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DETERMINANTS OF WATER QUALITY IN AGRICULTURAL WATERSHEDS

by

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ABSTRACT

Water quality was monitored for 17 months in six different agricultural watersheds to evaluate the impact of alterations in riparian vegetation and channel morphology. Sampling was conducted during both base flow and runoff periods.

During base flows, where riparian vegetation had been removed, interactions between biological processes of instream organic production and hydrological processes of seasonally low flows are the primary determinants of seasonal dynamics of suspended solids, turbidity and particulate phosphorus concentrations. Peak levels of all parameters are reached during the summer period of increased biotic activity. Instream organic production is of less importance in regulating water quality where riparian vegetation is maintained and flows are not intermittent. Concentrations of suspended solids remain relatively constant, and seasonal dynamics of phosphorus and turbidity appear to be controlled by leaf inputs in fall. Intermittent flow conditions in summer enhance the importance of instream organic production in controlling water quality, even when riparian vegetation is present.

During runoff events, a simple model based on the KLS factors of the Universal Soil Loss Equation accurately predicts spatial patterns of suspended solids, turbidity, and phosphorus levels in watersheds with a uniform channelized stream, well protected stream banks, and cultivation to the stream edge. The model was not an accurate predictor where heterogeneity in riparian vegetation and channel morphology existed. Suspended solids concentrations were greater than predicted in areas where unstable (fine) substates occur and potential energy of the stream is high due to removal of riparian vegetation and creation of a uniform and straight channel. Timing of the peak concentrations in these areas seemed to be related to major flushes of discharge due to rapid urban drainage or delayed addition of surface or subsurface inputs. This suggests that water quality during runoff events is primarily governed by hydrological processes. Biological processes determine incipient conditions. The hydrological processes involve complex interactions between watershed erosion potential, channel equilibrium, hydrological impacts of riparian vegetation, and magnitude of the runoff event.

These results indicate that the relevant theory for enhancement of water resources and for modelling water quality in agricultural watersheds varies depending on flow conditions. During base flow, emphasis should be placed on linking hydrological theory of instream transport of inorganic material to biological theory of production and transport of organic material. During runoff events, emphasis should be placed on linking of erosion predictions from agricultural theory to geomorphological theory of stream equilibrium and sediment transport. Such interdisciplinary linkages should provide resource management decisions which will have the greatest chance of success and broadest range of applicability.

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INTRODUCTION

Societal concern for deteriorating quality of water resources has resulted in major federal and state initiatives to halt and even reverse that degradation. The goal of these programs is preservation of the "physical, chemical, and biological integrity" of water resources (U. S. Congress, 1972). Early pollution control efforts emphasized point sources. More recently attention has shifted to control of nonpoint sources. In agricultural watersheds the primary strategy for achieving this goal involves two major steps (Beasley, 1977; Donnigan and Crawford, 1977; Miller et al., 1979): (1) modelling the terrestrial portion of the watershed to identify critical erosive areas, and (2) treating these areas with traditional soil conservation practices. This approach seeks to improve characteristics of water entering stream channels during transient runoff periods. The primary attributes of water quality considered in these efforts are suspended solids and nutrients (especially nitrogen and phosphorus fractions). A wide range of other pollutants may also be considered. The expectations of nonpoint control efforts are improvements in water resources both within the impact area and in downstreams reaches (U. S. Environmental Protection Agency, 1980).

The underlying assumptions of this approach are that: (1) physical processes in the terrestrial portion of the watershed are primary determinants of water quality and (2) quality of biological resources is controlled by transient conditions during runoff events. It is generally argued that annual mass export (loading) is determined by a few major runoff events (Lake and Morrison 1977). Thus regulation of water quality, it is argued, must focus on these events rather than on circumstances during the more common low-flow conditions.

A substantial body of theory and empirical evidence suggests that acceptance of these assumptions may not be in the best interest of the widest array of water resource objectives. Geomorphological (Leopold et al., 1964; Evans and Schnepper, 1977; Leedy, 1979), hydrological (Stall and Yang, 1972; Yang and Stall, 1974), and ecological (Moring, 1975; Bormann and Likens, 1979) studies suggest that physical and biological processes occurring in channel and riparian areas also have substantial impact on seasonal dynamics of water quality during both base flow and runoff conditions (Karr and Schlosser, 1978). Furthermore, the importance of water quality during base flow to biological integrity is firmly established (Hynes, 1970, 1974).

This accumulation of evidence demands an expanded perspective in the evaluation and control of nonpoint pollutants to streams in agricultural watersheds. The goals of this effort must be broadened to include reduction in mass export of sediment and related pollutants during runoff conditions as well as recognition of the role of water quality characteristics in determining biotic integrity during average flow conditions. The development of a management strategy using these principles must be based on a better understanding of the role of physical and biological processes in terrestrial, riparian, and aquatic portions of watersheds.

The purposes of this project were to initiate an evaluation of (1) the impact of riparian vegetation on water quality under base flow conditions, (2) the impact of point sources of pollution on water quality in agricultural watersheds under varying flow conditions, and (3) the role of riparian vegetation, channel morphology, and erosive potential in controlling water quality during runoff events.

Due to limited availability of funds, it was not possible to automate sampling sites. In addition, limited staff and funds for travel to the study watersheds, especially in the second year, precluded many valuable field activities as well as measurement of a number of water-quality parameters. Despite these financial and logistical limitations we have been able to show major variations in water quality characteristics as functions of nearstream vegetation and channel morphology as well as the more conventional parameters such as erosive potential in the watershed. The relative importance of these factors in governing water quality parameters varies with flow conditions. Thus, the body of this report is divided into two major sections which detail these dynamics during periods when no surface runoff had occurred for at least one week (base flow) and during periods of significant surface runoff.

STUDY AREAS

We studied six watersheds differing in impact of point-source inputs, channel morphology, type of riparian vegetation, and spatial pattern of erosive potential within the watershed. Five are located in Champaign and Vermilion counties within 50 km of Champaign-Urbana, Illinois (Fig. 1A,B). The other is located 100 km south of Champaign-Urbana in Coles and Cumberland counties (Fig. 1C). Three of the watersheds (Big Ditch, Spoon River, and Jordan Creek) were sampled during both base flow conditions and runoff events.

Three other watersheds (Hurricane Creek, Collison Creek, and the Embarras River) were sampled only during base flow conditions to evaluate the generality of results from low flow conditions in a wider array of streams.

Big Ditch

Big Ditch is a large watershed (75-90 km^2) originating 1 km east of Rantoul, Illinois in the Sangamon River drainage (Fig.1A). Land use is intensive agriculture with greater than 90% row crops (corn and soybeans). Soil types are dominated by the Sidell-Parr and Drummer-Brenton-Elburn association in the more rolling areas of the watershed and Drummer-Flanagan association in the level areas. The stream is channelized with cultivation to the stream edge and little pool-riffle development (Fig. 2). Entering the upper portion of the stream is a municipal wastewater input of approximately 75 million liters per day (30 CFS).

Spoon River

Spoon River is a moderately large watershed (30-40 km^2) located in Champaign County approximately 8 km north of St. Joseph, Illinois in the Salt Fork drainage (Fig.1A). Land use is intensive agriculture with more than 90% row crops. Soil types are predominantly the Elliott-Varna association in rolling areas and Drummer-Brenton-Elburn in level areas. The stream is channelized with cultivation to the edge and little pool-riffle development (Fig. 3). There are no municipal inputs, although some small septic inputs produce localized impacts on water quality.

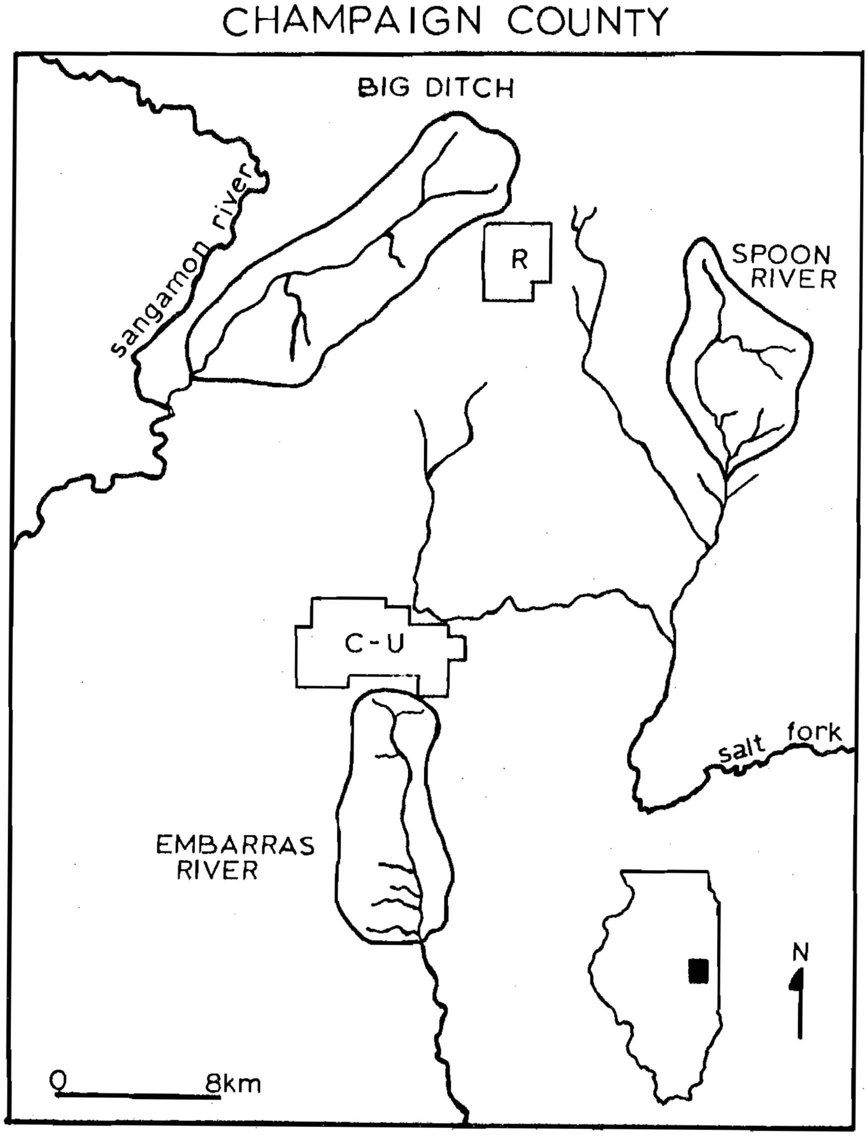

Figure 1A. Map of Champaign County showing locations of Big Ditch, Spoon River, and Embarras River watersheds. (C-U = Champaign-Urbana ; R=Rantoul)

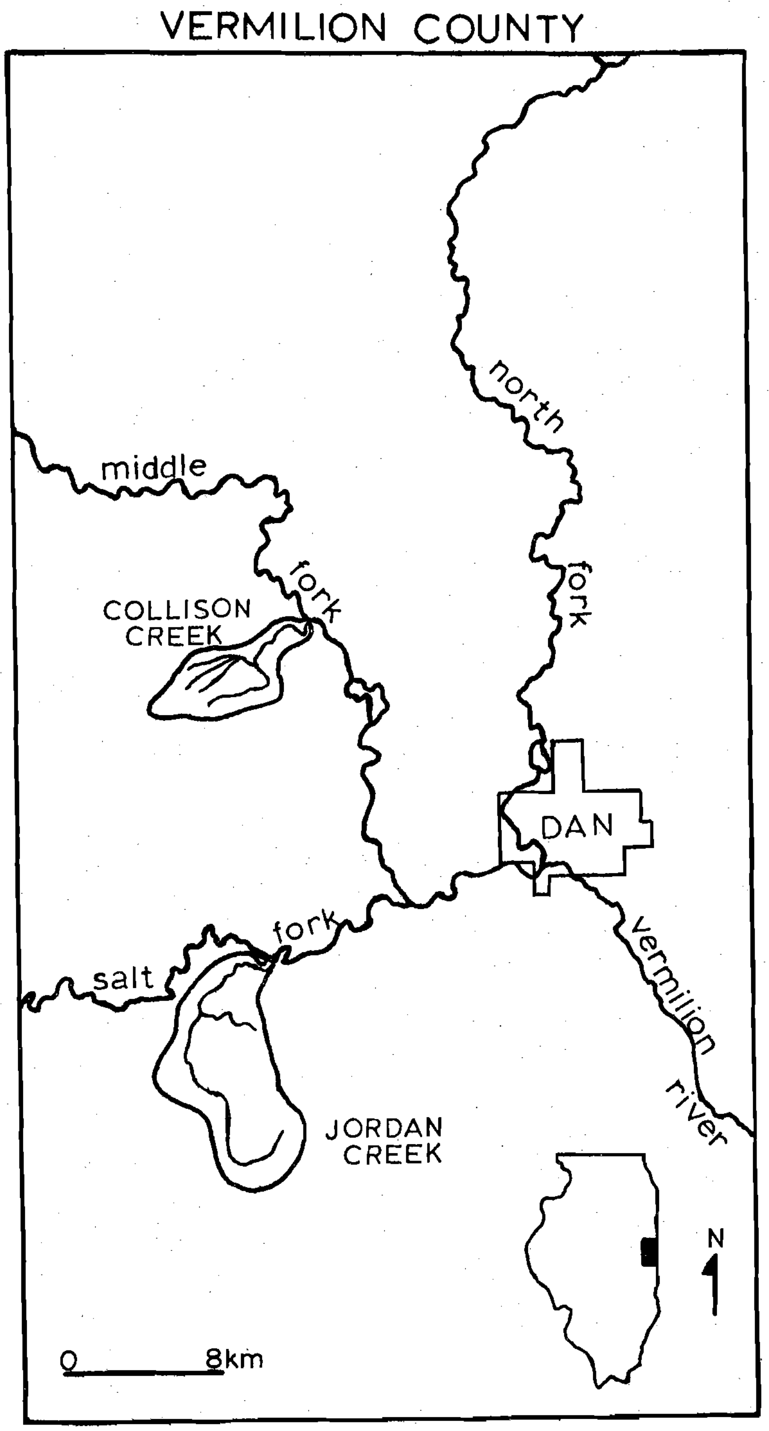

Figure 1B. Map of Vermilion County showing locations of Collison Creek and Jordan Creek watersheds. (DAN = Danville).

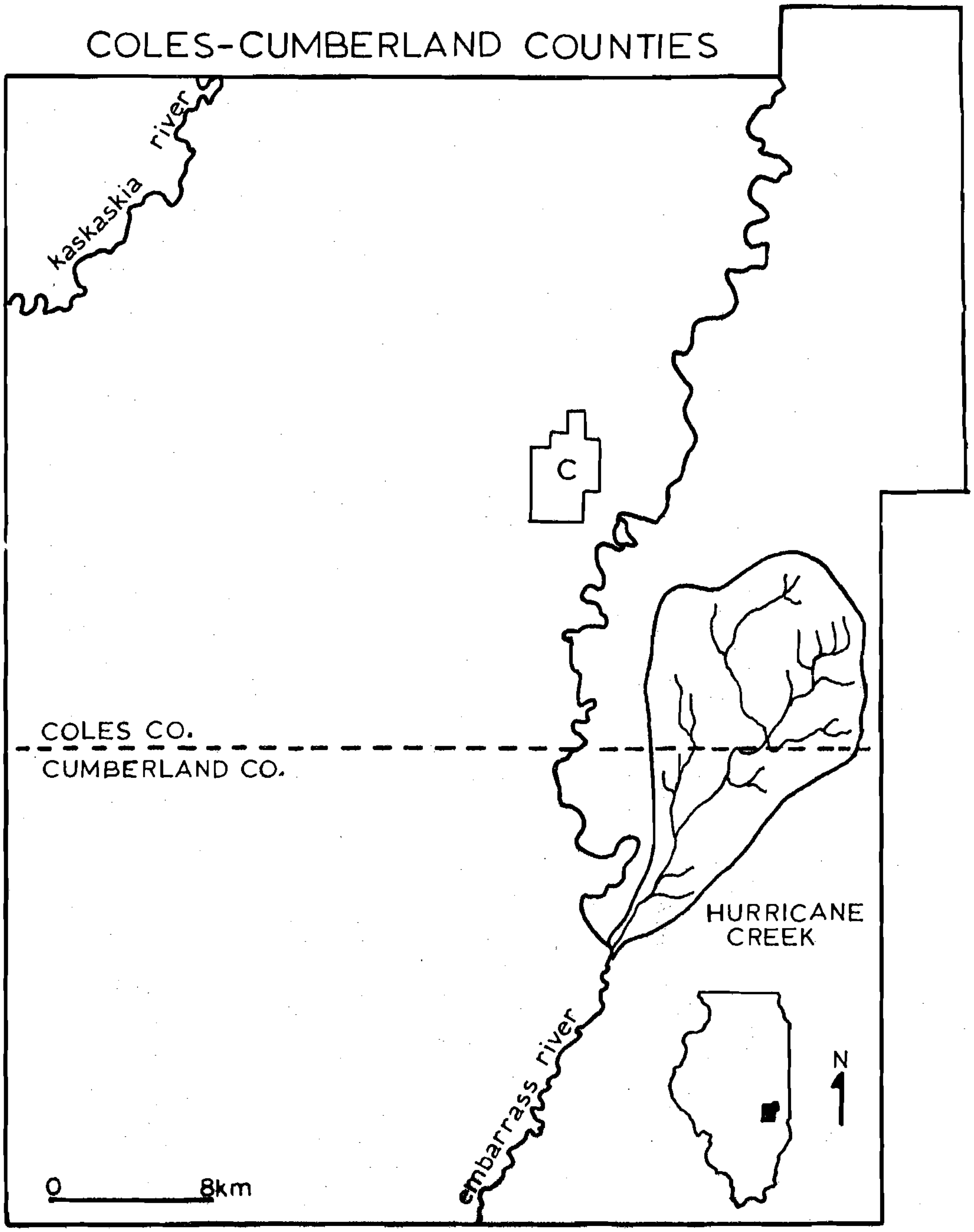

Figure 1C. Map of Coles and Cumberland counties showing location of Hurricane Creek watershed. (C = Charleston).

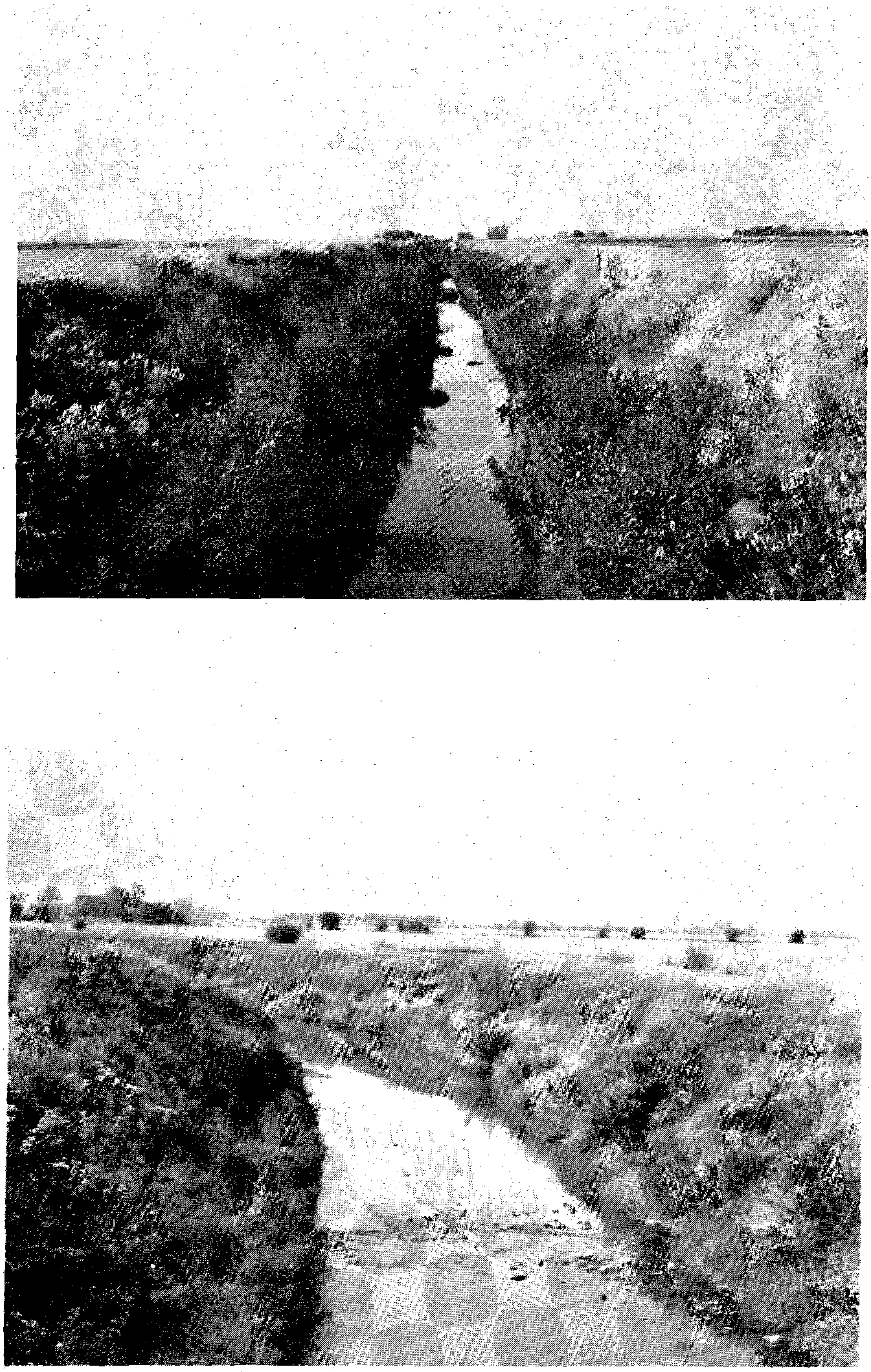

Figure 2. Channel and riparian conditions in upstream (top photo) and downstream (lower) Big Ditch, Champaign County, Illinois.

