main effect of channelization is alteration of stream morphology, clarification of relationships between morphometric variables and biological parameters should provide valuable information for improving engineering designs to minimize the biological impact of channelization (*27, 42*).

There is a significant positive correlation between channel sinuosity and variability (and diversity) of stream depth and stream velocity (*42*). As sinuosity increases (that is, as habitat diversity in-

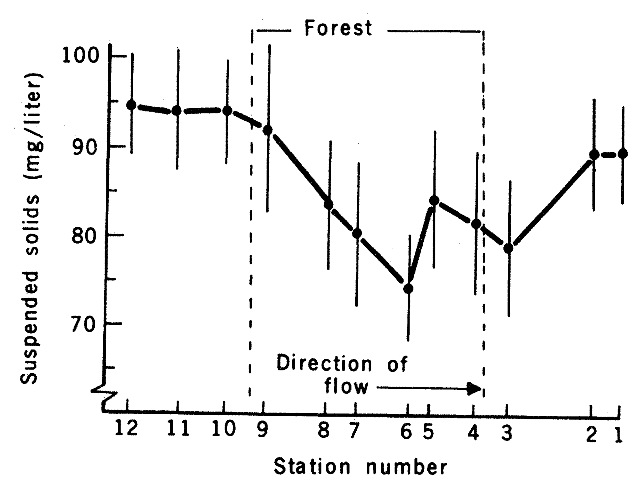

Fig. 2. Changing suspended solids loads in agricultural and forested sections of a headwater stream. Dashed lines indicate margin of forest. High sediment loads at station 5 are due to an erosion problem at the outlet of a field tile. Data from July 1974 to October 1975. Sample size varies from 12 to 16 at each station (*14*).

Table 2. Potential effects of varying management practices on equilibriums of equivalent watersheds. These are best estimates of relative effects for a variety of watershed conditions, including sources and amounts of sediment.

Management practice	Relative amount of sediment from		Suspended solids load in stream	Source of sediment
	Land surface	Stream channel		
Natural watershed	Very low	Very low	Very low	
Clear land for row-crop agriculture; maintain natural stream channel	High	Low*	Medium	Land surface
Channelize stream in forested watershed	Very low	High	High	Channel banks
Clear land and channelize stream	High	High	Very high	Land surface and channel banks
Best land surface management with channelization	Low	High	Medium to high	Channel banks
Best land surface and natural channel	Low	Low	Low to medium	Equilibrium between land and channel

*Will increase if hydrograph peaks (floods) are more severe.

creases), biomass and the number of organisms in the invertebrate drift increases. Further, there seems to be a direct relation between habitat diversity and diversity of fish communities (Fig. 4) among a sample of streams from Indiana and Panama (*27*). Habitat diversity was a composite of bottom type, depth of water, and velocity of flow.

These results confirm our earlier suggestion that money spent on preventing sediments from entering streams will have minimum return value in improving the quality of biota, if present channelization practices continue to destroy the habitat of stream organisms. High water quality is necessary for "fishable" streams but is insufficient in itself without suitable habitat. Data collected in forested watersheds (*12, 43*) and in agricultural areas (*14*) indicates that maintenance of a more natural nearstream vegetation and channel morphology will result in more productive, diverse, and stable stream biotas and should be essential components of section 208 plans to improve stream "fishability" in agricultural watersheds.

Discussion and Conclusions

The dynamics of water quality and biological communities are controlled by a complex interplay of biological, geological, chemical, and physical phenomena in both terrestrial and aquatic environments (*43a, 44*). In undisturbed watersheds both environments are in a dynamic equilibrium. Drastic fluctuations in water levels are uncommon in relatively moist areas. Rainfall is absorbed by the land surface and vegetation and is released over a long period (*45*). There is little surface runoff from natural watersheds during periods of normal rainfall, and nutrient cycles are "tight," with few nutrients being lost to drainage waters (*43a, 46*). The small amounts of nutrients lost from the terrestrial environment are readily assimilated by the biotic communities of the stream. Erosion in this equilibrium state is minimal (*47*).

