UNDERSTANDING NUTRIENT FATE AND TRANSPORT, INCLUDING THE IMPORTANCE OF HYDROLOGY IN DETERMINING LOSSES, AND POTENTIAL IMPLICATIONS ON MANAGEMENT SYSTEMS TO REDUCE THOSE LOSSES

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Introduction

Losses of the major nutrients, nitrogen (N) and phosphorus (P), from agricultural lands to water resources cause water quality concerns relative to the health of both humans and aquatic systems, and impair water resource uses. In addition to concerns for hypoxia in the Gulf of Mexico, work is currently underway by the States with guidance from the U.S. EPA, to develop nutrient water quality criteria to be protective of local lakes and streams.

At this time it is not clear on whether or how other cost and benefit factors such as production economics, sustainability and carbon sequestration/soil quality, and grain quality will be taken into account in the development of the criteria. Because of current water quality concerns and use impairments, and the expectation that the criteria, when developed and implemented, will lead to additional water bodies being listed as impaired, there is an immediate and continuing need to assess and improve tools to reduce nutrient losses from agricultural lands in the Corn Belt.

Understanding nutrient fate and transport is critical in designing and implementing the right practices/systems to effectively reduce nutrient losses (i.e. to do the “right thing”). However, it is probably equally as important, if not more so, to use that understanding to not do the “wrong thing.” Knowledge of the potential, limitations, and factors that affect the efficiency of individual practices is the first necessary piece of design. Being able to combine that knowledge, including that of any interactions between practices, with site-specific conditions is the second necessary piece to develop the overall system of in-field and off-site practices. Part of the discussion in choosing and implementing improved practices/systems, is predicting and measuring the water quality changes needed to meet the outcomes desired (assuming we know what we want and how much nutrient reduction is needed to get there - the possible topic of a future workshop). The evaluation or assessment of practices/systems can range from being “directionally correct,” to a strictly quantified reduction that is needed in a “performance-based” approach.

First and foremost in a “performance-based” approach is the question of whether there are even any practices/systems capable of reaching the stated criteria. Given that there are (and for drainage from a landscape driven by nature’s highly variable weather, it is not a given that there always will be), one advantage is that producers should have some flexibility in the choice of practices/systems to use. However, although the performance-based approach worked well for point-source pollution, and is appealing because performance (i.e. meeting water quality criteria) is what is sought, there are some issues/concerns that need to be overcome. The main four are: 1) that the number of legitimate choices of practices/systems available to producers will likely be fairly limited based on current economic constraints, 2) being able to accurately predict the nutrient reductions (i.e. outcomes) expected for practices/systems under a standard or hypothetical set of homogenous conditions is difficult, 3) the highly variable nature of weather (in time and space), and the highly variable spatial nature of soils and their properties that affect outcomes, makes predictions for realistic field/watershed conditions even more difficult, and 4) the high cost and effort needed to accurately monitor what the outcomes are, especially for large numbers of fields or watersheds, is prohibitive. To overcome the last three issues, nutrient criteria that allow some exceedence of a standard would be needed (based on frequency and duration of exceedence, as recommended by the NRI), as well as an acceptable mathematical modeling approach to quantify outcomes on a temporal basis (although some monitoring would still be needed to confirm water quality improvements).

In the following sections, transport mechanisms, hydrology , as well as nutrient availability and concentrations will be discussed relative to potential nutrient losses. Two general landscapes common to the Corn Belt: nearly flat, tile-drained areas; and rolling hills, with well-developed surface drainage will then be briefly discussed relative to the resultant impacts on the need for and choice of management practices/systems to reduce losses.

Transport Mechanisms
Nutrients can be lost dissolved in water and attached to eroded soil/sediment in surface runoff and dissolved in leaching water. These three transport mechanisms, or nutrient carriers, are illustrated in Figure 1. Concern is focused on the inorganic ions ammonium-nitrogen (NH_4-N), nitrate-nitrogen (NO_3-N), and phosphate-phosphorus (reactive-P), as well as total N and total P both in solution and associated with sediment (with P, there may need to be an additional delineation; that of "bioavailable-P"). Regional guidelines proposed for standing waters are 0.7 mg N/L and 0.035 mg P/L; regional guidelines for flowing waters are still in development. National guidelines for flowing waters for the western Corn Belt ecoregion are 2.18 mg N/L and 0.076 mg P/L (www.epa.gov/waterscience/criteria/nutrient/ecoregions/index.html).