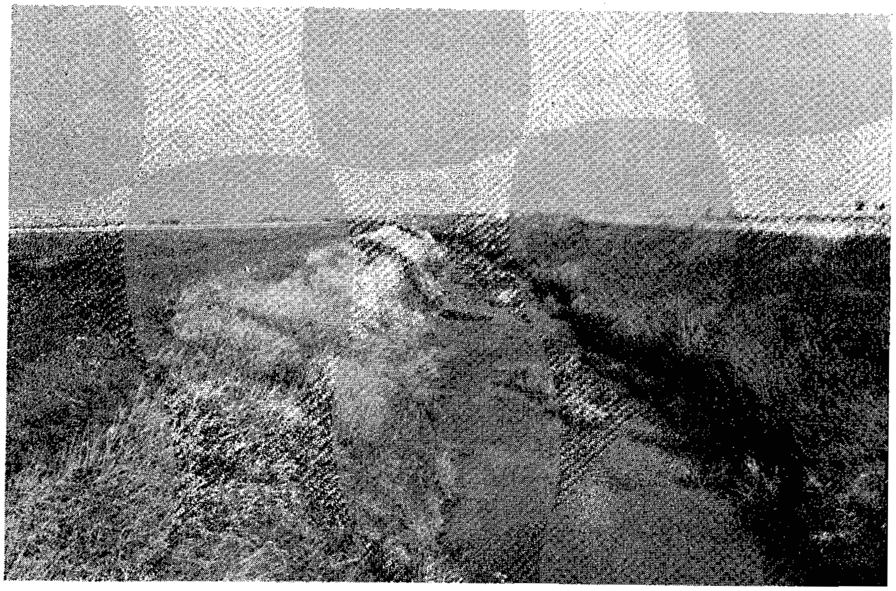

Figure 3. Channel and riparian conditions in upstream (top photo) and downstream (lower) Spoon River, Champaign County, Illinois.

Jordan Creek

The watershed of Jordan Creek (25-50 km^2) is located in Vermilion county 50 km east of Champaign-Urbana in the Salt Fork drainage (Fig. 1B). Land use is intensive agriculture with 80-90% row crops. Soil is primarily the Drummer-Flanagan association, except in rolling areas near the Salt Fork river where Fincastle-Russell dominates. Since riparian vegetation and channel morphology vary along the length of the stream, we divided the stream into four distinct regions.

In Region 1 the stream is channelized with cultivation to the edge and no pool-riffle development (Fig. 4). Region 2 has moderate pool-riffle development and is bordered on each bank by an 8-10 meter strip of riparian vegetation (Fig. 5). The vegetation is composed of a mixture of maple (*Acer* spp.), willow (*Salix* spp.), box elder (*Acer negundo*), hackberry (*Celtis occidentalis*), ash (*Fraxinus* spp.), black cherry (*Prunus serotina*), elm (*Ulmus* spp.), osage orange (*Maclura pomifera*), multiflora rose (*Rosa multiflora*), poison ivy (*Rhus radicans*), and golden rod (*Solidago* spp.). Region 3 is a side branch entering the mainstream below Region 2. The stream is channelized (no pool-riffle development) and cultivated to the stream edge (Fig. 6) except in isolated areas where riparian vegetation similar to that of Region 2 is present. This side branch receives a septic input from Fairmount, Illinois during base flows and combined storm-sewer inputs during storm events. Region 4 has well developed pools and riffles and is bordered on each side by a belt of relatively mature forest 10-400 m wide (Fig. 7). Vegetation is dominated by maple, oak (*Quercus* spp.), cottonwood (*Populus deltoides*), sycamore (*Plantanus occidentalis*), ironwood (*Carpinus caroliniana*), poison ivy, and multiflora rose.

Hurricane Creek

Hurricane Creek with an area of 75-90 km^2 is located approximately 100 km south of Champaign-Urbana in Cumberland and Coles Counties in the Embarras River drainage (Fig. 1C). Land use is intensive agriculture with greater than 80% row crops. Soils in rolling areas of the watershed are dominated by the Russell-Miami association. The more level areas consist

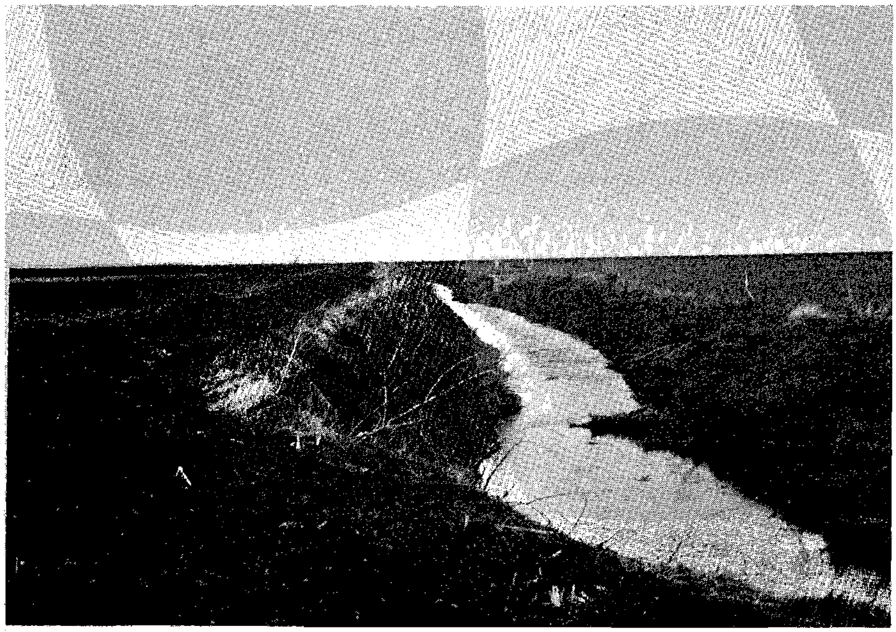

Figure 4. Channel and riparian conditions in Region 1 (headwaters) of Jordan Creek, Vermilion County, Illinois.

Figure 5. Riparian vegetation (top photo) and channel conditions (lower) in Region 2 of Jordan Creek, Vermilion County, Illinois.

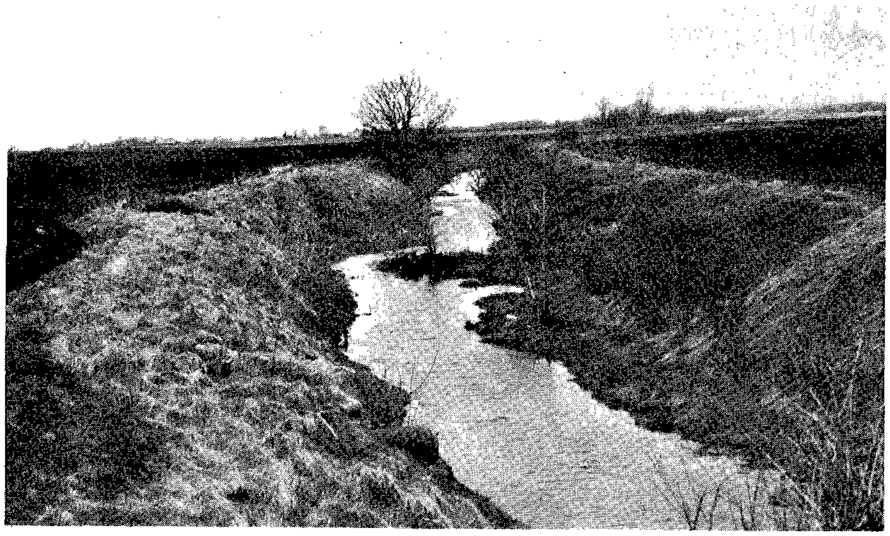

Figure 6. Riparian vegetation and channel conditions in Region 3 of Jordan Creek, Vermilion County, Illinois.

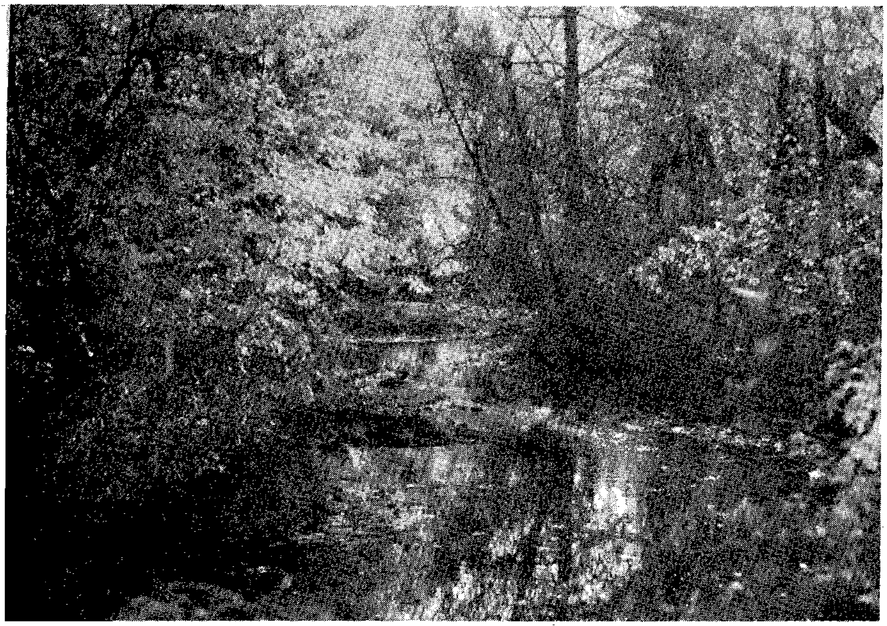

Figure 7. Riparian vegetation and channel conditions in Region 4 of Jordan Creek, Vermilion County, Illinois.

primarily of Cowden-Weir and Stoay-Hickory associations. The stream has moderately well developed pools and riffles. It is bordered by a 10-20 meter strip of riparian vegetation dominated by cottonwood, willow, and sycamore with only scattered individuals of maple, elm, and ash. Very few oaks occurred along this stream. There are no municipal inputs to the stream, but feedlot inputs in the upper portion of the watershed have localized impacts on water quality.

Collison Creek

Our smallest watershed (Collison Creek, 15-18 km^2) is located in northeast Vermilion County in the Vermilion River drainage system (Fig. 1B). It is bordered by a strip of riparian vegetation 10-75 meters wide composed of a mixture of oak, maple, osage orange, box elder, black cherry, ash, hackberry, bluegrass (Poa) pasture. The major land use is intensive agriculture with greater than 90% row crops. Soils in the more level areas of the watershed are the Ashkum-Elliott-Andres and Elliott-Varna associations. More rolling and bottomland areas bordering the creek are of the Blount-Morely and Howson-Strawn associations. The stream has moderately well developed pools and riffles. Because of the small watershed size, the stream is intermittent during low flows, when it forms a series of isolated pools.

Embarras River

The Embarras River study area includes a moderately large watershed (50-65 km^2) located in the headwater of the Embarras River drainage (Fig. 1A). Land use is intensive agriculture with greater than 90% corn and soybeans. Soil type in the watershed is predominantly of the Drummer-Flanagan association, although areas adjacent to the stream are of the Drummer-Brenton-Elburn association. The stream has a low gradient and is channelized with poorly developed pools and riffles. Cultivation is to the stream edge along most of its length, except in isolated areas where bluegrass pastures are maintained or willows have colonized. A point input of municipal wastewater from Savoy, Illinois occurs in the upper portion of the watershed. Daily inputs averaged approximately 430,000 liters per day until January, 1979, when flow was diverted.

SELECTION OF SAMPLE SITES

General surveys were conducted in each watershed to identify the major patterns of land use, topography, and channel conditions. A total of 54 stations were located throughout the six watersheds. The number of sample stations per watershed varied from 7 to 12, with stations located in both headwater and downstream areas and above and below point inputs. Appendix I provides locations of stations in each watershed.

COLLECTION AND ANALYSIS OF WATER SAMPLES

When conditions permitted, the six watersheds were sampled at monthly intervals for 1-1/2 years from November 1977 through April 1979. The sampling period covers the summer and fall of 1978 and the winter and spring of both 1978 and 1979.

Sampling during runoff events was limited to three watersheds in closer proximity to Champaign-Urbana: Big Ditch, Spoon River, and Jordan Creek. These streams also represented extremes of watershed conditions including nearstream vegetation and channel morphology.

Sampling protocols during runoff events were designed to yield data at several points along the hydrograph. As a result, only a subset of the stations within each watershed could be sampled effectively with the available manpower. Sites were selected from among the 54 sites sampled during base flows based on distribution of critical erosive areas within the watershed, channel morphology, riparian conditions, and presence or absence of point inputs. Initiation of sampling always occurred within one hour of initiation of surface runoff.

Local weather broadcasts and weather radar on a cable television station were monitored to assess the movement of frontal systems over the study watershed. It was possible to be at watersheds either before precipitation started or within 45 minutes of initiation of rainfall. Samples were collected at preselected stations usually on an hourly basis (except in Big Ditch), although sometimes more frequently. Big Ditch samples were collected 2, 6, and 13 hours into the event because of its larger watershed size and slower change in water quality during runoff events. Sampling was most intense during the rising portion of the hydrograph, which was usually during the first 6-7 hours after initiation of runoff. Limited sampling was done during the receding hydrograph. Since no rainfall gauges were present within the watersheds, we have used daily precipitation records from the nearest weather station to estimate amounts of rainfall.

The weather station records used were Rantoul for Big Ditch, Rantoul and Urbana for Spoon River, and Urbana and Danville for Jordan Creek.

All water samples were collected by attaching a 1-liter sample bottle to a long metal pole and lowering it at a uniform rate to the bottom at the center of the stream. The bottle was instantly reversed upon contact with the bottom and raised to the surface at a uniform rate. This technique follows standard United States Geological Survey procedures (Evans and Schnepper, 1977) and allows sampling throughout the water column.

Samples were chilled in an ice chest between the time of collection and freezing. Samples were frozen within 2-6 hours of collection and held in a freezer until analysis. All chemical analyses were conducted at the Water Quality Laboratory, Illinois Natural History Survey. The following parameters were measured on all samples: conductivity, dissolved solids, hardness, turbidity, total phosphorus, soluble orthophosphorus, nitrate, nitrite, ammonia and suspended solids. Measurement of particulate phosphorus was based on the difference between total and soluble phosphorus and includes a variety of phosphorus forms (American Public Health Association, 1976). Procedure for analysis of water samples are given in Appendix II.

WATER QUALITY DURING BASE-FLOW CONDITIONS

Definition of Seasons

A major goal of base flow sampling was to evaluate seasonal differences in water quality. Our hypothesis was that alterations in riparian vegetation have significant impacts on the seasonal dynamics of water quality. Emphasis was placed on analyzing the dynamics of suspended solids, turbidity and phosphorus. Four seasons were established based on periodicity of biological activity and flow conditions observed during the sample period. December through February was defined as winter, with March through mid-May defined as Spring. Only a small number of samples was obtained in winter due to ice cover. Furthermore, because of similarity in water quality between winter and spring, samples were combined into one winter-spring (WS) period. This represents a time of well-maintained flows with decreased primary production. Mid-May through August was defined as summer (S), a period of moderate to low-flow conditions and the period of most intense primary production, especially in areas where riparian vegetation had been removed. The fall (F) period extended from September through November. During this period primary production declined as water temperatures decreased and flow rates were generally low. In addition, areas with riparian vegetation experienced high detrital (leaf) inputs.

Pooling of Data

Unless otherwise indicated, all statistical analyses referred to in this report are based on t-test comparisons of means of independent samples with a two-tailed hypothesis. Where populations had unequal variances, t was based on a separate rather than a pooled variance estimate (Nie et al., 1975).

Data were pooled by season for each sample site on each stream. Pooling across years was necessary for the WS period. Jordan Creek was the only stream with a large number of WS samples from both 1978 and 1979. No significant differences ($P>.10$) were detected for water quality parameters between years.

The possibility of pooling stations within watersheds was also examined. Comparison within a stream of stations with similar riparian conditions and no point inputs indicated no significant difference (P>.05) in all parameters over all seasons. Furthermore, a comparison between Region 1 of Jordan Creek and Spoon River, both areas without riparian vegetation or municipal inputs, yielded no significant difference (P>.10) across all seasons for all parameters. Therefore, for the watersheds sampled, samples from areas with similar riparian habitats and no muncipal inputs were not significantly different. Thus, they can be pooled both within and between streams for analysis of seasonal trends. Because of the major municipal input in the upper region of Big Ditch and the Embarras River, significant (P<.01) differences among stations occurred within the stream. Therefore, pooling of samples between stations was not possible and analyses emphasized seasonal changes in the gradient of water quality downstream from the municipal input.

Streams Without Point Inputs

Suspended Solids. When areas without point inputs are compared, the effect of riparian vegetation varies with season. Suspended solid concentrations are not significantly different (P<.05) during the winter-spring season (Fig. 8) independent of near-stream vegetation. However, suspended solids increase significantly (P<.01) in the summer in streams without riparian vegetation (Fig. 8A). In contrast, suspended solids concentrations do not change significantly (P>.10) throughout the year in areas that maintain flows and are bordered by riparian vegetation (Fig. 8B, 8C). Where riparian vegetation is present but flows are intermittent, significant (P<.01) increases in suspended solids occur during summer but a significant (P<.01) decrease occurs when flow resumes in fall (Fig. 8D).