When natural vegetation is removed, instabilities in the terrestrial environment are an inevitable result, especially if conservation practices are not employed. These instabilities disturb the equilibrium in the aquatic environment. Often, man's response is to modify the stream channel to improve drainage of the land surface and to reduce natural bank erosion and other bank instabilities stimulated by agriculture and urban development. These channelization activities create more instabilities in the aquatic environment. The combined effects of modifications on land and restructuring of channels result in disequilibria in both aquatic and terrestrial areas. Readily observed disequilibrium signs include: (i) Rapid runoff resulting in drastic fluctuations in water levels of streams (*47*). (ii) Large amounts of nutrients and sediments lost from the terrestrial to aquatic component of ecosystems, often over short time periods (*43a, 46, 47*). (iii) Increased fluctuations in stream temperature (*13, 14, 48*). (iv) Increased streambank erosion as the stream attempts to reestablish its equilibrium by forming a

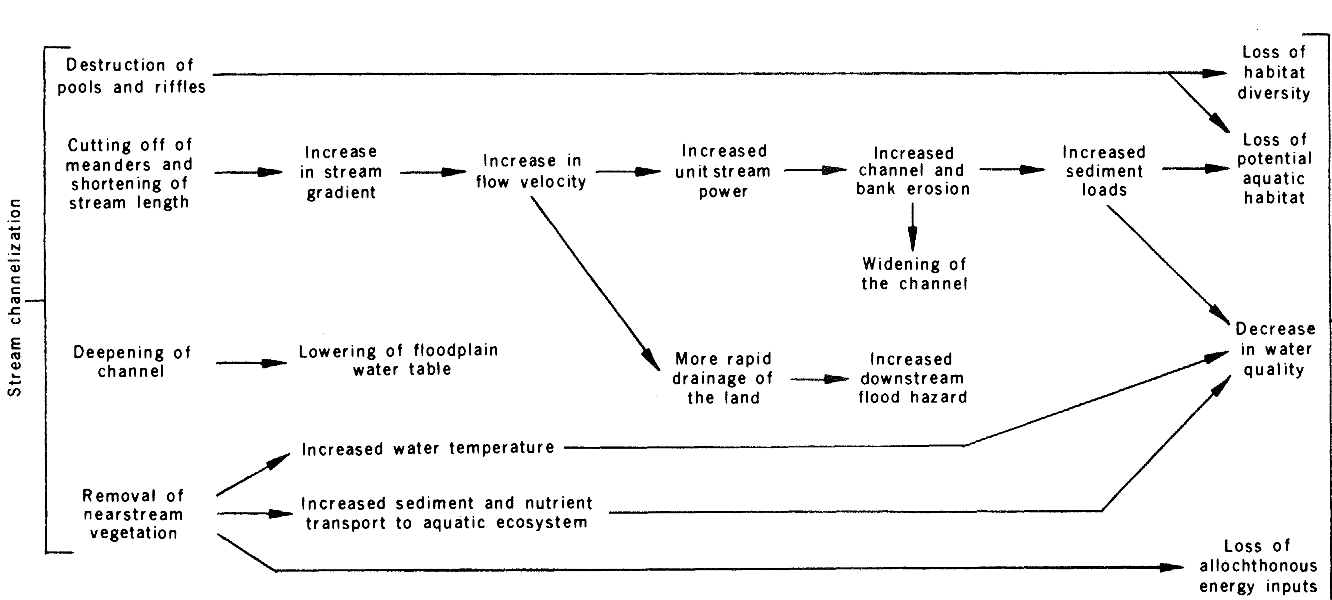

Fig. 3. Effects of channelization on the physical environment and biota of streams [modified from (*37*)].

meandering, pool-and-riffle topography (39, 49). (v) Decreased diversity and stability in the biotic component of the aquatic ecosystem as a result of the less stable environment produced by a complex of sediment, nutrient, temperature, and stream morphology effects (14, 27, 50).

We can utilize this equilibrium concept to demonstrate how amounts and sources of sediments and quality of stream biota might vary with management on six hypothetical, identical watersheds (see Table 2). In a natural watershed, suspended solids will be very low because sources of sediment will be minimal in both terrestrial and aquatic areas. When land is cleared for row-crop agriculture, sources of sediment will be increased. Water quality will decline because of increased availability of sediment and surface runoff. A channeled stream flowing through a forested watershed may have high sediment loads because of higher unit stream power and unstable channel bottom and slopes. The source of sediments is the channel itself. Simultaneous clearing of the land (without conservation measures) and channeling of streams produces very high sediment loads and low-quality stream biota since both the land and the channel are unstable and instream habitat is destroyed. This is the situation throughout much of the United States, especially in the heavy agriculture areas of the Midwest.