Nutrient loss from cropland (either in total or for individual forms) is equal to the summation of the products of the masses of the carriers times the nutrient concentrations in the respective carriers, i.e.:

$$\text{Total loss} = \sum_{n=1}^{3} mass_n \, x \, concentrations_n$$

where n = 1 through 3 represent surface runoff water, leaching water (including artificial subsurface drainage, commonly called "tile drainage"), and sediment. Thus, a management practice/system that reduces a carrier mass and/or concentration in that carrier reduces loss with that carrier. However, the overall impact will be determined by the summation for all three carriers, as well as the consideration of individual nutrient forms. When a single management practice is not sufficient to provide the desired level of control, a system of practices will be needed. To devise a single or a system of management practices that is efficient in reducing nutrient transport to water resources, knowledge of the major mechanism of transport is needed. This requires information on the nutrient properties, the source(s)/availability of the nutrient, and the soil and climatic conditions that exist. A system may include a combination of in-field and off-site practices.

Hydrology
On the large-scale, probably the most important hydrologic factor affecting nutrient losses from agricultural lands is whether tile drainage has been installed which significantly affects the relative volumes of surface runoff and subsurface drainage. Tile drainage has both positive and negative effects on water quality as alluded to below and discussed later (see reviews by Gilliam et al., 1999 and Baker et al., 2004).

On the small-scale, probably the most important hydrologic factor is the soil water infiltration rate, which is highly variable, both temporally and spatially (Baker, 1997). Infiltration refers to the entry of water into the soil profile from the surface. Two forces drive water to infiltrate into the soil, one is gravity, and the other is the “suction” of water by dry soil. Since water infiltration causes the soil to become wetter, the wetting front advances down into the soil with time. During the early stages of infiltration (at the beginning of a rainfall event), the suction forces predominate over the force of gravity and the infiltration rate is at its highest. As time goes on, the infiltration rate decreases because the wetting front moves down into the soil, and the suction forces decreases. When the rainfall rate is less than the initial infiltration rate of the soil but greater than the final gravity-dominated rate, a point will eventually be reached where the water cannot be taken up by the soil profile as fast as it is being added. At this time, the surface soil becomes saturated, and ponding (and runoff from sloping soils) begins.

It is the infiltration rate, in conjunction with rainfall intensity (both of which can change by the minute, and which makes measurement and prediction so difficult), that determines the volume and timing of surface runoff. By subtraction of runoff volume from precipitation, the volume of water that enters the soil can be calculated. This water is temporarily stored for later evapotranspiration or movement from the root zone via percolation (either to groundwater or back to surface water resources through natural or artificial subsurface drainage). In general, with the exception of possibly more nitrate-nitrogen (NO_3-N) leaching, the higher the infiltration rate and more the infiltration, the lower the field losses of all other nutrient/forms.

Infiltration rate can also play a role in determining concentrations as well as the masses of carriers. As shown in Figure 1, there is a thin “mixing zone” at the soil surface that interacts with and releases sediment and nutrients to rainfall and runoff water. The volume of rainfall that infiltrates before runoff begins, as well as the soil adsorption properties of the nutrient form of interest, affects the amount of a particular nutrient form remaining in the “mixing zone” (illustrated in Figure 1 as having a thickness of 1 cm) potentially available to be lost. During a rainfall event the amount of chemical remaining in this mixing zone decreases with movement of water either over or down through this zone. Obviously the higher the rate of infiltration, the longer it is before runoff begins and the lower the chemical concentration in runoff water (and to some degree in sediment derived from soil in the mixing zone).

A second important small-scale hydrologic factor that affects nutrient leaching loss is the route of infiltration. This determines whether the infiltrating water moves through the whole soil matrix, or whether it finds “macropores” or preferential flow paths through which to move quickly deeper, thereby, “by-passing” much of the soil. This is also illustrated in Figure 1. If the chemical of concern is within soil aggregates, flow through macropores can by-pass the chemical and leaching will be reduced. However, if the chemical is on the soil surface and dissolves in infiltrating water that is moving though macropores, leaching will be greater, quicker, and deeper than otherwise expected.