Budgetary limitations precluded sample analysis to evaluate the relative contributions of organic and inorganic fractions to suspended solids. However, information in the literature strongly suggests instream organic production is the primary source of elevated suspended solids

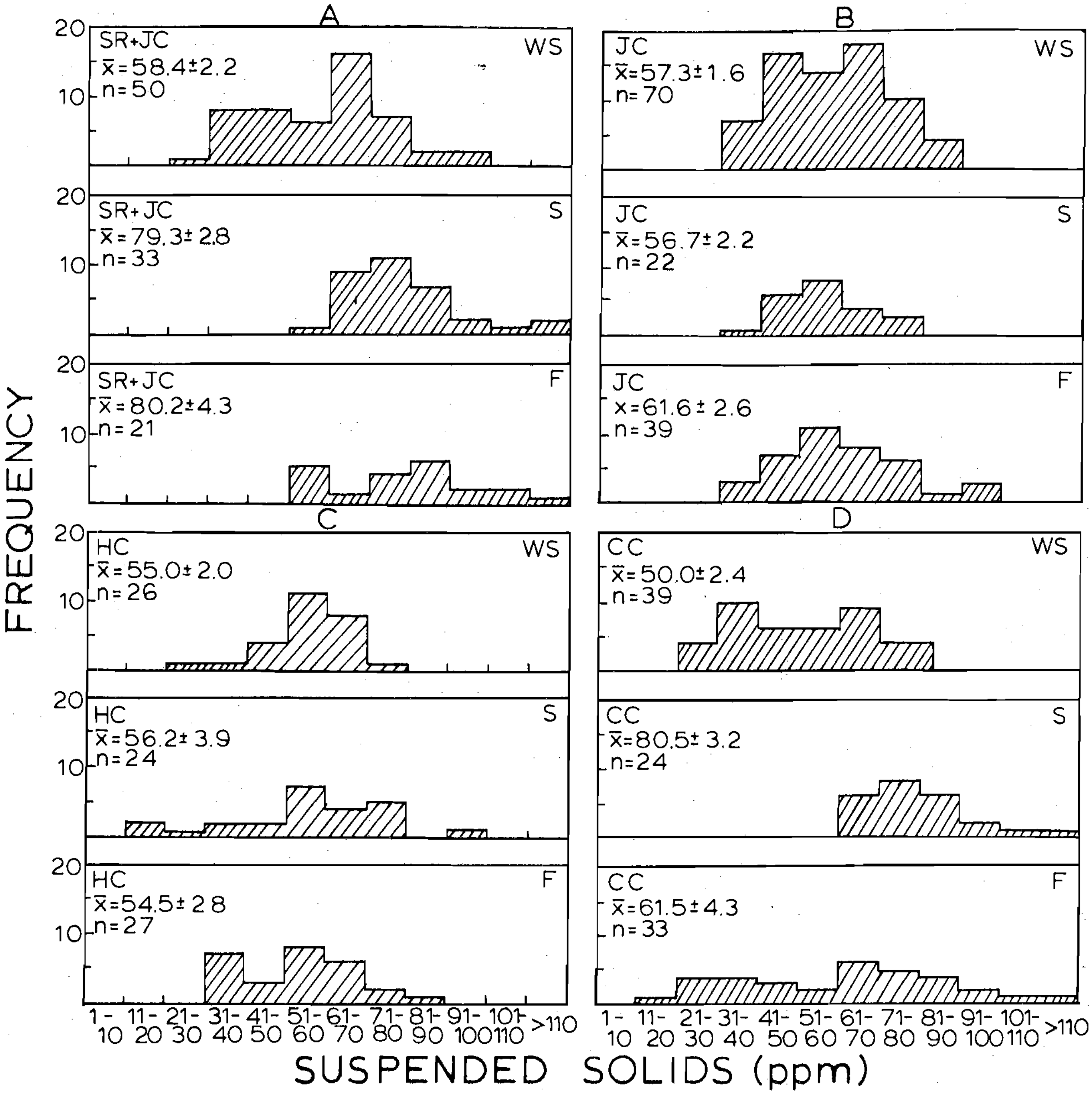

Figure 8. Frequency distribution of suspended solids concentrations in four different streams. A - Spoon River and Jordan Creek (SR + JC), Regions with no riparian vegetation. B - Jordan Creek (JC), Regions with riparian vegetation. C - Hurricane Creek (HC). D - Collison Creek (CC). Seasons: WS - Winter - Spring; S - Summer; F - Fall.

during summer and fall when low flows occur and/or where riparian vegetation has been removed. In a sampling program on 14 streams in Iowa, Kilkus (1972, in Swanson and Bachman, 1976) found average summer levels of suspended algae of 24,500 cells/ml and 55 mg/m^3 of chlorophyll a. Kilkus et al. (1975) concluded that due to elevated levels of essential nutrients, physical parameters were major factors limiting algal densities. Physical parameters were statistically related to changes in concentrations of suspended algae and, during the summer, volume of flow was the most significant variable. Greater densities were found at lower flows. As flows decrease from 10 m^3/sec to $1m^3/sec$ in the Skunk River, Iowa, concentrations of suspended chlorophyll a increase hyperbolically from less than $10mg/m^3$ to greater than $90mg/m^3$ (Swanson and Bachman 1976). Other physical parameters positively associated with increasing algal densities include temperature (Kilkus et al., 1975), light (Blum, 1956) and upstream bottom area (Swanson and Bachman, 1976). The latter relationship between upstream bottom area and algal density suggests these suspended algae originate from benthic populations rather than being truly planktonic in origin (Butcher, 1932; Blum, 1954; McIntire, 1968).

Therefore, the seasonal fluctuations in suspended solids concentrations observed during base flows in this study appear to be a function of interactions between in-stream benthic algae production and hydrological transport and dilution of this material. The burst of summer production and increase in suspended solids concentration is not as extreme where riparian vegetation is present to reduce temperatures and light intensities (Karr and Gorman, 1975) and where flow is maintained to dilute the algal densities (Swanson and Bachman, 1976).

Turbidity. Turbidity levels in the four streams show seasonal patterns similar to but somewhat different from suspended solids. All areas have similar turbidity levels during the winter-spring period (Fig. 9). Following the pattern of increased levels of suspended solids in summer and fall, streams not bordered by riparian vegetation experience

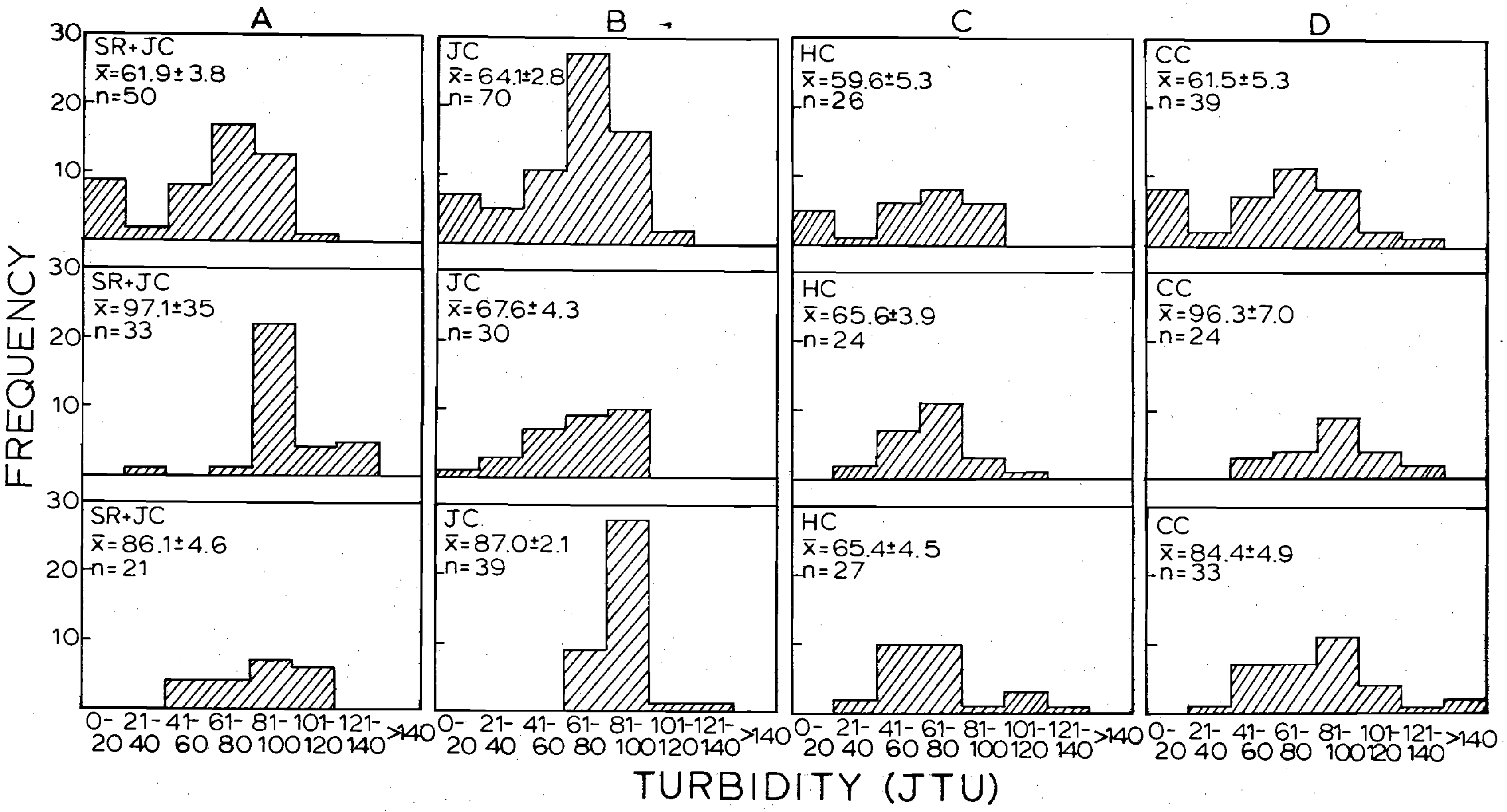

Figure 9. Frequency distribution of turbidity (Jackson Turbidity Units) in four different streams. A - Spoon River and Jordan Creek (SR + JC), Regions with no riparian vegetation. B - Jordan Creakk (JC), Regions with riparian vegetation. C - Hurricane Creek (HC). D - Collison Creek (CC). Seasons: WS - Winter - Spring; S - Summer; F - Fall.

significant (P<.01) increases in turbidity in summer. High turbidities persist through the fall in these areas (Fig. 9A). Streams bordered by riparian vegetation and with continuous flow have turbidity levels in summer not significantly (P>.10) different from winter-spring (Fig. 9B, 9C).

However, the two streams differ in the fall. Fall turbidity in Hurricane Creek is not significantly (P>.05) different from summer levels while turbidity increases (P<.01) from summer to fall in Jordan Creek, even though levels of suspended solids remain constant during the same period (Fig. 8B). Thus, caution must be used in relating turbidity to suspended solids concentrations, especially during base flow conditions. Suspended solids is a function of density of material in suspension, while turbidity is a function of its capability to scatter light. The two are not always equivalent. Increases in turbidity during fall in Jordan Creek seem to be due to an increase in concentration of organics from leaf inputs (Nykvist, 1959, 1962; Cummins et al., 1972; I. J. Schlosser, pers. observ.). Differences between Jordan Creek and Hurricane Creek may be due to differences in type of nearstream vegetation and leaf composition (see description of study areas regarding these differences).

Collison Creek is bordered by riparian vegetation and experiences periods of intermittent flow. This results in different seasonal patterns in turbidity (Fig. 9D). Turbidity increases significantly (P<.01) during summer in association with elevated suspended solids (Fig. 8D). However, even though suspended solids decrease from summer to fall, turbidity levels are not significantly different (P>.05) between the two seasons. Riparian vegetation along Collison is similar to that along Jordan, and elevated turbidity levels are probably due to organics leached from leaf inputs.

These results indicate that seasonal fluctuations in turbidity correspond to fluctuations in suspended solids except in fall. Significant increases in both parameters occur in summer in streams not bordered by riparian vegetation and/or with intermittent flow. However, increases in turbidity in the absence of increases in suspended solids occur during the fall in streams bordered by riparian vegetation, apparently due to leaching of organics from leaf inputs. The amount of increase seems to be influenced by species composition of the leaf inputs from riparian vegetation.

Phosphorus. Analysis of seasonal dynamics of phosphorus components shows a similar pattern regarding the importance of instream production versus leaf inputs (Fig. 10). In winter-spring, similar levels of total, particulate, and soluble phosphorus occur in streams (Fig. 10). In summer, areas not bordered by riparian vegetation experience significant $(P<.01)$ increases in total phosphorus, especially the particulate fraction (Fig. 10A). A nearly significant $(P<.06)$ decrease in total phosphorus occurs in fall, again caused by changes in particulate phosphorus (Fig. 10A). Areas bordered by riparian vegetation which are not intermittent experience significant $(P<.05)$ increases in total and particulate phosphorus in fall (Fig. 10B, 10C) rather than in summer. In areas with riparian vegetation but with intermittent flow, total and particulate phosphorus increase significantly $(P<.01)$ during the summer (Fig 10D). However, unlike areas not bordered by riparian vegetation, no significant $(P>.10)$ decrease in turbidity occurs in the fall.

Therefore, during base flow conditions in areas not impacted by major point sources or septic inputs, seasonal dynamics of phosphorus concentration are tied primarily to seasonal dynamics of particulate phosphorus (Fig. 10). Peak phosphorus levels in streams without riparian vegetation occur during summer periods of elevated instream organic production. Peak phosphorus levels in streams with riparian vegetation and well maintained flows occur during periods of leaf inputs in fall. Streams bordered by riparian vegetation but with intermittent flow have elevated phosphorus levels during both summer and fall, apparently due to elevated organic production during extreme low-flow conditions and leaf inputs in fall.

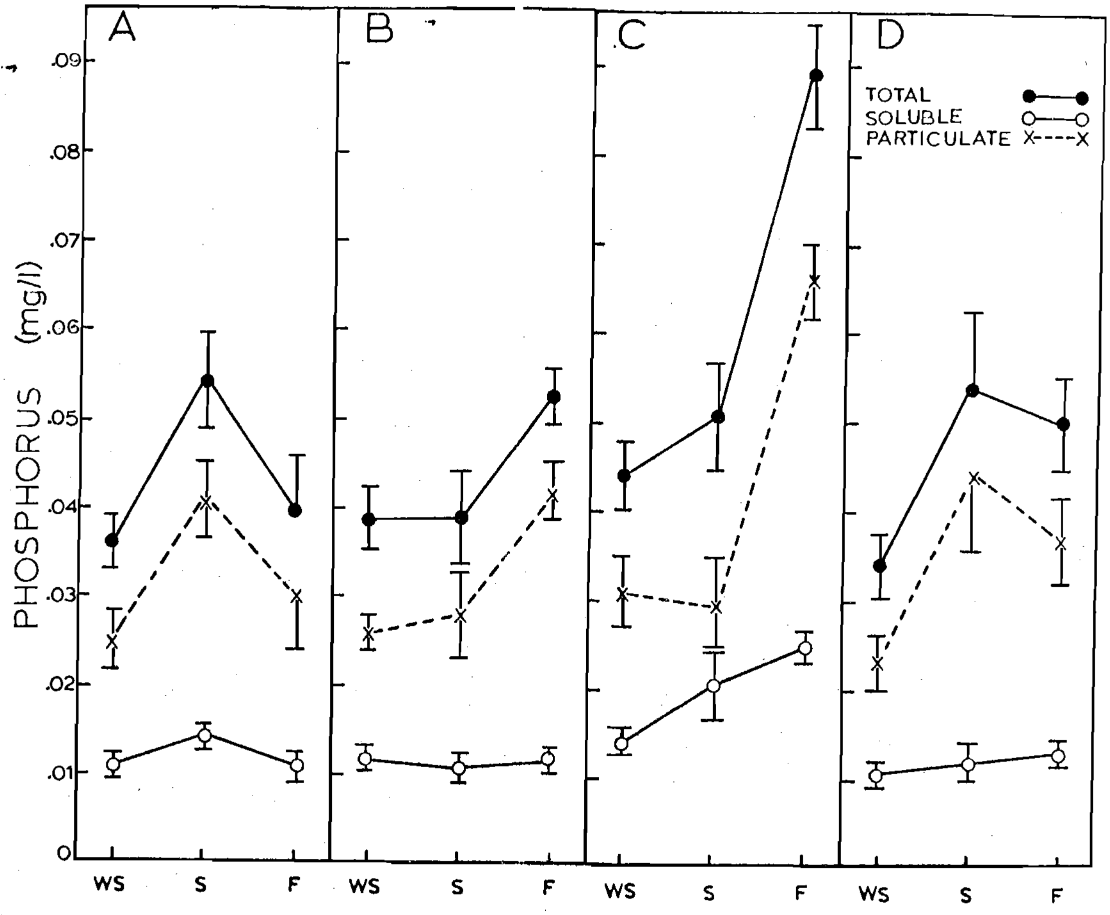

Figure 10. Seasonal dynamics of phosphorus concentrations (mean ± 1 SE) in four streams. A - Spoon River and Jordan Creek (without riparian vegetation). B - Jordan Creek (with riparian vegetation). C - Hurricane Creek. D - Collison Creek. Seasons: W-S: Winter - Spring; S: Summer; F: Fall.

Streams with Point Inputs

Impact of point inputs on these patterns is illustrated by examining data from Big Ditch and the Embarras River. Three things must be kept in mind when examining these data:

1. As in the other four watersheds, flow in Big Ditch and the Embarras River decreased throughout the summer and fall of 1978. However, unlike the other streams, Big Ditch and the Embarras River received an average point discharge of 75 million and 430,000 liters of wastewater per day, respectively. Therefore the flows present in these streams were maintained by an input of municipal wastewater.

2. The watersheds of Big Ditch and the Embarras River are twice as large as the Spoon River, the other watershed without riparian vegetation. Thus higher discharge should be considered as a variable which may account for some of the differences independent of the point input.

3. Limited replication of samples prevents statistical analysis of patterns. However, consistency of results among streams suggests the patterns are real.

Suspended Solids. Concentrations of suspended solids in Big Ditch and the Embarras River vary as a function of season and distance from the site of point source inputs (Fig. 11). Winter-spring levels are relatively constant with a tendency to increase in downstream stations where discharge and velocity are greater. This tendency is especially strong in Big Ditch, the larger watershed with an increased gradient in downstream areas. Winter-spring and summer concentrations of suspended solids are similar in extreme upper and lower reaches (Fig. 11). Summer suspended solids levels are depressed near the point input. However, they gradually increase below it, with peak levels occurring 5-6 miles below the point input rather than farther downstream where discharge is greatest. This mid-watershed peak is likely due to organic production, rather than strictly hydrological processes.

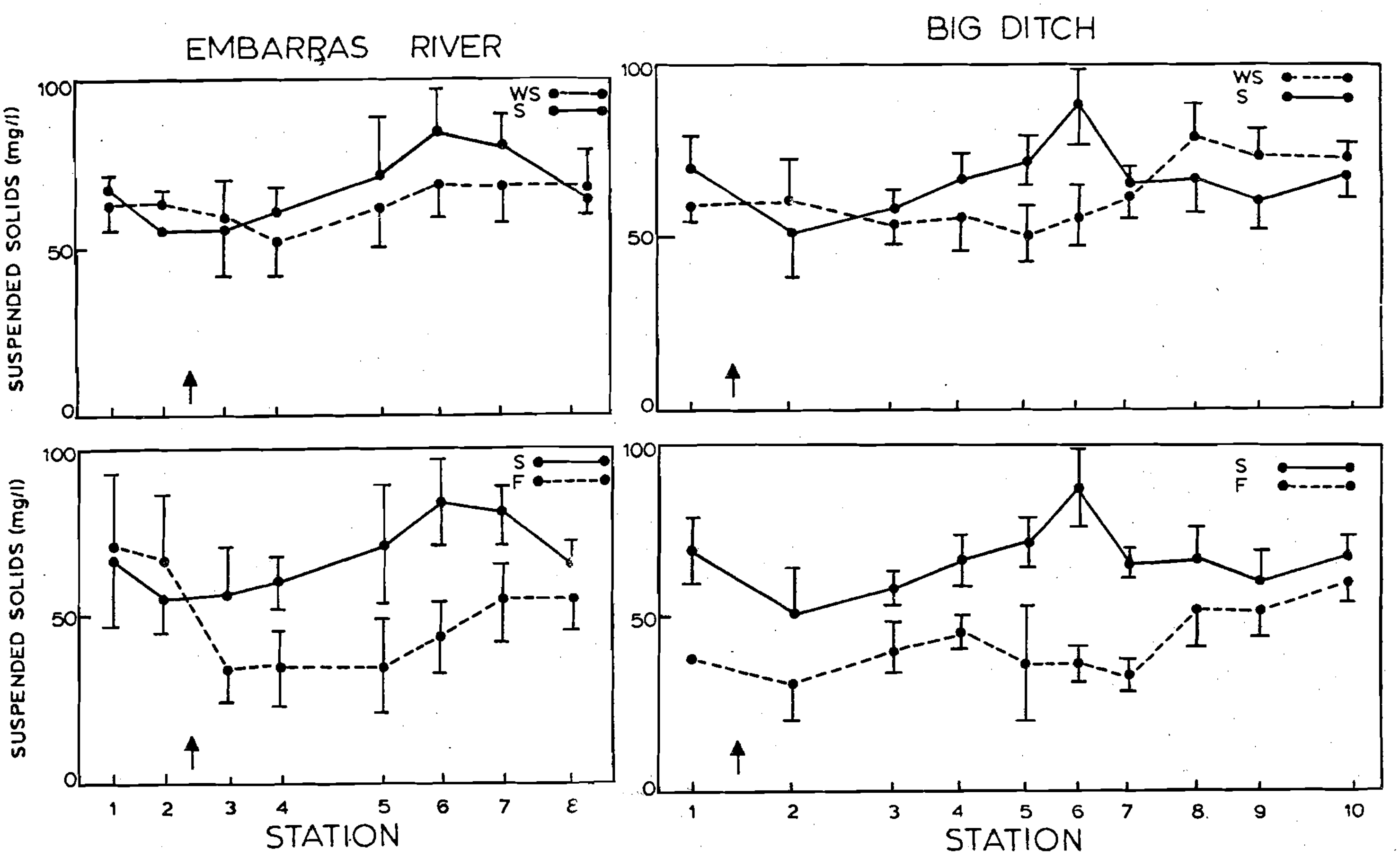

Figure 11. Seasonal variation in suspended solids concentrations (mean ± 1 SE) in Big Ditch and the Embarras River. WS: Winter - Spring. S: Summer. F: Fall. Position along abcissa proportional to distance from Station 1. Arrow indicates location of point input.

