TECHNIQUES FOR STUDYING NONPOINT WATER QUALITY

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Introduction

While the results and techniques described in this paper apply to Midwestern watersheds, there is no reason they can not equally apply to western and eastern watersheds as well. This paper might more properly be titled "Techniques for Studying Undefined Contributions to Water Quality". The more common distinction between sources for water quality is, of course, between point- as opposed to nonpoint sources. The authors, in their work to help develop a more efficient water quality control program in the State of Illinois, have found the more useful distinction to be between defined sources of water quality and undefined sources. A defined source is one for which the amount of a water quality constituent delivered per unit time to the active stream channel and its location of delivery are known. The active stream channel is defined as that part of the stream bed and floodplain with greater than 50% probability of being flooded in any given year, i.e. the 2-year floodplain.

The distinction between defined and undefined sources is more important than between point- and nonpoint sources. Effective and efficient water quality management can only be applied to defined sources. Water quality models to deal with management options can only simulate defined sources. Defined sources can be either point sources as, for example, waste treatment facilities, or nonpoint sources as is floodplain farming. Undefined sources, as well, can be either point sources, as are some illegal gravel operation discharges, or nonpoint sources such as upland farming.

In our work in Illinois, we studied several hundred watersheds to distinguish defined and undefined sources of water quality. Prospects for effective and efficient water quality control were seen to be poor given the very large proportion of water quality deriving from undefined sources (Wilkin and Flemal, 1980). Our analyses suggested that, except in a few urban-dominated watersheds, undefined sources were accounting for nearly 100% of the total constituent load in the stream and that total control of defined, and mostly nonpoint, sources would effect little in the way of water quality improvement.

The work suggested several crucial kinds of information needed to convert undefined sources of water quality to defined sources. These are:

1. A fixed network of monitoring locations, including both instream and all effluent locations;
2. periodic sampling for chemical water quality analysis using both filtered and unfiltered analysis techniques;
3. a record of effluent discharge or stream flow at the time of water quality sampling;
4. land use information for critical locations in the watershed;
5. watershed loading information on the amounts and locations and timing of chemical constituents introduced to the watershed; and
6. further theoretical and empirical studies on the movement of chemical constituents in the watershed.

No state has the ideal program for gathering this information. Nonetheless, Illinois has had an unusually good monitoring program for water quality that provides a significant amount of this required information. This paper describes our use of these data and what we have learned therefrom about defining presently undefined sources of water quality.

The Illinois Water Quality Monitoring Network

At times, the State of Illinois has monitored over 400 stations in a fixed network around the State. Each station was sampled monthly, and each sample was analyzed for a suite of over 50 constituents or characteristics. These fixed stations allowed us to divide the state into as many water quality subbasins, with drainage divides determined by the station locations. Within each subbasin, the location of any defined sources was noted including the flow distance from that source down to the water quality monitoring station. In addition, we attempted to identify the theoretical "center" of the subbasin for

estimating the average flow distance for nonpoint contributions within the subbasins. Figure 1 is a schematic representation of the upper Sangamon River in east-central Illinois showing the subbasin or subsegment breakdown, the location of point sources, monitoring stations, and subsegment centers.

Subsegment or Subbasin Drainage Divides

▲ Point Source

■ IEPA Ambient Water Quality Monitoring Station

● Hypothetical Center of Undefined Subbasin Inputs

Figure 1. Schematic representation of the upper Sangamon River in east-central Illinois. Station E18 is the downstream delimiter.

Mass Balance Accounting

Mass balance accounting (Wilkin and Flemal, 1979) is the primary technique used for identifying the relative importance of defined and undefined sources in the water quality subbasins. In effect, this procedure, which was ultimately computerized, uses the monitored constituent concentration at each monitoring station, multiplied by flow or discharge and corrected to an annualized rate of metric tons per year of chemical constituent flowing past that point in the stream. In the Illinois network, flow data were not routinely taken, so estimates of flow had to be made based on U.S. Geological Survey stream flow records and drainage area at the sampling station.

Each defined water quality contributor to the subbasin, including the next upstream water quality monitoring station or stations, was accounted for assuming first order assimilation. The rate of assimilation had to be obtained by solving a series of simultaneous equations, one for each subbasin in the analysis of which there had to be at least two. The computer does this by successive approximation.

When the assimilation rate is determined, it can be applied to the constituent load at the upstream station or stations and to all intervening defined sources. These calculations result in the total defined portion of the subbasin load arriving at the downstream monitoring station. Anything left over by simple difference between the total constituent load measured at the downstream station and the various defined contributions from upstream is presumed to be an undefined load originating in the subbasin. This is the starting point for the search for undefined sources.