A common management program involves use of conservation practices on the land and maintenance of channelized streams. Frequently this involves wholesale changes in channels. We suggest that caution be applied in channel management. In some circumstances local stabilization of channels may be required (51), but in other areas long-established programs of channel control may be unwise (14) and counterproductive to water quality goals.

Many planners tend to equate erosion control as measured by the universal soil loss equation (USLE) with improvements in water quality (52). The inadequacy of USLE in predicting water quality is best illustrated by studies of sedimentation in reservoirs (53). Predicted soil losses in several Illinois watersheds averaged 3.2 tons per acre whereas deposition in reservoirs averaged only 1.0 ton per acre. The proportion of eroded soil which reaches lake beds varies from 10 to 50 percent. We suggest that the low delivery rates may be due to deposition of sediment in low areas, and in nearstream and channel areas.

For long-term benefit to society, the best management option for improved water resources is to continue high-yield agriculture with best management practices on the land surface and more natural (equilibrium) channel management (54). The development of integrated programs based on knowledge of practices from a number of disciplines (best management systems) should replace the more fragmented approach of the past. This should result in the best possible water quality and stream biota. We think that this can be accomplished with little or no negative effect on production of food and fiber for modern society except in areas where production is limited by wetness. Further study is required to determine if ecologically sound channel maintenance is compatible with maintenance of production on poorly drained lands.

Perhaps the economic technique of decision theory (55) should be applied to water resources management in agricultural areas. This will require substantial new research efforts on a number of questions raised in this article. These must be dealt with at individual drainage and watershed levels before the environmental and economic value of these management strategies can be fully evaluated. Without such information section 208 planning efforts will be incomplete and only partially successful in attaining the objective of improved water quality and stream biota under the guidelines of Public Law 92-500.

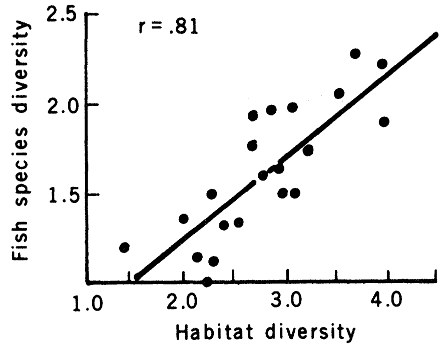

Fig. 4. Regression of fish species diversity on habitat diversity. Habitat diversity is calculated from a combination of substrate, depth, and current characteristics (27).

References and Notes

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4. See E. W. McMunn (*The Ohio Farmer*, 3 September 1977) for an inappropriate use of Black Creek data which violates this important principle.
5. Channel morphology refers to a number of structural characteristics of channels including bank slope, depth, cross-sectional area, and sinuosity.
6. The principles outlined here may not be applicable in all circumstances. However, we feel they are general enough to be valid throughout the high intensity agriculture areas of the midwestern United States. Considerable effort must be expended to determine the validity of these principles under a range of circumstances.
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19. More complex considerations of lift force, critical velocity, drag force, and particle diameter have been added to this basic concept. See (18) for detailed discussions of these factors. Also see C. T. Yang and J. B. Stall [*Proc. Am. Soc. Civ. Eng. J. Hydrol. Div.* **102**, 559 (1976)], F. T. Mavis (*ibid.*, p. 1790), P. R. Jordan [*ibid.* **103**, 290 (1977)], C. F. Nordin, Jr. (*ibid.*, p. 209), B. D. Taylor and V. A. Vanoni (*ibid.*, p. 331), D. W. Hubbell (*ibid.*, p. 455), and G. Parker (*ibid.*, p. 811) for a developing controversy on the use of unit stream power.
20. Roughness factor (n) is an index of the irregularity in a drainage channel. Irregularities reduce the velocity of water flow. For example, n for a clean straight channel at full stage and without

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