This conclusion is supported by the close correspondence of these results to a classic study on production of benthic algae below inputs of municipal wastewater (Butcher, 1947). Butcher found algae to be considerably reduced in close proximity to pollution inputs. However, from the point of entry, algae increased gradually and then suddenly, reaching a maximum 5-8 miles downstream. The algae then decreased sharply. This trend is apparently due to toxic effects (perhaps chlorine) below the point input, followed by a gradual utilization of nutrients until nutrient depletion occurs. The pattern observed for suspended solids during summer periods suggests that organic material in the water column also follows this pattern. The lower levels of suspended solids downstream might also be due to increased discharges diluting algal concentrations.

In fall, low and relatively constant levels of suspended solids occur below the point input (Fig. 11). Big Ditch dried up above the input; but the Embarras maintained flow, and the data from this stream clearly indicate that the municipal input depressed levels of suspended solids. Low levels below the point input are probably due to: (1) lower algal production during fall and (2) flow during this period largely being maintained by municipal inputs which have extremely low (10-20 ppm) levels of suspended solids.

Turbidity. Turbidity in streams receiving point input is highly variable. Generally, turbidity is low below sites of point inputs, with gradual increases downstream. The increases are greatest during summer periods of biological production and least during fall periods of low flow and decreased organic production. The variability in these patterns is presumably due to variation in type and amount of organic compounds being increased by the municipal input.

Phosphorus. Seasonal dynamics of phosphorus components in Big Ditch and the Embarras River illustrate how flow conditions and biological processes interact to regulate this water quality parameter (Fig. 12).

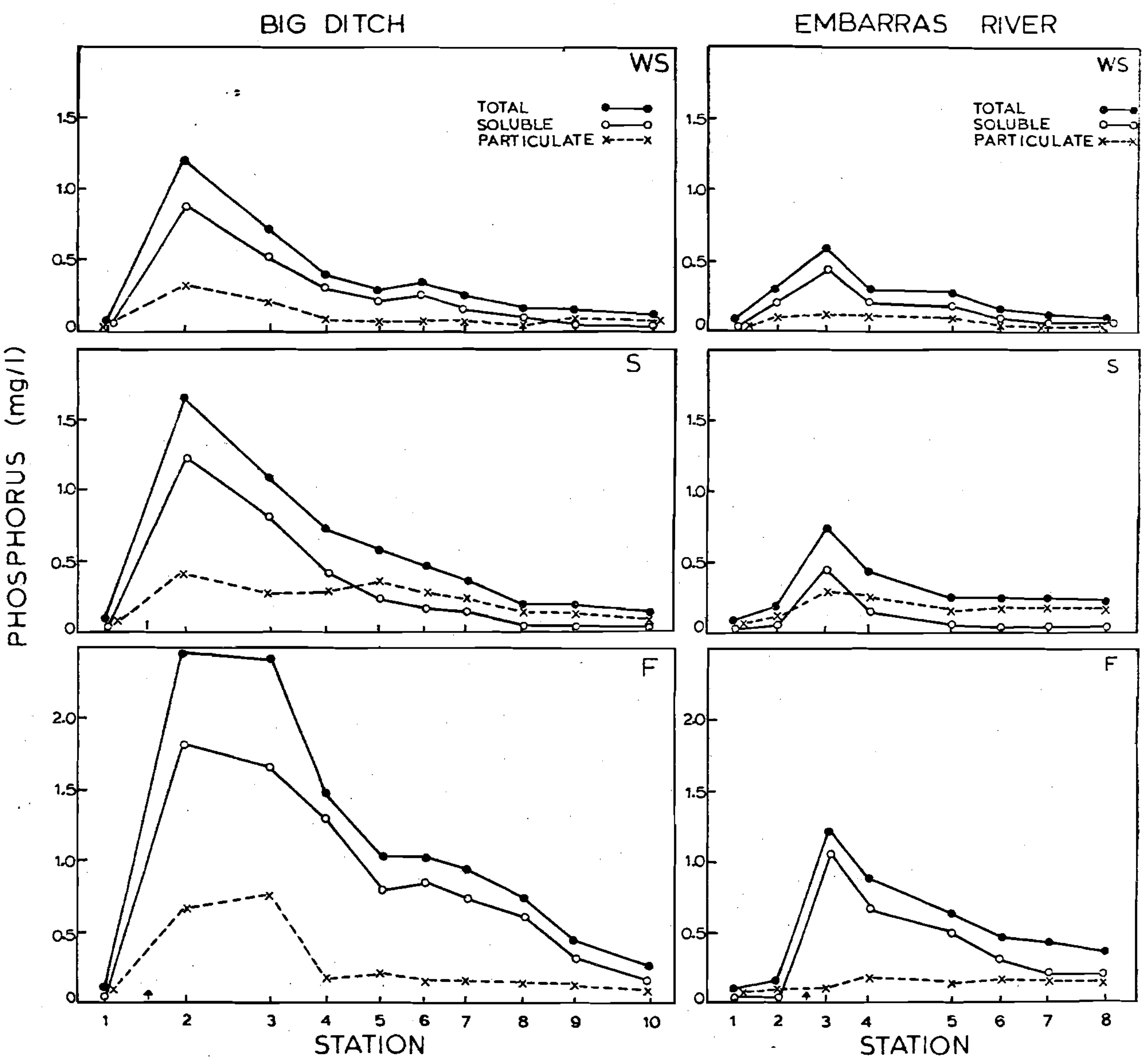

Figure 12. Seasonal variation in phosphorus concentrations in Big Ditch and the Embarras River. WS: Winter - Spring. S: Summer. F: Fall. Position along abcissa proportional to distance from Station 1. Arrow indicates location of point input.

The point input increases both particulate and soluble phosphorus. The increase is greater in Big Ditch across all seasons due to its larger municipal input. During winter-spring, both forms decrease below the point input; the soluble form persists at higher concentrations than does particulate until low concentrations of each are reached at downstream stations. Due to low flow in summer, both forms occur at higher concentrations below the input. As one proceeds downstream, soluble phosphorus decreases rapidly while particulate remains at higher concentrations. This correlates with the previously discussed increases in organic production and suspended solids in downstream stations (Fig. 11) during summer periods. Due to extreme low flows in fall, very high concentrations of both components occur below the point input (Fig. 12). However, soluble phosphorus persists as the dominant form at high concentrations even at downstream stations. Particulate phosphorus behaves much as in spring, with rapid decreases and constant levels maintained throughout the remainder of the stream.

In summary, even in watersheds with major point-source inputs, seasonal dynamics of suspended solids and phosphorus components during base flow are controlled by interactions between hydrological and biological processes. In summer increased organic production downstream from the point input results in increased levels of suspended solids, turbidity and particulate phosphorus, with decreased levels of soluble phosphorus. Because of low flows and decreased biological production in fall, low levels of suspended solids but high levels of soluble phosphorus occur below the point input. High soluble levels are maintained farther downstream due to low flows and decreased biological uptake.

Summary

These results support the hypothesis that alterations in riparian vegetation significantly shift seasonal dynamics of water quality. They also illustrate the importance of linking the impact of these alterations on water quality to the seasonal dynamics of the flow regime in streams.

Where riparian vegetation has been removed, interactions between biological processes of instream organic production and hydrological processes of seasonally low flows interact to determine the seasonal dynamics of suspended solids, turbidity, and particulate phosphorus. Peak levels of all parameters are reached during the summer period of increased algal production and decreased flow, increasing the concentration of algae in suspension (Swanson and Bachman, 1976).

Streams without riparian vegetation receiving major municipal inputs, reach similar summer peaks, but spatial variability is increased as peaks are shifted downstream--probably because of toxicity effects. Temporal variability is also increased since point inputs low in suspended solids but high in soluble phosphorus dominate flows during low flow periods in fall when instream organic production is decreasing; as a result, soluble phosphorus increases and suspended solids levels decline.

Where riparian vegetation is maintained and flows are not intermittent, instream organic production is less important in regulating water quality. Suspended solids levels remain relatively constant and peak levels of phosphorus and turbidity occur during leaf inputs in fall. Intermittent flow conditions in summer enhance the importance of instream organic production in controlling suspended solids, turbidity and phosphorus levels, even when riparian vegetation is maintained.

It is important to put these results in the context of present efforts to enhance the water quality and biological integrity of streams in agricultural watersheds. Attempts at developing models for predicting levels of suspended solids over a range of flow conditions are based almost entirely on hydrological theory (Yang and Stall, 1974, Stall and Yang, 1972). This theory predicts decreasing concentrations of suspended solids as the potential energy of the stream transporting these solids decreases. Potential energy is primarily a function of velocity of the water and slope of the streambed. The present study suggests this theory may not be successful at predicting levels of suspended solids and related pollutants during low flow conditions. This failure will occur where riparian vegetation has been removed and instream organic production is high. The contradiction between our results and predictions of hydrological theory is probably the result of organic matter in suspension not following the same physical principles as do inorganic materials on which most hydrological theory is based. Therefore, efforts to enhance water quality and model its dynamics during base flows in agricultural watersheds should place emphasis on linking hydrological theory of transport of inorganic material (Stall and Yang, 1972, Yang and Stall, 1974) to the biological theory of production and transport of organic material (Cummins, 1974, Swanson and Bachmann, 1976).

In terms of biological integrity in agricultural watersheds, our results also have a substantial number of implications. They indicate that riparian vegetation in these small headwater streams is the major component of the watershed regulating the seasonal dynamics and nature of organic input to the stream. Where riparian vegetation is present, organic inputs occur during fall as leaf inputs which are processed throughout the winter (Cummins, 1974). Where riparian vegetation has been removed, organic inputs occur primarily during summer in the form of increased benthic algal production. Such shifts in organic inputs are reflected in the water quality parameters examined in this study. These shifts in both the seasonal dynamics and nature of organic inputs significantly degrade the biological integrity of higher trophic levels in these streams (Karr and Dudley, 1978; Schlosser, in prep.). Therefore, efforts by resource managers to improve biological integrity in agricultural watersheds must recognize the role riparian vegetation plays in regulating both water quality and the energy dynamics in stream ecosystems.

WATER QUALITY DURING RUNOFF EVENTS

During periods of intense rainfall, water accumulates on the land surface more rapidly than it can infiltrate into the soil profile. As a result, lateral movement of water over the soil surface occurs with transport of considerable volumes of soil. When this soil reaches stream channels and drainage ditches, it creates major sediment problems.

Erosion Modelling

The scale of the erosion and sedimentation problem resulting from surface runoff in agricultural watersheds requires mathematical models for identifying major source areas of sediment and related pollutants. This has come to be identified as the "critical areas" approach, since its main function is to locate areas with potential for excessive soil loss so they can receive highest priority in land treatment programs.

The most commonly used models are based on the Universal Soil Loss Equation (USLE) (Miller et al., 1979). Detailed discussion of the use and misuse of the Universal Soil Loss Equation is provided by Wischmeier and Smith (1965) and Wischmeier (1975,1976). The equation, used to predict average soil loss in tons per acre per year, is of the following form:

$$A = R\ K\ L\ S\ C\ P.$$

Each term is defined and discussed below.

Computed Soil Loss (A): The average soil loss in tons per acre per year as computed from the six factors of the USLE.

Rainfall Factor (R): The number of erosion-index units in the average year of rain. An erosion-index unit is a measure of erosive force of specific rainfall, reflecting combined effects of rainfall impact to dislodge soil particles and runoff to transport particles.

Soil-Erodibility Factor (K): The susceptibility of soil to erosion. Since erodibility varies with slope, cover, management, and other factors, it is essential that erodibility be measured under controlled conditions. Generally, it is expressed as a relative value for a specific soil in cultivated continuous fallow on a 9% slope that is 22.1 meters (72.6 feet) long. Soil characteristics which affect the K-factor include, among others, infiltration rate, permeability and total water holding capacity.

Slope-Length Factor (L): The ratio of soil loss from a field of any length to a standard field with a length of 22.1 meters (72.6 feet). Soil type and gradient are assumed to be constant.

Slope-Gradient Factor (S): The ratio of soil loss from the field to that from a 9% slope, other factors held constant.

Cropping Management Factor (C): The ratio of soil loss from land cropped under specified conditions to corresponding losses from tilled, continuous fallow land. This factor attempts to evaluate combined effects of cover, crop sequence, and management practices. Crop residues may be left on the surface, removed, chopped, or plowed under. Crops may be grown continuously or rotated in various combinations. These and other variations in land management which change erosion rates are incorporated into C.

Erosion-Control Practice Factor (P): The soil loss with a specific practice relative to soil loss with straight-row farming. Up and down slope, contour tillage, stripcropping on the contour, terrace systems, and stabilized waterways are the most important practices involved in the P factor of the USLE. A number of practices such as improved tillage regimes, sod-based rotations, and fertility treatment contribute to erosion control, but these are considered conservation cropping and management practices and are, therefore, incorporated in the factor C discussed above.

With this equation, one can predict long-term average annual losses under specific cropping conditions as well as how these losses will be modified by implementation of alternate erosion control plans.

In order to predict where "critical erosive areas" are in the watershed: a reduced form of the equation is used. Present models calculate an RKLS factor for each soil unit (Miller et al., 1979). RKLS is the potential rate of soil erosion occurring from fields kept in continuous fallow with no conservation practice applied. For watersheds in close geographical proximity, such as those described in this report, the rainfall erosion index (R) has identical values (Wischmeier and Smith, 1962). Therefore, KLS alone can serve as an indication of erosive potential of a given soil type on a specific gradient and slope.

Erosive potential (EP) as measured by the KLS factor was determined for the Big Ditch, Spoon River, and Jordan Creek watersheds. Soil maps of the watersheds were taken from general soil surveys for Champaign and Vermilion Counties published by the Soil Conservation Service, U. S. Department of Agriculture. Soil erodibility values (K) were obtained from Technical Guild Section II-A prepared by the Soil Conservation Service (1977). Slope length (L) and gradient (S) were calculated from topographic maps of the three watersheds, where (L) is the field slope length in feet and (S) is the gradient expressed as slope percent. Slopes were determined in each region of our watersheds and LS measured several times along the width of each slope. In areas where very little slope was present, LS values were measured at irregular intervals on slopes nearest the stream. An LS factor was then calculated according to the equation presented in Wischmeier and Smith (1962). The LS factor is the expected ratio of soil loss per unit area on a field slope to corresponding losses from the basic 9% slope, 22.1 meters (72.6 feet) long. KLS values were then used to classify various parts of the watershed into one of five erosion potential (EP) categories: very low, low, moderate, high, and very high. These categories were arbitrarily based on the range of KLS values observed in the watersheds studied. At this level of discrimination the procedure is meant only to give relative erosive potentials in general areas of watersheds, rather than field or plot specific erosion rates. Mean KLS values and erosion potential (EP) categories for each area of the Spoon River, Big Ditch and Jordan Creek watersheds are given in Appendix III.

Our objective is to determine if the measure "erosive potential" is sufficient to predict relative suspended solids concentrations among areas with differing riparian vegetation and channel morphology.

Spoon River

Estimates of erosion potential (EP) in the Spoon River watershed (Fig. 13) indicated the existence of three areas with major differences as potential sources of sediment and related pollutants. The upper portion of the watershed has a moderate EP while the lower portion has very shallow slopes and low EP. The area with greatest EP, located in the east-central portion of the watershed, is drained by two man-made channels which transport runoff to the main stream. Based on this information, six sample stations were located in the watershed. Station 1 is in the area with moderate EP while 2 and 3 are downstream in areas with lower EP. Station 4 is located in an area of low EP but below the entrance of the man-made channels transporting runoff from the high EP area. Stations 5 and 6 are downstream of 4 in low EP areas. The in- and near-stream conditions in the Spoon River were as follows: homogeneous channel with minimal pool-riffle development, cultivation to the stream edge, and channel banks well protected by sod.

Two runoff events were monitored in this watershed. The first occurred on July 13, 1978 when 2.5-5 cm (1-2 inches) of rain fell in about 1 hour. The second event (July 30, 1979) produced approximatley 7.5 cm (3 inches) in two events over a 3-hour period.

Suspended solids. Areas identified by the model as having high and moderate EP produced the highest suspended solids concentrations (Figs. 14, 15). Stations in close proximity to erosive areas (1 and 4) responded most rapidly and intensively. The area identified by the model as having highest erosion potential (Station 4) produced the highest concentrations of suspended solids. Suspended solids peaked more slowly and at substantially lower levels in downstream areas with lower EP. Apparently, high concentrations in critical areas are diluted as they pass into less erosive portions of the watershed. Rate of increase in suspended solids was also a function of the stations' proximity to an erosive area. Close proximity, as at Station 1, resulted in immediate increases in suspended solids. As shown

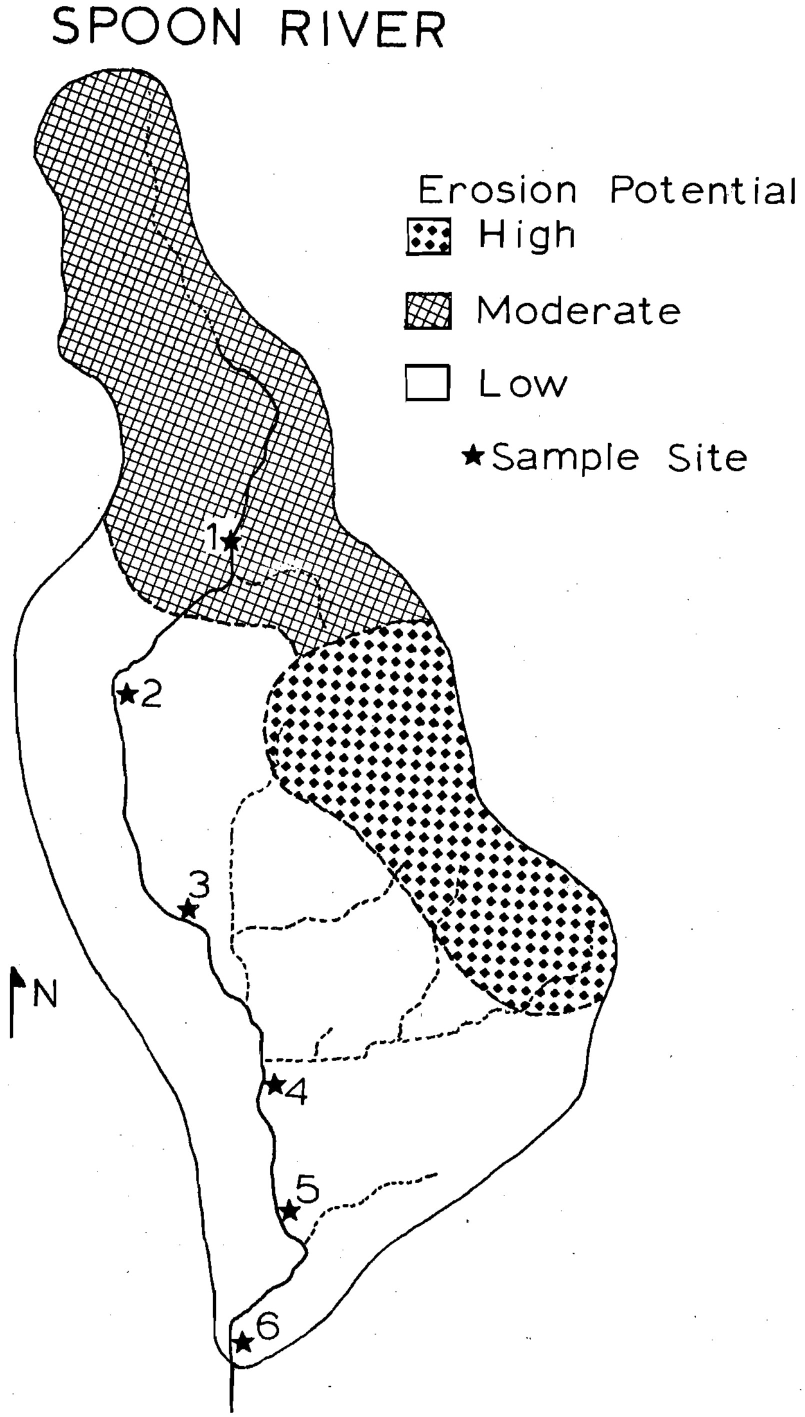

Figure 13. Erosion potential and location of sample sites during runoff events in Spoon River watershed.