Wilkin and Flemal have studied the fraction of load deriving from undefined sources across Illinois. Findings from the upper Sangamon River were typical of the state as a whole, outside urban areas. The upper Sangamon consists of 494 square miles of drainage area with mean total discharge of 1.03 cubic feet per second per square mile. The basin consists of five subbasins and has eight point sources contributing, on the average, 0.5 percent of the toal stream flow. Land use in the basin is 2% urban and industrial, 96% agricultural, and 2% other. Table 1 shows the proportion of constituent loads from undefined sources in the upper Sangamon watershed.

Table 1. Fraction of load from
undefined sources, upper Sangamon
River, east-central Illinois.

Constituent	Fraction Undefined
Ammonium Nitrogen	0.84
Barium	0.99
Boron	0.99
Chloride	0.99
Copper	0.99
Fecal coliform	0.62
Fluoride	0.99
Iron, total	0.99
Lead	0.99
Manganese	0.99
MBAS	0.99
Mercury	0.94
Nitrate nitrogen	0.99
Phenol	0.99
Phosphorus, total	0.93
Sulfate	0.99
Total dissolved solids	0.99
Zinc	0.99

An analysis of individual water quality constituents is instructive. The mean basin concentration for iron is 1.09 mg/l with 32% of the samples violating the Illinois general use standard of 1.0 mg/l. Only 1% of the total iron load derives from defined sources. Even if there were total removal of defined sources, there would be no significant reduction in the violation rate for iron.

Mean basin concentration for fecal coliform organisms is 3,200 MPN/100 ml. Sixty-nine percent violate the Illinois general use standard of 200 MPN/100 ml. Total load from defined sources amounts to 38%, with 62% undefined. Even with total elimination of defined sources, the minimum feasible violation rate would be in the range of 59%.

Phosphorus, again, has a mean basin concentration of 0.29 mg/l with 90% of the samples violating the Illinois general use standard of 0.05 mg/l. Only seven percent of the total load is from defined sources, so the minimum feasible violation rate, with total removal of defined sources, is still 87%.

Other constituents show the same general story. Clearly, until we can define a larger proportion of the total constituent load, we have no chance of controlling these sources to accomplish our water quality goals. The following describes the various means by which we have attempted to define previously undefined water quality contributions.

Concentration/Discharge Relationships

The importance of monitoring concentration and discharge together cannot be overestimated. For point sources, of course, it is essential to know both concentration and discharge in order to determine the amount of the constituent being introduced to the stream. For streamflow measurements, it is the only way to estimate the total load of the constituent arriving at that point in the stream. Both are essential in knowing what fraction of the load is deriving from defined and undefined sources. Further benefits, however, can be gained in the attempt to identify and define water quality sources. Especially where the monitoring is frequent and where individual flood events can be recorded, we can begin to gain clues to the delivery mechanisms of the constituent to the stream.

For example, where the constituent is being delivered to the stream at a constant rate, as might be the case for constituents entering with ground water seepage, there should be a clear inverse relationship between concentration and discharge. This is the result of dilution. Where a constituent shows such a pattern, the presumption is that of relatively constant delivery. Nitrate nitrogen seems to follow this general pattern.

Where the constituent is delivered to the stream more rapidly at higher stream discharges, while the concentration may do anything from raising to reducing on the rising limb of the hydrograph, the product of discharge and concentration will increase significantly. Phosphorus is a constituent whose concentration tends to increase with discharge. This could be a combination of bed load entrainment and delivery of phosphorus-bearing eroded sediments to the stream channel. Where high concentrations tend to persist after return of the hydrograph to baseline levels, the probable cause is bed load entrainment.

A different pattern is observed for iron. Iron concentrations in our study streams increase sharply with increased flow. Then, at the peak of the hydrograph, they decrease sharply to levels equal to or below baseline levels. This is thought to indicate a "first flush" phenomenon. Temporarily higher flows entrain material that was not otherwise involved in streamflow. This can happen either for

materials being deposited on banks or for materials washed in as urban storm runoff. In the case of iron, ground water contains high concentrations of soluble ferrous iron. Seepage of ground water along stream channels allows oxidation to insoluble ferric iron form which precipitates onto the dry banks. Not until the early stages of the next major flood event is this material delivered downstream.

The point of relating discharge and concentration is that we can begin to infer certain characteristics of delivery of the constituent to the stream. This can be of significant help in pinpointing the source.

Sediment-Related Pollution

Sediment has been identified as our most serious water quality problem. The list of problems and costs associated with sediment is lengthy. It includes reservoir sedimentation, disruption of navigation, disturbance of fisheries and wildlife habitat, and added treatment costs for water supplies. Sediment is also implicated in the delivery of a significant chemical fraction to water quality. The Illinois Environmental Protection Agency Task Force on Nonpoint Sources of Pollution (1978) estimated that over 90% of the organic nitrogen and phosphorus from upland agriculture delivered to streams is adsorbed to eroded soil sediment. Clearly, other pollutants can either be delivered to surface waters adsorbed to sediment or can move as unadsorbed particulate by the same pathways as soil sediments. Our groups attempted to study sediment movement in order to gain some ideas about the sources of this kind of water quality constituent.