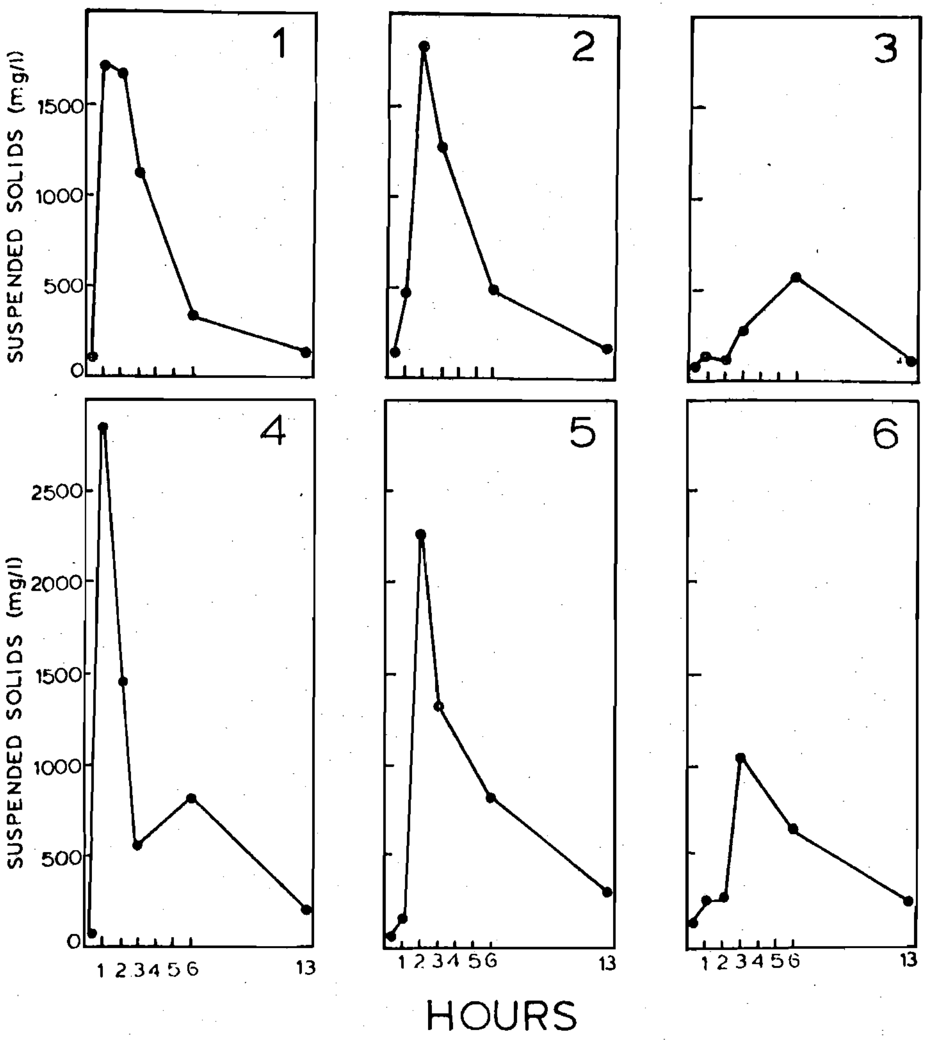

Figure 14. Suspended solids concentrations as a function of time since initiation of rainfall for six stations in Spoon River, July 13, 1978.

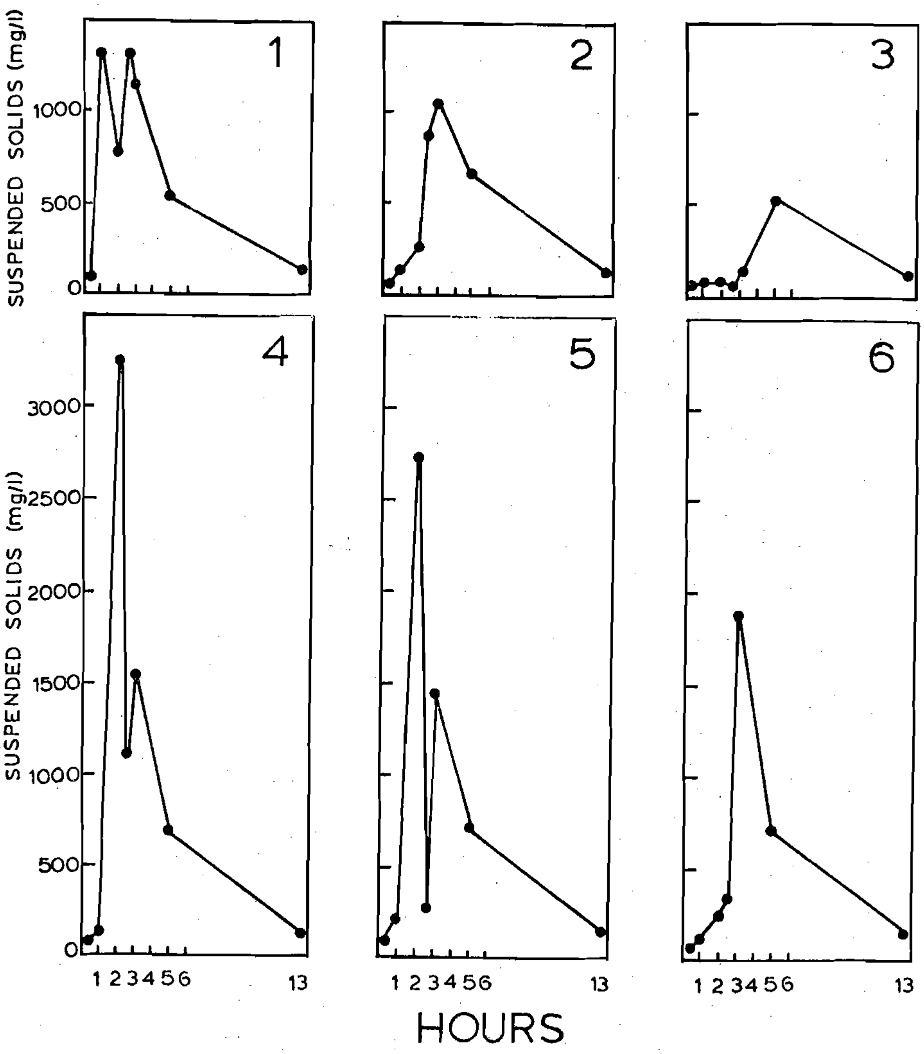

Figure 15. Suspended solids concentrations as a function of time since initiation of rainfall for six stations in Spoon River, July 30, 1979.

by the second event (Fig. 15), more distantly located erosive areas, such as those recorded at Station 4, produced slower increase in suspended solids in the main channel. Dual peaks in curves of stations nearest critical areas in the 1979 event resulted from two bursts of rainfall initiating two pulses of runoff. Areas located a greater distance from the critically erosive portions of the watershed did not experience increases in suspended solids associated with subsequent bursts of rainfall.

Turbidity. Because of equipment limitations, turbidity levels above 500 JTU were not measured for the first event. Changes in turbidity below 500 JTU coincided with changes in suspended solids levels during this event. Turbidity was measured on all samples during the second event. Turbidity followed fluctuations in suspended solids since the same material determines both parameters during runoff periods (Fig. 16). For a given level of suspended solids, higher turbidity indicates that the material is composed of smaller particles scattering more light. Thus, the ratio of suspended solids to turbidity provides a coefficient of fineness (CF) of the materials in suspension (Grassy, 1943). (This procedure is not applicable during base flow conditions when organics of low density may determine turbidity.) Calculation of the coefficient of fineness at peak suspended solids levels for each station yields higher coefficients ($P=.05$, Mann-Whitney U, one-tailed test) at stations in close proximity to critical erosive areas (Stations 1, 4, and 5 with CF values of 1.74, 1.62, and 1.70, respectively) than at stations in less erosive areas (Stations 2, 3, and 6 with values of 1.31, 1.41, and 1.35, respectively). Thus, suspended solids during peak runoff periods are composed of larger particles in areas with higher erosive potential.

Phosphorus. Particulate phosphorus follows patterns similar to suspended solids (Fig. 17, 18). Concentrations at stations in closest proximity to critical areas increase most rapidly and reach higher levels. However, the area identified as having the greatest erosion potential (Sta. 4), does not peak at higher levels than the area of moderate potential (Sta. 1), indicating some differences in the nature of the suspended solids early in

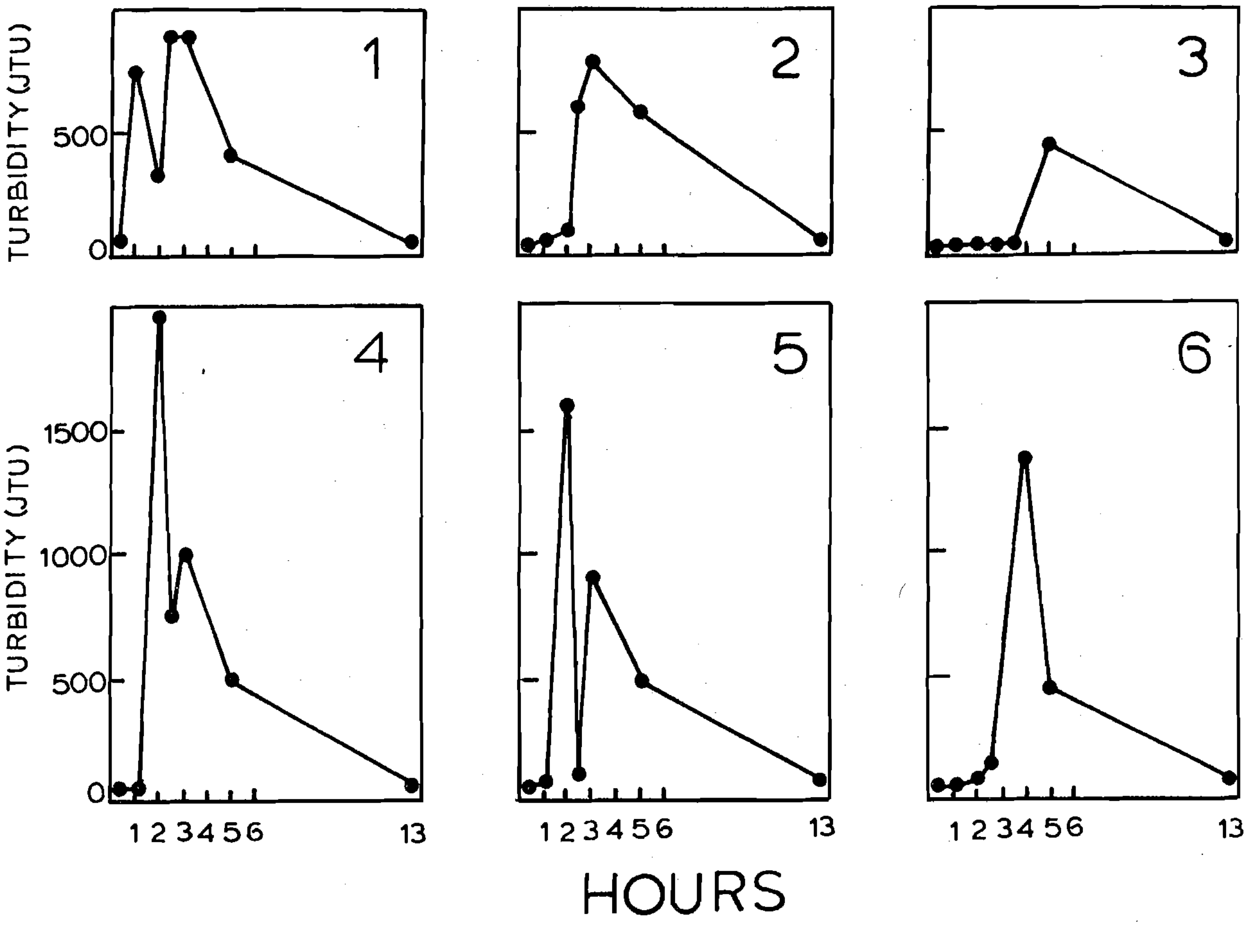

Figure 16. Turbidity levels at six Spoon River locations as a function of time since initiation of rainfall, July 30, 1979.

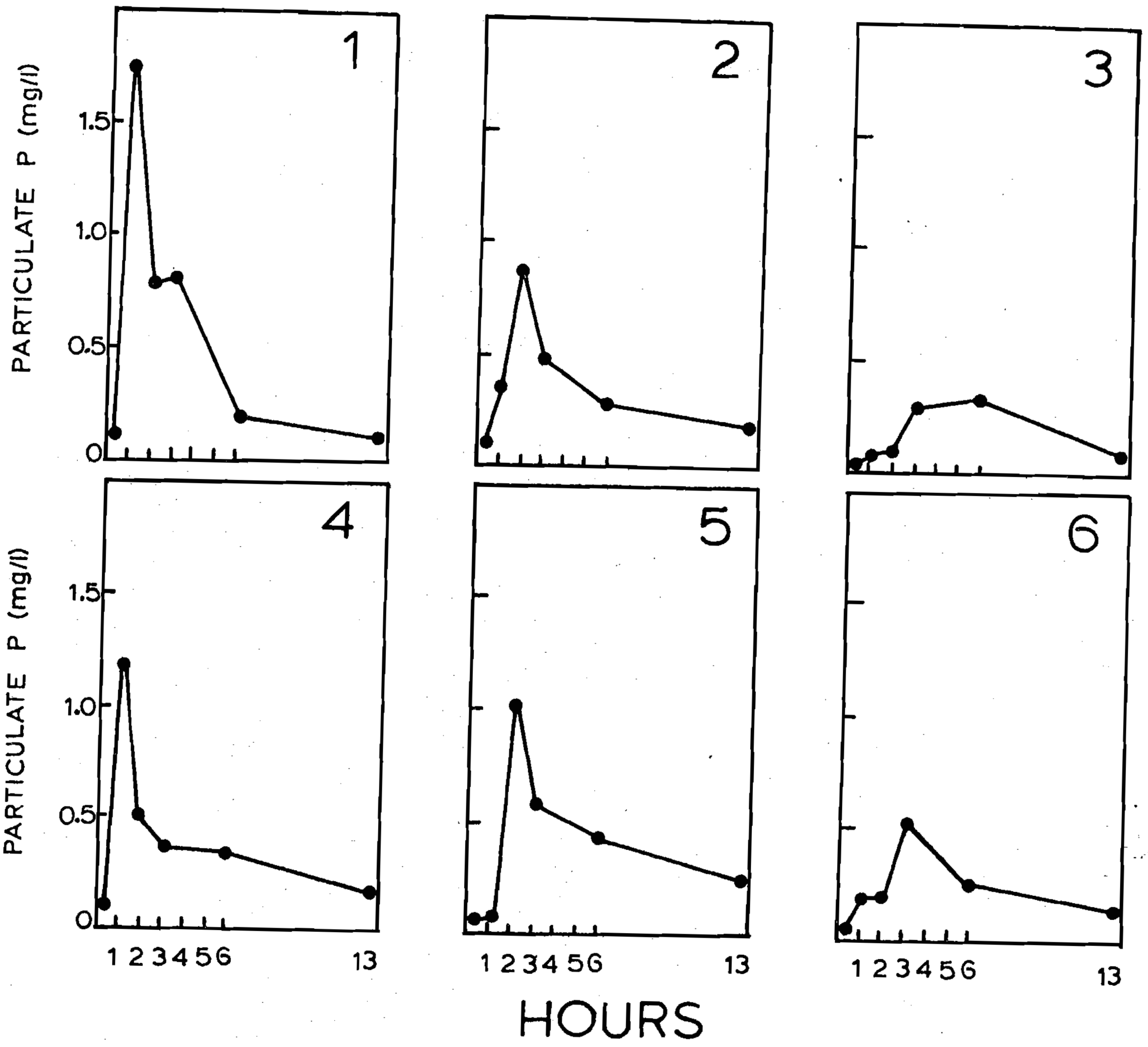

Figure 17. Particulate phosphorus concentrations as a function of time since initiation of rainfall at six stations in Spoon River, July 13, 1978.

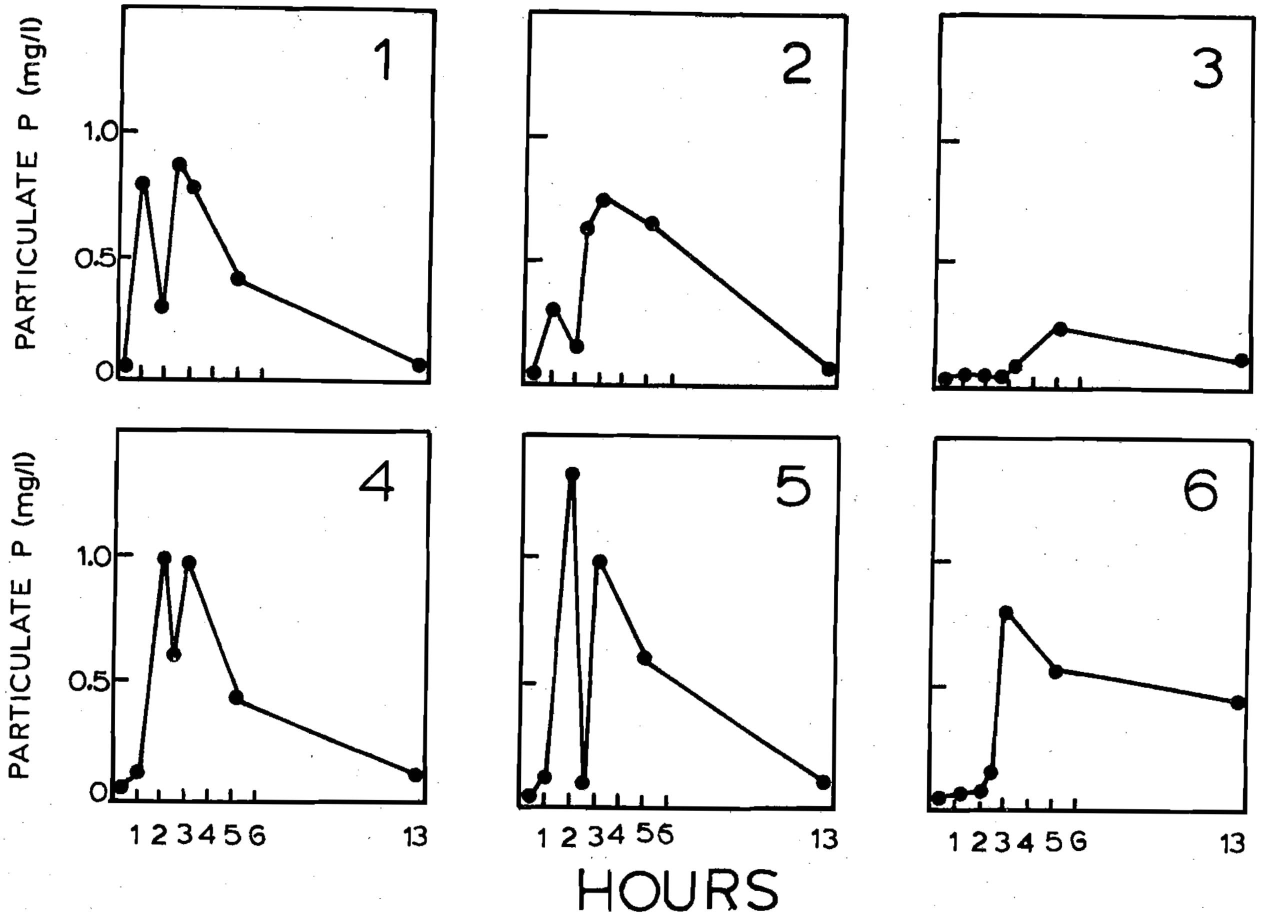

Figure 18. Particulate phosphorus concentrations as a function of time since initiation of rainfall for six Spoon River sample stations, July 30, 1979.

the hydrograph. Because the two areas have the same soil types and land use, soils in the most critically erosive area (Sta. 4) may be "nutrient depleted" due to more frequent runoff events, or in-channel processes may be causing these differences. Septic inputs do occur above Station 1 but not above 4. Flushing of organic material produced within the channel in vicinity of these inputs may be the reason for the elevated phosphorus levels at this station, especially during summer periods like those observed 1978 when low flow conditions persisted for some time before the runoff event.

Soluble orthophosphate concentrations do not follow the same temporal dynamics as suspended solids, turbidity, and particulate phosphorus. Stations in closest proximity to critically erosive areas undergo rapid increases associated with the period of intense surface runoff (Fig. 19). The magnitude and decline of this early peak appears directly related to intensity and cessation of surface runoff. These stations then undergo a second increase later in the event. Stations located farther downstream from major erosive areas (3 and 6) undergo a different response. Here there is a delayed and gradual increase in soluble orthophosphate without an early peak associated with surface runoff.

Two alternative explanations can be proposed for this secondary increase in soluble orthophosphate. They may be due to subsurface inputs or to release of soluble phosphorus from suspended sediments. Generally, subsurface inputs of soluble phosphorus are of minor importance except where septic contamination of tile inputs is common (Lake and Morrison, 1977). The minimal importance of septic inputs in the watersheds examined, and the generality of the secondary increase observed, suggests that subsurface inputs are probably not the primary cause. Rather it probably involves release of phosphorus from suspended sediments. Such releases have been documented (Sommers et al., 1975) but they involve complex interactions between temperature, aeration and turbulence, and relative abundance of organic and inorganic phosphorus.

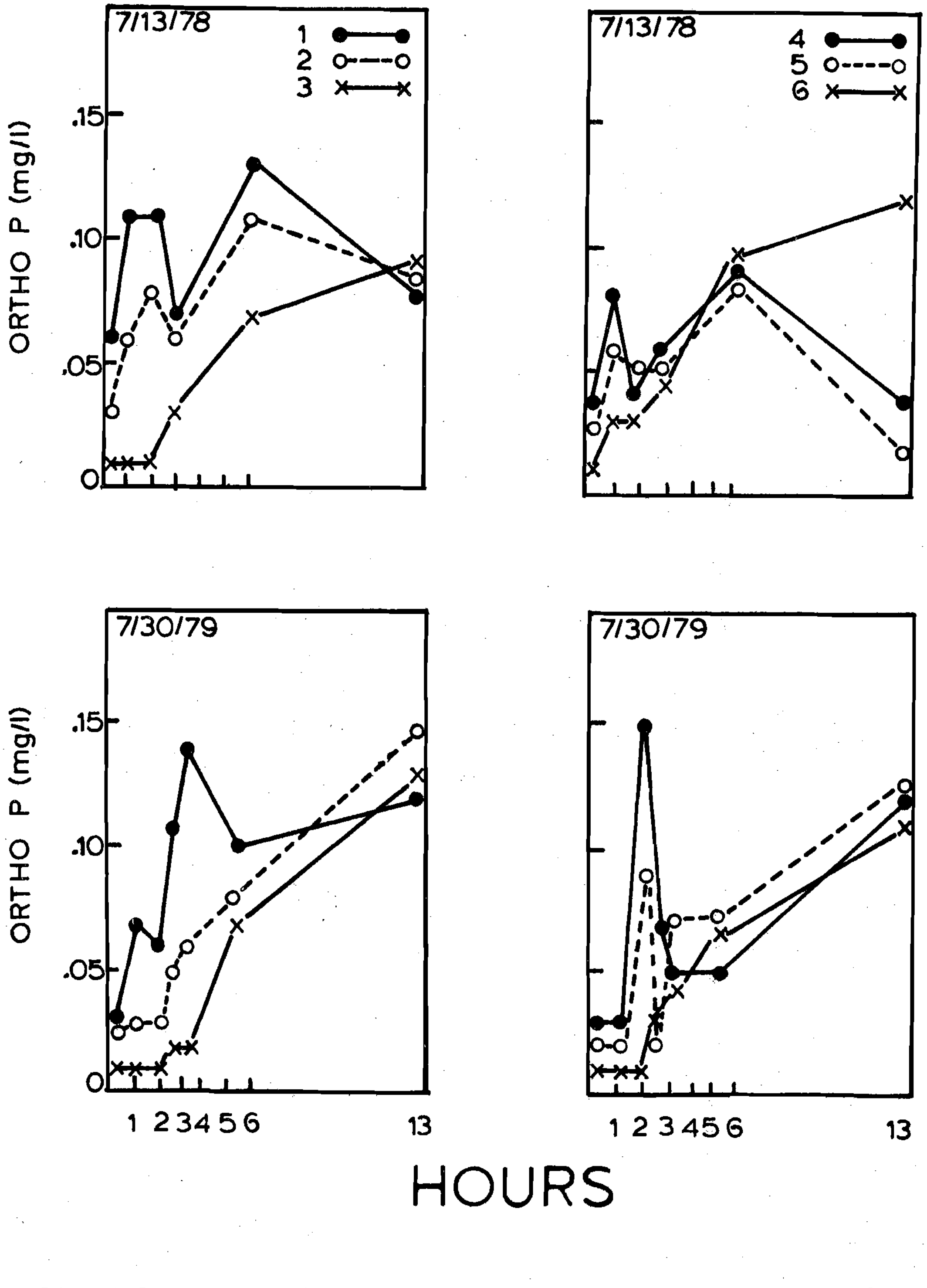

Figure 19. Soluble orthophosphate concentrations during two runoff events as a function of time since initiation of rainfall for six stations in Spoon River.

Big Ditch

Big Ditch was sampled during one major runoff event in 1979, to determine the generality of the Spoon River results in a watershed with a major point input. Erosion potential is very high in two areas of the Big Ditch watershed (Fig. 20): the northern portion, which has its greatest impact on Stations 1, 2 and 3 and the southeast with major impact on Stations 7 and 8. High EP exists in the southwestern area of the watershed (Stations 9 and 10). As in Spoon River, the stream channel in Big Ditch is uniform, with minimal pool-riffle development, cultivation to the stream edge, and channel banks well protected by sod. The main point input in the stream occurs just above Station 2. All 10 stations were sampled during the event of April 11, 1979 when approximately 2.5 cm (1 inch) of rain fell over a 2-3 hour period on saturated ground. The stream was sampled the night before the runoff event and 2, 6, and 13 hours into the event.

Suspended solids, turbidity, and particulate phosphorus results show patterns similar to Spoon River (Fig. 21). During base flow, concentrations are constant throughout the stream with no significant impact of the point input. Two hours into the hydrograph, subareas of the watershed respond at different rates and intensities. Stations in close proximity to major erosive areas (1, 2, 3, 8 and 9) peak rapidly and intensively, while stations more distant (4, 5 and 6) undergo a slower and less intensive increase in suspended solids, turbidity, and particulate phosphorus. Six hours after initiation of the event, stations in the vicinity of highest EP have similar concentrations of these parameters. Stations located in the central portion of the watershed, where erosive potential is low, have elevated but substantially lower levels of suspended solids, turbidity, and particulate phosphorus. By 13 hours into the event, the hydrograph is receding with low and relatively constant levels upstream but elevated levels of suspended solids, turbidity and particulate phosphorus downstream.

Soluble orthophosphate (PO_4) shows different temporal dynamics (Fig. 22). During base flows soluble orthophosphates are elevated below the point input.

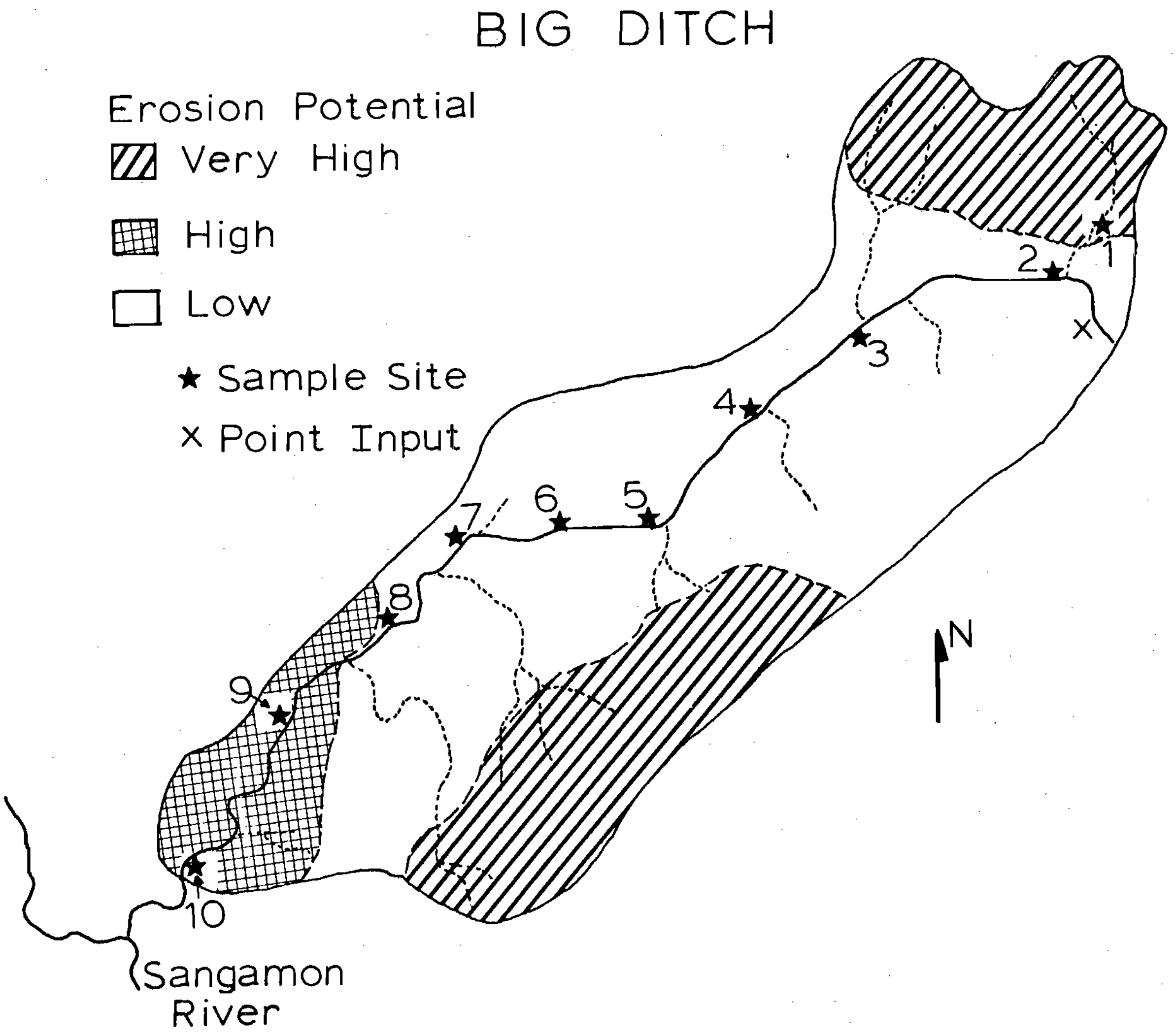

Figure 20. Erosion potential and location of sample sites during runoff events in the Big Ditch watershed.

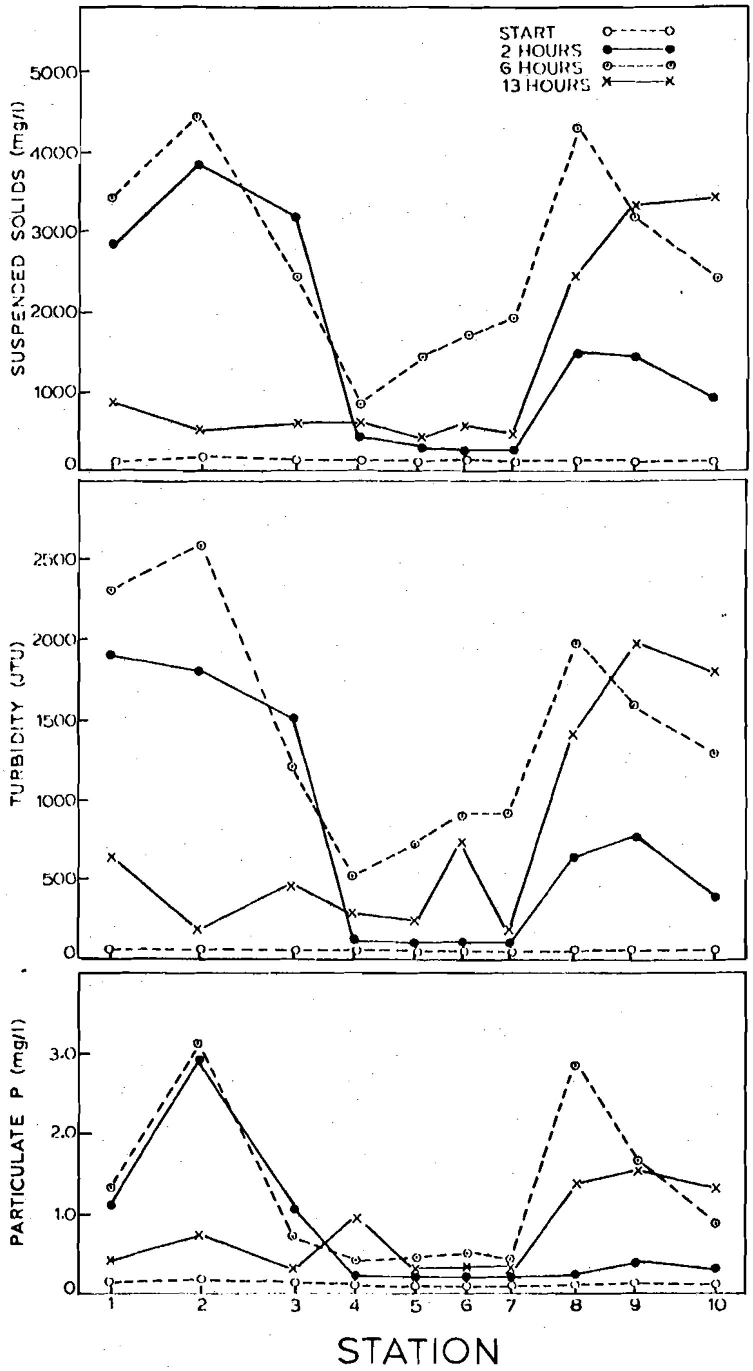

Figure 21. Suspended solids concentrations, turbidity levels, and particulate phosphorus concentrations in Big Ditch during a runoff event, April 11, 1979.

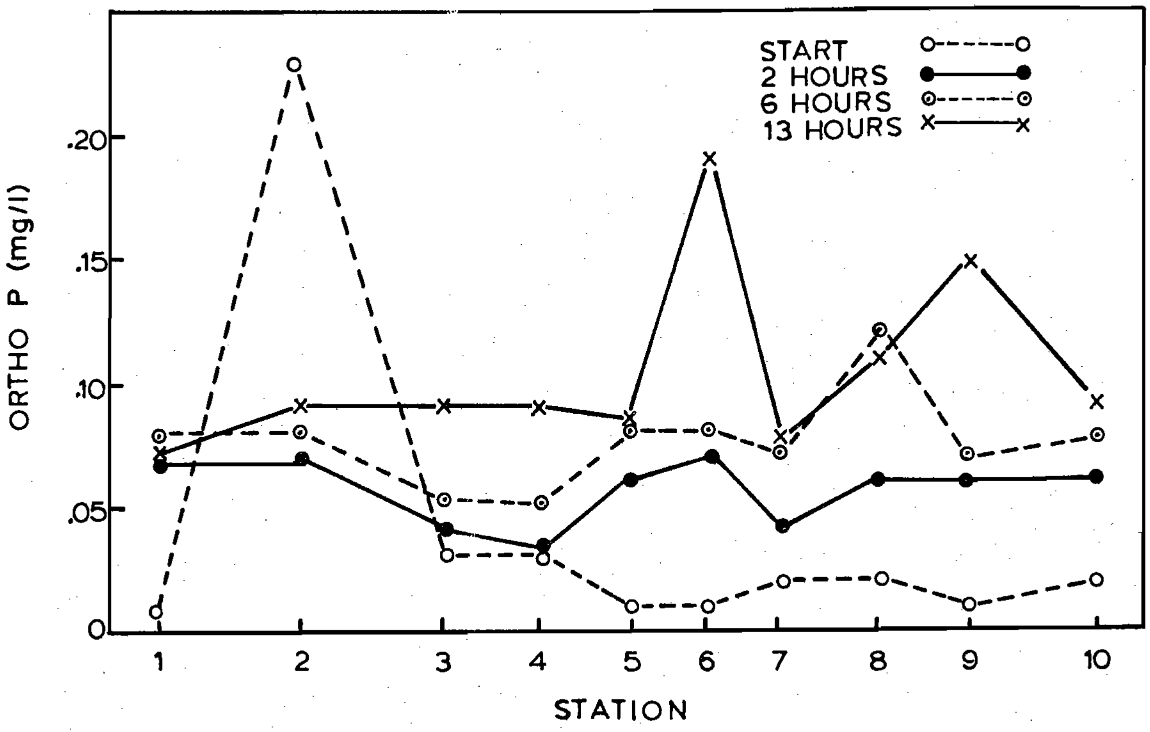

Figure 22. Soluble orthophosphate concentrations at 10 sample sites in Big Ditch, April 11, 1979.

Initiation of surface runoff dilutes concentration in the vicinity of the point input but results in elevated levels throughout the remainder of the stream. As the event proceeds, the concentration of soluble orthophosphate continues to rise. Distinct peaks associated with surface runoff and delayed peaks later in the event, like those in Spoon River, were not observed in Big Ditch, probably because of the less intense temporal sampling scheme.

These results from Spoon River and Big Ditch indicate that in relatively simple systems with homogeneous channel conditions, EP in the watershed is an accurate predictor of spatial patterns of suspended solids, turbidity and particulate phosphorus levels. The next step in testing the hypothesis is to move to a complex system where differences in riparian vegetation and channel morphology occur in the watershed.