This work will be reported at length elsewhere, but it can be summarized here. It was necessary to find a tracer that would allow us to study sediment movement across the watershed, to find its areas of erosion and its areas of redeposition. Sediment delivery was defined, for our work, as the process of sediment movement to the active flood plain. Once sediment is at the active floodplain, it can be considered delivered to surface waters since it is only a matter of months, normally, before a flood event suspends the material and moves it downstream. Work had been done with fallout Cesium-137, a byproduct of the atmospheric testing of atomic weapons. Fallout Cesium-137 adsorbs strongly to surface soils. Little of significance is removed with crops. The inference is that, in areas of strong erosion, the surface Cesium-137 concentrations are lower than the average for the watershed. In areas of strong redeposition, they should be higher than average.

The surprising results were that, for a large part of the watershed similar to the upper Sangamon, eroded sediments appear to be trapped by such things as upland depressions, fence rows, hedge rows, roadside ditches, and other obstructions. The fraction of upland sediment delivered to the active floodplain seems very low indeed. No attempt was made to estimate this accurately, but figures in the range of 10% delivery seem appropriate based on our field observations. Sediments eroded from lands very near the floodplain, particularly on the steeply sloping land immediately next to it, are redeposited by obstructions much less frequently. Thus, these eroded soils are delivered at a much higher rate. Floodplain soils, in areas of floodplain farming, are not only among the most severely eroded soils in the watershed, but, since this sediment is by definition already delivered when it is eroded, it has maximum effect on instream sediment levels.

Similar logic, of course, can be applied to those chemical constituents delivered to the stream adsorbed to soil particles, or to those whose physical form causes them to move in the same manner as eroded soil particles. Phosphorus, of course, is one such chemical constituent. It remains now to identify not only what chemicals use such a delivery pathway, but to find out where, when and how they are loaded into the watershed in the first place, since this has a strong influence on the probability of delivery to surface waters.

Land Use/Water Quality Relationships

Early statistical studies relating land use over the entire watershed and the undefined portion of the constituent loading gave largely negative results. The only constituent for which positive results were obtained was nitrate nitrogen. This model explained just over 30% of the variability for nitrate nitrogen. This can be explained logically. Nitrate nitrogen is highly soluble and is primarily loaded into the watershed as nitrogen fertilizer, an activity occurring relatively uniformly over the watershed. Its high solubility and its tendency to persist in ground water suggests that a relationship should be found between land use over the entire watershed and stream water quality.

As noted previously, a constituent like phosphorus, however, being relatively insoluble and strongly adsorbed to soil particles, should show a very different pattern. Based on the foregoing sediment work and our understanding of the chemical properties of phosphorus, land use close to the stream should be more important in determining instream phosphorus levels.

LANDSAT imagery was used to obtain land use within the 100-year floodplain of the upper Sangamon. To this was added any urban land use found in each subbasin. These, then, were used in a statistical analysis of the effects of land use on two water quality constituents. Because nitrate nitrogen and total phosphorus seem to be so different in delivery pathways, the former moving with groundwater and the latter with eroded sediment, these were chosen. The early expectation was that phosphorus levels

would be better predicted by land use close to the stream than would nitrate nitrogen levels. Results, however, suggested that both instream constituents are strongly predicted by knowing land use close to the streams.

For phosphorus, of course, these findings are consistent with those from the sediment movement work mentioned previously. For nitrate nitrogen, however, based on highly significant regression coefficients, the inference is that enough can happen to ground water constituents, between the point of watershed loading and the stream, that land use close to the stream still tends strongly to control constituent concentrations instream. These effects can be both additive and subtractive, depending on the land use.

Conclusions

These results only scratch the surface. We can not claim to have truly defined any previously undefined water quality sources. This work suggests some fruitful directions to take this kind of research. It seems obvious, both from a theoretical standpoint, and from our empirical results, that land uses close to the streams seem to be unusually important in determining instream constituent concentrations. This would suggest that more work should be done closer to the streams than before.

Much more can be done, however. Constituent loadings into the watershed, their locations and timing could be easily monitored. More effort could be spent in monitoring water quality during the course of storm runoff events to give better definition to the relationship between discharge and concentration. More effort could also be given to distinguishing the water quality constituents whose delivery pathway primarily involves movement as, or adsorbed to, eroded sediment, and to those moving primarily as groundwater. Of course, more could be done in long-term, fixed station monitoring of instream water quality.

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