Jordan Creek

Jordan Creek varies in channel morphology and riparian vegetation and thus is an ideal location for evaluating the impact of these factors on water quality predictions based on erosion potential. Four major regions of this watershed can be distinguished based on erosion potential and channel characteristics (Fig. 23, Table 1). The terrestrial portion of Region 1 is characterized by intensively tiled flat topography of very low EP with cultivation to the stream edge. The low gradient channel is uniform with no pools or riffles and unstable silt-sand substrates. Region 2 is characterized by moderately rolling topography with low to moderate EP. An 8-to-10 meter-wide strip of mixed woody and herbaceous vegetation borders the stream. The low gradient channel has poorly developed pools and riffles with silt, sand, and gravel substrates. Region 3 has low EP, isolated patches of nearstream vegetation, and a uniform, low-gradient channel with a silt-sand substrate. It receives urban runoff from a small town, Fairmount (population, 750). Region 4 has rolling topography and highly erodible soils resulting in the highest erosion potential in the watershed. A belt of mature forest 10-400 meters wide borders this high gradient channel with well developed pools and riffles. Channel substrates are dominated by sand, gravel, and rock. The rolling nature of Region IV in combination with land-use patterns has resulted in major gullies through

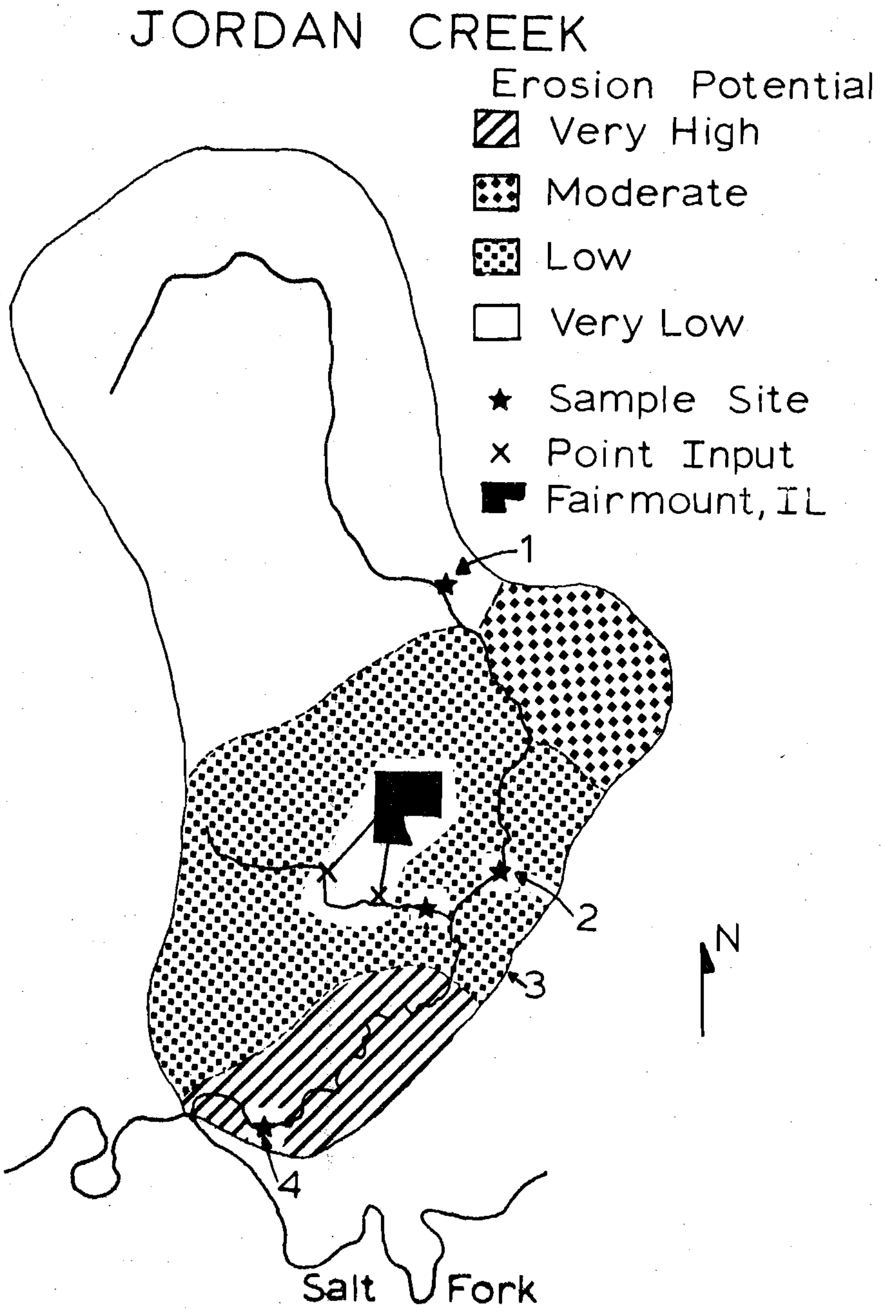

Figure 23. Erosion potential and location of sample sites during runoff events in the Jordan Creek watershed.

Table 1. Channel characteristics of the four regions of Jordan Creek

Region	Nearstream Vegetation	Channel Gradient	Channel Morphology	Substrates
1	Cultivation to the stream edge	.65 m/km	Uniform: No pools or riffles	Silt-sand
2	8-10 meter strip of Riparian Vegetation	.72 m/km	Poorly developed pool-riffles	Silt-sand-gravel
3	Cultivation to stream edge	.76 m/km	Uniform: No pools or riffles	Silt-sand
4	10-400 meter strip of mature forest and pasture	4.0 m/km	Well developed pools and riffles	Sand-gravel-rock

the riparian vegetation. In contrast to the variable riparian environments among the regions, all areas have greater than 80% of their area in intensive row crops. Four sample sites (Fig. 23) were sampled routinely during 3 runoff events. Samples were collected at hourly intervals during increasing hydrographs and irregularly during decreasing hydrographs.

The smallest rainfall event occurred on March 28, 1979 when less than 1.25 cm (0.5 inch) of rain fell in 1 hour. Little agricultural runoff was observed during this event for Regions 1 and 2, apparently due to the low intensity rainfall in combination with level topography. As a result, suspended solids concentrations in these regions were constant throughout the sample period (Fig. 24).

Suspended solids concentrations increased most rapidly and reached the highest levels in Region 3, an area with low EP (Fig. 24). Very little agricultural runoff was observed in Region 3 due to the relatively level topography. Urban runoff from Fairmount seems to be responsible for the increased hydrograph in this region. Limited sampling of this urban runoff (see p. 58) suggests it was relatively low in suspended solids. Thus, high suspended solids concentrations in this area are apparently derived from a combination of urban inputs and scour of the unstable silt-sand substrates of the channel.

Region 4 was the only portion of the watershed where signficant agricultural runoff was observed during the event. The rolling topography and high soil erodibility resulted in surface runoff and erosion. Surface runoff carrying sediment was entering the stream channel via well-developed gullies cut through the riparian vegetation. Therefore, the elevated levels of suspended solids observed in Region 4 (Fig. 24) are due to the rolling topography and higher erodibility of this portion of the watershed rather than to sediment transport from Region 3.

Turbidity levels show patterns similar to those of suspended solids (Fig. 24). Only Regions 3 and 4 showed major turbidity increases. Region 3 peaked more rapidly and intensively than Region 4 early in the hydrograph.

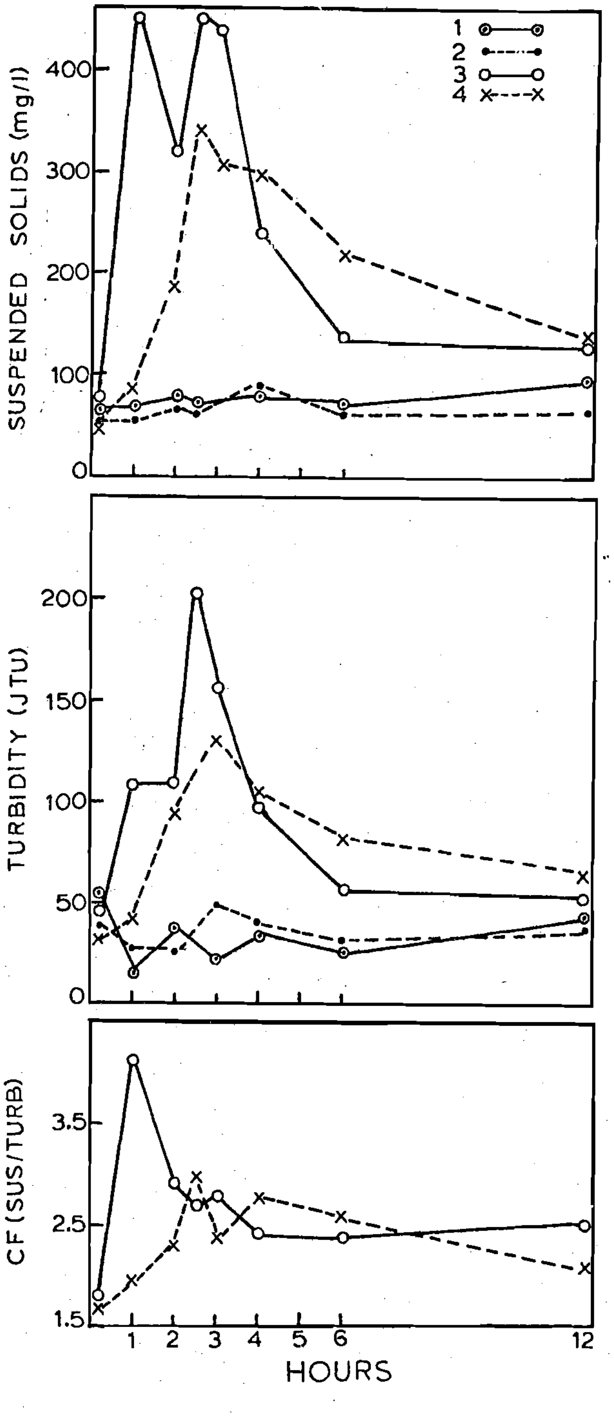

Figure 24. Suspended solids concentrations, turbidity levels, and coefficient of fineness as a function of time since initiation of rainfall in Jordan Creek, March 28, 1979.

The uniform channel of Region 3 yielded a particle size distribution with larger particle size (increase CF) than that in meandering channel with pools and riffles in Region 4 (Fig. 24). The higher potential energy of the uniform channel under intermediate flow conditions (Stall and Yang, 1976) is probably responsible for this pattern. Later in the hydrograph, particle size (as indicated by CF) decreases in Region 3 and both regions have similar particle sizes. Particulate phosphorus concentrations did not consistently follow those of suspended solids (Fig. 25). In Regions 1 and 2 particulate phosphorus remained at low levels because there was very little surface runoff. Region 3 particulate phosphorus concentrations increased sharply when suspended solids shifted from larger to smaller particles, probably because of the greater surface area for phosphorus attachment. Region 4 particulate phosphorus levels increased only slightly (Fig. 25), even though there was a significant increase in suspended solids (Fig. 24). Thus, for similar suspended solids concentrations, particulate phosphorus levels are substantially higher in Region 3 than in Region 4. These differences may be due to the urban input or to inherent differences in the nutrient characteristics of the soil associations in the two regions (see study area description). Phosphorus-suspended solids differences also substantiate the earlier suggestion that water quality in Region 4 is somewhat independent of Region 3 and is not merely a function of inputs from Region 3.

Soluble orthophosphates in Region 1 and 2 remained at constant and low levels (<.02 ppm). Soluble orthophosphates in Regions 3 and 4 increased in parallel with particulate phosphorus (Fig. 25). The only substantial difference is the slower decline in Region 3. This slow decline is probably due to the septic system in Fairmount being linked with the storm water system, so that soluble orthophosphate continues to be flushed from the septic system.

A second runoff event occurred on July 25, 1979, when 5 cm (2 in.) of rain fell on relatively dry ground (1.25 cm of rain over the previous 3 weeks). Rainfall lasted about 1 hour. As in the small event just discussed, suspended solids in Region 1 and 2 did not increase substantially (Fig. 26).

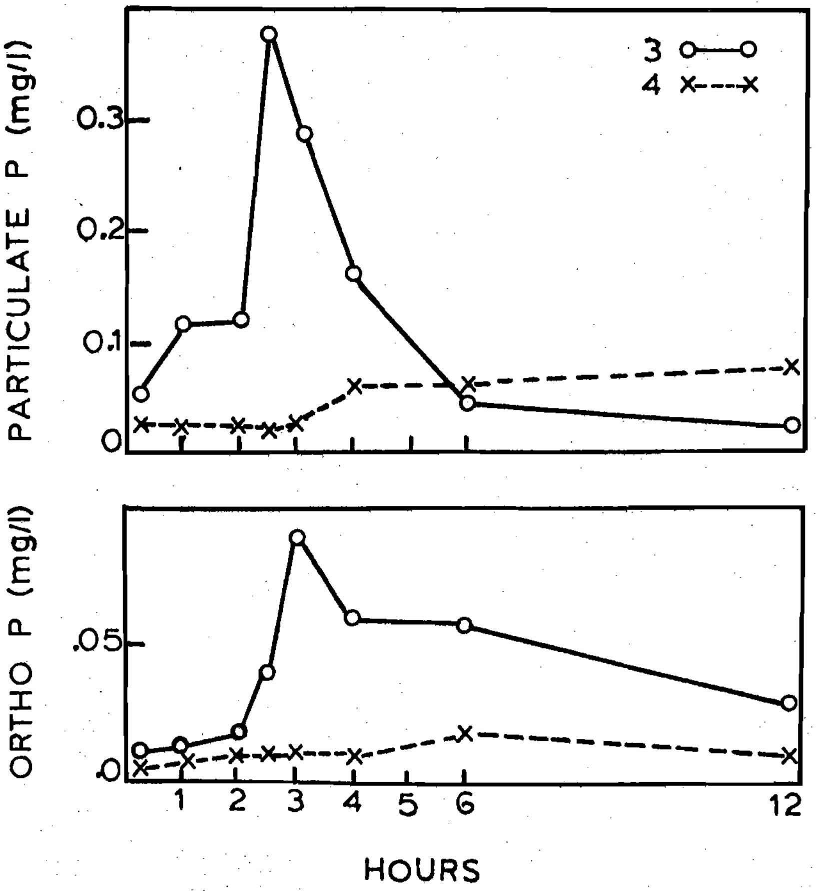

Figure 25. Particulate phosphorus and soluble orthophosphate concentrations as a function of time since initiation of rainfall at Stations 3 and 4 in Jordan Creek, March 28, 1979.

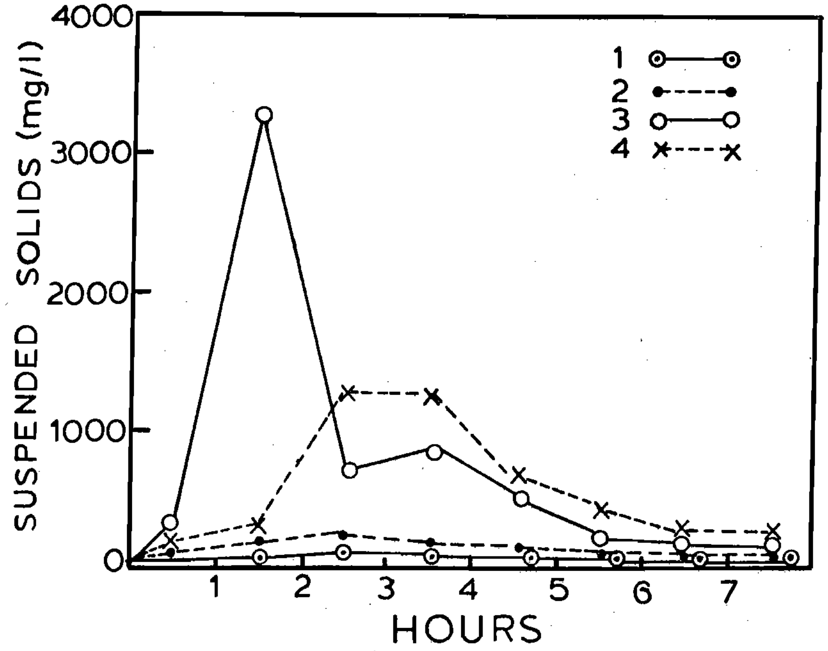

Figure 26. Suspended solids concentrations as a function of time since initiation of rainfall at 4 sample stations in Jordan Creek, July 25, 1979.

Peak levels in Regions 1 and 2 were 122 and 218, respectively. Only small amounts of surface runoff occurred in the areas due to level topography, dry antecedent conditions, and well developed ground cover.

Suspended solids in Region 3 increased sharply to over 3,000 ppm, then declined sharply. (By comparison, the peak in the earlier small event was about 450 ppm.) Recall that Region 3 has low EP. As previously suggested, we believe these high levels of suspended solids are derived from in-channel scour rather than strictly surface or urban runoff. Because of time limitations due to sampling the other stations, it was not possible to sample urban inputs throughout the event.

However, to clarify the causes of the observed patterns, we collected one sample from each of the urban inputs approximately 3 hours into the hydrograph and made observations on flow conditions above the urban inputs. The downstream urban input (Fig. 23) had a suspended solids concentration of 96 ppm. The upper urban input which was damaged and received some surface runoff, had suspended solids concentrations of 280 ppm. Water samples taken from the outflow of this region just prior to and after these samples had suspended solids levels of 896 and 772 ppm. Observations on flow conditions above and below the most upstream urban input indicate flow above the input was not elevated and was similar to those in Regions 1 and 2. In the vicinity of the urban input some flow was actually going upstream because the channel could not carry the runoff away as fast as it was entering from the urban area.

We fully acknowledge the limitations of our urban sampling, but we also feel that these data and observations suggest the increased discharge in this region is due to urban rather than agricultural runoff. They also suggest that much of the suspended solids are being derived from scour of unstable, in-channel substrates rather than strictly urban inputs.

Analysis of these two events suggests the following conclusions for small storms or for intense storms occurring after a dry period when crop cover is adequate:

1. Only rolling areas of the watershed with relatively high EP have signficant erosion and surface runoff. This is indicated by the data from Regions 1, 2, and 4.

2. Even if riparian vegetation is present in rolling regions with high EP, disequilibrium on the land surface can cut gullies through the vegetation from the land to the stream. This prevents the riparian vegetation from achieving its full potential for reducing sediment transport to the aquatic system in these regions.

3. Level upland areas do not experience substantial changes in water quality (see results from Regions 1 and 2).

4. Under certain conditions high levels of suspended solids and related pollutants can occur during this class of storm events. In areas (Region 3) where urban runoff is introduced into a channel with unstable (fine) substrates and high potential energy (due to creation of a uniform channel and removal of riparian vegetation), high levels of suspended solids and related pollutants can occur. In this situation, in-channel scour and suspended solids in the urban input, rather than EP in the watershed, are the primary determinants of water quality.

These conclusions suggest the greatest impact of riparian vegetation on water quality during runoff events will probably occur in relatively level upland areas where gully formation is not common. They also suggest that in addition to retarding flow of water from the land to the stream, a major impact of riparian vegetation on water quality will be a function of how the vegetation interacts with channel morphology to determine the potential energy of the stream to carry sediment, once the surface runoff is in the channel.

To document such impacts of riparian vegetation and channel morphology, we monitored a rainfall event in which there was significant surface runoff throughout the watershed. On March 3, 1979, a moderately intense storm dropped 2.5 cm (1 in.) of rain in a two-hour storm period on unfrozen ground saturated from snow melt. Only small patches of snow were still present in the watershed and no ice or snow was in the channel. All regions of the watershed produced substantial surface runoff during this storm. However, water quality did not vary solely as a function of erosion potential in the watershed. It was more a function of interactions between watershed (land surface) and in-channel processes.

Suspended solids increased abruptly in Regions 1 and 3 where nearstream vegetation had been removed and a uniform channel was present (Fig. 27). The sharp, early rise in Region 3 is due to stormwater input from urban areas and surface runoff from agricultural fields. Region 1 increases next most rapidly even though its EP is less than the EP of either Region 2 or 4. The absence of riparian vegetation in Regions 1 and 3 allowed rapid transport of runoff from agricultural areas to the stream (Fig. 28). Both regions bordered by riparian vegetation (2 and 4) had slower increases in suspended solids. Of these two areas, the region with the more rolling topography (4) experiences the most rapid increase in suspended solids. Rate of increase in suspended solids is slowest in Region 2 where riparian vegetation resulted in slower release of water to the stream and some sediment deposition was observed (Fig. 28).

In addition to variation in rate of increase, peak levels of suspended solids vary in magnitude and timing among the regions. The highest concentration (928 ppm) occurred in Region 4 where erosion potential in the watershed and stream gradient are highest. Regions 1 and 3 peak at lower levels (879 vs. 809 ppm, respectively) with different temporal dynamics. Region 3 peaks early in the event associated with the most intense period of surface and stormwater runoff. Suspended solids in Region 1 increase to a point and remain relatively constant at a level consistent with the very low erosion potential in this region. However, in Region 1, a secondary increase in suspended solids occurs 4 to 6 hours into the event. Discharge increased

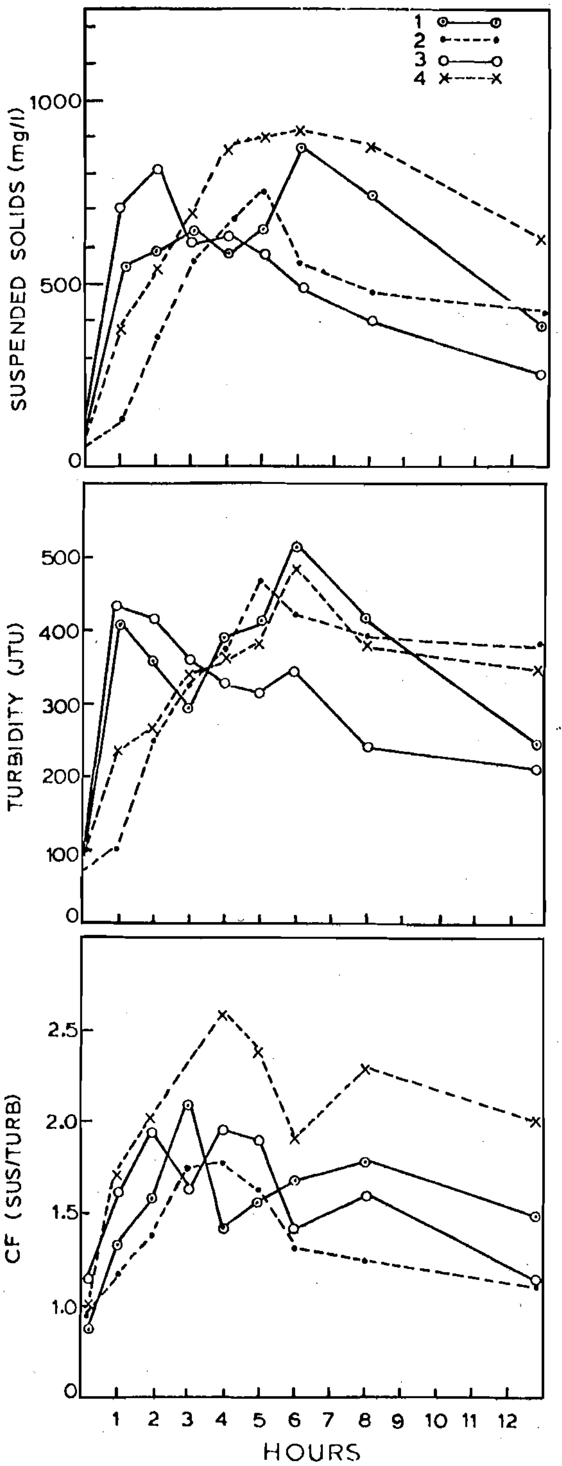

Figure 27. Suspended solids concentrations, turbidity levels, and coefficient of fineness as a function of time since initiation of rainfall at 4 sample stations in Jordan Creek, March 3, 1979.

Figure 28. Top Photo - Runoff in Region 1 during March 3, 1979 event indicating rapid and unimpeded transport of runoff when riparian vegetation is absent.

Lower Photo - Because of slower release of runoff to the stream channel in Region 2 during the same event, sediment deposition occurred along the riparian vegetation.

significantly during this period (I. J. Schlosser, pers. observ.). The delayed increase in discharge and suspended solids is probably due to slower surface inputs from the more distantly located parts of this very flat region of the watershed and/or subsurface inputs from the intensive tilling in this region. Our data do not allow determination of the primary cause for the increased discharge. Such secondary increases did not occur in Region 3 because of the smaller area of its more rolling watershed and less intensive tilling. The lowest level of suspended solids (784 ppm) and most abbreviated peak occurs in Region 2 where low-to-moderate erosion potential exists, but the channel has a relatively low gradient and is bordered by a well-developed strip of riparian vegetation.

Thus, we conclude that erosion potential of the land surface is not sufficient to accurately predict spatial patterns of suspended solids concentrations in relatively level upland areas during an intense runoff event where differences in channel morphology and riparian vegetation exist. The rate of increase in suspended solids concentrations is greater than predicted in areas (Region 1 and 3) lacking riparian vegetation. This is due to rapid sediment delivery rates from the land surface to the stream. Intensity of response is greater than predicted (Region 1 and 3) where unstable (fine) substrates occur, and potential energy of the stream is high due to creation of a uniform channel and removal of the riparian vegetation. Timing of the peak level of suspended solids in these areas seems to be related to major flushes of discharge. In Region 1 this is a function of delayed addition of surface and/or subsurface inputs, while in Region 3 it seems to be due to rapid stormwater drainage.

Turbidity dynamics are somewhat different from those of suspended solids (Fig. 27). An area which lacks nearstream vegetation and has a uniform channel (Region 3) experiences the most rapid increase. As with suspended solids, Region 3 peaks early and declines gradually. The other three regions increase to similar turbidity levels. The differences in peak suspended solids indicates a difference in the size composition of the particles in suspension. Calculations of coefficents of fineness for the regions (Fig. 27) indicate higher values, i.e., larger particle sizes for the high-gradient pool-riffle stream. Increased particle sizes are predictable in high-gradient areas when pool-riffle development does not reduce the potential energy of the channel under high-flow conditions (Stall and Yang, 1974). Intermediate CF values occur in the low-gradient, channelized areas (Regions 1 and 3) and lowest values occur in the low-gradient, unchannelized stream bordered by vegetation (Region 2). This ranking of coefficients of fineness is in agreement with the ranking of peak suspended solids levels. This suggests that potential energy of the stream, rather then erosion potential in the watershed, may be the primary determinant of suspended solids levels and particle size during intense runoff events when erodible substrates are readily available in the stream bed or bank. The potential energy is determined by flow conditions, gradient, pool-riffle, and meander characteristics as well as roughness of the channel perimeter (Yang and Stall, 1974).

Particulate phosphorus differences (Fig. 29) for Regions 1, 2, and 3 are a function of suspended solids levels. Region 1, though lowest in erosion potential, has the highest particulate phosphorus concentration. Even though Region 4 has the highest levels of suspended solids, its particulate phosphorus levels are quite low, suggesting some difference in the nature of its sediment load. As suggested earlier, these differences may reflect inherent nutrient differences in soils located in Region 1, 3, and 4 (see description of study area). Or they may be related to the particle sizes transported in these regions.

In all regions soluble orthophosphate increases throughout the event (Fig. 29). Rapid initial increases occur in association with surface runoff. These increases are most rapid and intense in Region 1. Major increases in soluble phosphorus occur 4 to 8 hours into the event in areas not bordered by nearstream vegetation. Areas bordered by vegetation experience more gradual increases during this period. Highest concentrations were consistently found in Region 1.

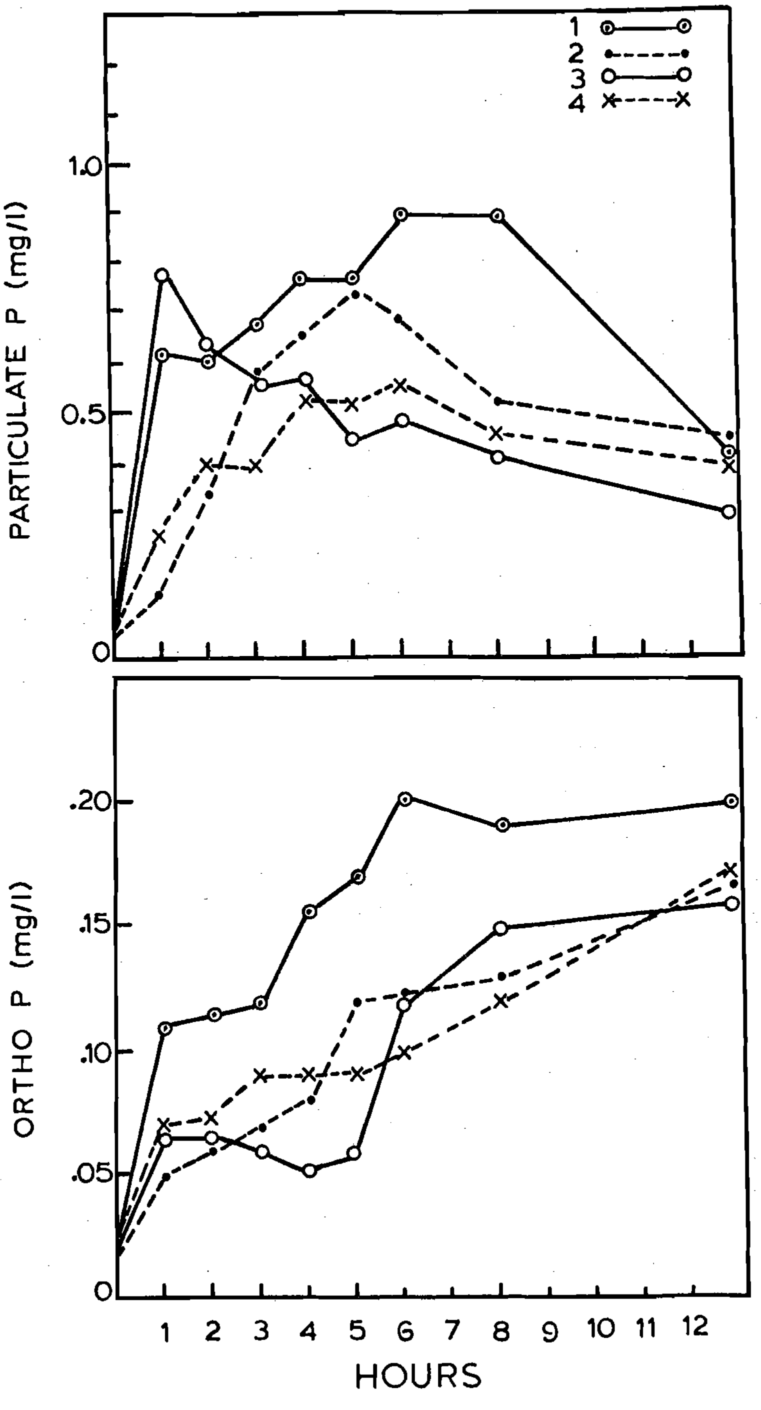

Figure 29. Particulate phosphorus and soluble orthophosphate concentrations as a function of time since initiation of rainfall at 4 sample stations in Jordan Creek, March 3, 1979.

Summary

A simple model based on the Universal Soil Loss Equation accurately predicted spatial patterns of suspended solids, turbidity, and phosphorus levels in watersheds with a uniform channelized stream, well-protected stream banks, and cultivation to the stream edge. In a watershed where heterogeneity in riparian vegetation and channel morphology existed, the model was not an accurate predictor. Furthermore, the ability to make such predictions in this kind of watershed varies with the magnitude of runoff event. Rate of response of such a watershed was faster in areas lacking in riparian vegetation, regardless of erosion potential. Intensity of response was greater than predicted in areas where unstable (fine) substrates occurred and where potential energy of the stream was high due to removal of nearstream vegetation and creation of a uniform straight channel. Timing of the peak level of response in these areas seemed related to major flushes of discharge due to delayed addition of surface and/or subsurface inputs or rapid urban drainage.

These results suggest that water quality in agricultural watersheds during runoff events is primarily governed by hydrological processes, while biological processes are limited to determining incipient conditions. The hydrological proceses involve complex interactions between watershed topography, channel morphology and equilibrium, hydrological impacts of riparian vegetation, and magnitude of the runoff event. Neither modelling efforts to predict water quality, nor management efforts to enhance water resources, will be widely applicable or successful if they are based solely on erosive potential in the watershed and ignore near- and in-channel processes.

CONCLUSIONS

Results from this study show that the relative importance of various processes regulating water quality in headwater streams of agricultural watersheds changes depending on season and type of flow conditions considered. During base flows, seasonal dynamics of water quality parameters examined were determined by interactions between biological processes of both instream and riparian organic production and hydrological processes of seasonally low flows. During runoff events, hydrological processes in both the watershed and channel determined water quality, with channel processes becoming increasingly important during intense runoff events.

These observations suggest that the relevant theory for enhancement of water resources and modelling water quality in agricultural watersheds will vary depending on flow conditions. During base flow, emphasis should be placed on linking the hydrological theory of transport of inorganic material (Stall and Yang, 1972, Yang and Stall, 1974) to the biological theory of production and transport of organic materials (Cummins, 1974, Swanson and Bachmann, 1976). During runoff events, emphasis should be placed on linking the agricultural theory of erosion prediciton (Wischmeier and Smith, 1962) to the geomorphological theory of stream equilibrium and sediment transport (Leopold et al., 1964). Such interdisciplinary linkages should provide resource management decisions which will have the greatest chance of success and broadest range of applicability.

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Appendix I. Locations of water sample sites on the six study watersheds.

Big Ditch

Station	Location
1	SE corner, SW 1/4, Sec. 22, T 22 N, R 9 E, Champaign Co.
2	SW corner, NW 1/4. Sec. 27, T 22 N, R 9 E, Champaign Co.
3	S side, SW 1/4, Sec. 29, T 22 N, R 8 E, Champaign Co.
4	NE corner, NE 1/4, Sec. 1, T 22 N, R 8 E, Champaign Co.
5	SW corner, SW 1/4, Sec. 1, T 22 N, R 8 E, Champaign Co.
6	SW corner, SW 1/4, Sec. 2, T 22 N, R 8 E, Champaign Co.
7	SW corner, SW 1/4, Sec. 3, T 22 N, R 8 E, Champaign Co.
8	S side, SW 1/4, Sec. 9, T 22 N, R 7 E, Champaign Co.
9	SW corner, SW 1/4, Sec. 17, T 22 N, R 7 E, Champaign Co.
10	E side, NE 1/4, Sec. 25, T 21 N, R 7 E, Champaign Co.

Spoon River

Station	Location
1	SW corner, SW 1/4, Sec. 12, T 22 N, R 10 E, Champaign Co.
2	SW corner, SW 1/4, Sec. 13, T 22 N, R 10 E, Champaign Co.
3	E side, NE 1/4, Sec. 23, T 21 N, R 10 E, Champaign Co.
4	S side, SW 1/4, Sec. 23, T 21 N, R 10 E, Champaign Co.
5	N side, NW 1/4, Sec. 35, T 21 N, R 10 E, Champaign Co.
6	S side, SE 1/4, Sec. 35, T 21 N, R 10 E, Champaign Co.
7	SW corner, SE 1/4, Sec. 1, T 21 N, R 10 E, Champaign Co.
8	S side, SE 1/4, Sec. 12, T 21 N, R 10 E, Champaign Co.
9	SE corner, SW 1/4, Sec. 13, T 21 N, R 10 E, Champaign Co.

Embarras River

Station	Location
1	SW corner, NE 1/4, Sec. 29, T 19 N, R 8 E, Champaign Co.
2	S side, SE 1/4, Sec. 30, T 19 N, R 8 E, Champaign Co.
3	E side, SE 1/4, Sec. 31, T 19 N, R 8 E, Champaign Co.
4	S side, SW 1/4, Sec. 5, T 19 N, R 8 E, Champaign Co.
5	S side, SW 1/4, Sec. 17, T 19 N, R 8 E, Champaign Co.
6	SW corner, SE 1/4, Sec. 20, T 18 N, R 8 E, Champaign Co.
7	S side, SE 1/4, Sec. 29, T 18 N, R 8 E, Champaign Co.
8	SW center, SE 1/4, Sec. 32, T 18 N, R 8 E, Champaign Co.

Appendix I. Continued

Jordan Creek

Station	Location
1	E side, NE 1/4, Sec. 27, T 18 N, R 13 W, Vermilion Co.
2	NW corner, NW 1/4, Sec. 15, T 19 N, R 13 W, Vermilion Co.
3	SE corner, SW 1/4, Sec. 9, T 19 N, R 13 W, Vermilion Co.
4	NE corner, NE 1/4, Sec. 8, T 19 N, R 13 W, Vermilion Co.
5	NW corner, NW 1/4, Sec. 4, T 19 N, R 13 W, Vermilion Co.
6	SW corner, SE 1/4, Sec. 33, T 19 N, R 13 W, Vermilion Co.
7	E side SW 1/4, Sec. 33, T 19 N, R 13 W, Vermilion Co.
8	NE corner, NE 1/4, Sec. 33, T 19 N, R 13 W, Vermilion Co.
9	SW corner, SW 1/4, Sec. 27, T 19 N, R 13 W, Vermilion Co.
10	S side, NE 1/4, Sec. 27, T 19 N, R 13 W, Vermilion Co.
11	NW corner, SW 1/4, Sec. 26, T 19 N, R 13 W, Vermilion Co.
12	N side, SW 1/4, Sec. 26, T 19 N, R 13 W, Vermilion Co.

Collison Creek

Station	Location
1	W side, NW 1/4, Sec. 3, T 21 N, R 14 W, Vermilion Co.
2	S side, NE 1/4, Sec. 3, T 21 N, R 13 W, Vermilion Co.
3	SW corner, SW 1/4, Sec. 2, T 21 N, R 13 W, Vermilion Co.
4	SW corner, SW 1/4, Sec. 35, T 21 N, R 13 W, Vermilion Co.
5	W center, SW 1/4, Sec. 35, T 21 N, R 13 W, Vermilion Co.
6	E center, SW 1/4, Sec. 35, T 21 N, R 13 W, Vermilion Co.
7	W side, SW 1/4, Sec. 36, T 21 N, R 13 W, Vermilion Co.
8	N side, SW 1/4, Sec. 36, T 21 N, R 13 W, Vermilion Co.

Appendix I. Continued

Hurricane Creek

Station	Location
1	NW corner, SW 1/4, Sec. 15, T 12 N, R 9 E, Coles County
2	SW corner, NW 1/4, Sec. 23, T 11 N, R 10 E, Coles County
3	SW corner, SW 1/4, Sec. 22, T 11 N, R 9 E, Coles County
4	SE corner, SW 1/4, Sec. 28, T 11 N, R 9 E, Cumberland Co.
5	W side, SW 1/4, Sec. 33, T 11 N, R 9 E, Cumberland Co.
6	SW corner, SW 1/4, Sec. 5, T 11 N, R 9 E, Cumberland Co.
7	W side, SW 1/4, Sec. 18, T 11 N, R 9 E, Cumberland Co.

Appendix II. Procedures used for analysis of water samples

Specific Conductance (μmho/cm): YSI Model SCT meter
Total Dissolved Ionizable Solids (mg/l NaCl): By calculation from specific conductance table
Hardness (mg/l $CaCO_3$): EDTA colorimetric method (autoanalyzer)[2]
Turbidity (JTU): Monitek model 150 turbidimeter
For Turbidity>500 Jackson candle turbidimeter
Total Phosphorus (mg/lP): Ascorbic Acid Reduction method (autoanalyzer)[2]
Soluble Orthophosphate (mg/lP): Ascorbic Acid method (autoanalyzer)[1,2]
Nitrate (mg/l N): Cadmium reduction method (autoanalyzer)[1,2]
Nitrite (mg/l N): Diazotization method (autoanalyzer)[1,2]
Ammonia (mg/l N): Berthelot reaction method (autoanalyzer)[3]
Suspended Solids (mg/l): Dry at 180° C, Gelman Type A Glass Fiber Filter [1]

[1] American Public Health Association, American Water Works Association, and Water Pollution Control Federation. 1976. Standard Methods for Examination of Water and Wastewater, 14th ed. Washington D. C. 1193 pp.

[2] U. S. Environmental Protection Agency. 1974. Methods for chemical analysis of water and wastes, 2nd ed. Rept. No. EPA-625/6-74-003. Washington, D. C. 298 pp.

[3] Methodology Formulated by Technicon Corporation, Tarrytown, New York.

Appendix III. KLS values (mean ± 1 S.E.) and erosion potential (EP) category for each erosion area identified in Spoon River, Big Ditch and Jordan Creek.

Stream	$\bar{X}$ KLS ± 1 S.E.	EP
Spoon River	.232 ±.009	Moderate
"	.262 ±.010	High
"	.157 ±.010	Low
Big Ditch	.367 ±.020	Very High
"	.315 ±.007	Very High
"	.252 ±.013	High
"	.145 ±.007	Low
Jordan Creek	.117 ±.008	Very Low
"	.238 ±.013	Moderate
"	.162 ±.007	Low
"	.369 ±.035	Very High