Antecedent soil moisture content is one of the important and variable factors affecting infiltration. Other important factors are soil compaction, soil structure, and surface residue cover. Besides affecting infiltration rate, surface residue cover (and soil “roughness”) creates ponding conditions which extend the opportunity time for infiltration (and therefore the volume of infiltration). All these factors can be affected to some degree by management practices such as artificial drainage, cropping, implement traffic/compaction, residue management, and tillage.

Of these, the first two, artificial drainage and cropping, go hand-in-hand and have the greatest effect on hydrology, where installation of artificial subsurface drainage has in turn allowed intensive annual row-cropping. Over the last 120 years in Illinois and Iowa, wetlands have been drained and the prairie-wetland landscape, where it existed, has been transformed from perennial vegetation to primarily annual, shallow-rooted, corn and soybean row-crops. Figure 2 shows the reduction in wetland area in Iowa over the years, and Figure 3 shows the trend in drain tile produced in Illinois during the period of more intense drainage activity. Figure 4 shows the trends in U.S. cropping, with the current cropping of oats almost totally eliminated by the advent of soybeans.

Analysis of streamflow data over the second half of the 20th century (Schilling, 2005) indicated that generally baseflow and baseflow percentage have increased in that time frame and are "significantly related to increasing row crop intensity." The subsurface drainage that has been installed reduces the moisture contents of the surface soils, increasing infiltration rates, and in turn, reducing surface runoff volumes but increasing subsurface flows. In addition, this finding is directly in line with the fact that there is less evapotranspiration and more subsurface drainage with row-crops than there would be with grasses. In a six-year study in Minnesota (Randall et al., 1997), it was shown for wet years that drainage from row-crops exceeded that from perennial crops by 1.1 to 5.3 times. This is especially evident and important in the April-May-June period when rainfall amounts usually far exceed the water needs of shallow-rooted corn and soybean crops just getting established. This is also a time before the major uptake of nutrients, N and P, by the row-crops. Data show that a major portion of annual subsurface drainage takes place in that April-May-June period. For example, in a 15-year study in north-central Iowa (Helmers,et al.; 2005), over 70% of the tile flow occurred in those three months. In another 15-year study in southern Minnesota, Randall (2004) found that 68 to 71% of the flow and 71-73% of the NO_3-N leaching losses occurred in those three months. Kladivko et al. (2004) in a 15-year study in Indiana showed most of the flow and NO_3-N leaching losses occurred during the fallow season. Jin and Sands (2003) in a hydrologic analysis of subsurface drainage for south-central Minnesota showed on average for an 85-year climatic period that 74% of infiltration in the March to June period was removed by subsurface drainage.

While farming the tile-drained landscape presents an environmental challenge with respect to NO_3-N leaching, the challenge would seem to be less than the multiple challenges for the undrained landscapes that have better drainage and more surface runoff because of their sloping/rolling topography. Use of subsurface drainage (under most designs) generally reduces losses of pollutants in surface runoff (because of not only reduced surface runoff volume but also reduced pollutant concentrations in the surface runoff water). Thus to meet this challenge and preserve use of these drained and highly productive lands, special attention will need to be paid to in-field soil, cropping, and nutrient (N) management to minimize NO_3-N leaching, and/or use of improved water managementpractices and wetlands in the overall system design.

Nutrient Forms/Availability

Three chemical properties largely determine the fate and possible off-site transport of individual forms of nutrients with water: resistance to transformation, solubility, and soil adsorption. Solubility and adsorption are usually related, with adsorption generally increasing with decreasing solubility.

Table 1 provides a set of numbers for the important nutrient forms for N and P relating their concentrations in the soil and water of a field (at or near equilibrium) to expected concentrations in the three carriers, surface runoff water, sediment, and subsurface drainage. Although these numbers in reality are highly variable, both temporally and spatially, for simplicity of comparison, a single set of numbers are given to represent the annual averages for the row-crop planted, corn rotated with soybeans, in much of the Corn Belt.

As shown for N in the soil water, NO_3-N dominates over ammonium-nitrogen (NH_4-N); while in the solid soil itself, organic-N dominates. When comparing what is in the soil water with what is in runoff water, the stronger adsorption of NH_4-N compared to NO_3-N “traps” the NH_4-N nearer the soil surface so the reduction is less for NH_4-N (part of the reduction between concentrations in soil water at equilibrium, and what is in runoff, is due to dilution as well as incomplete mixing of rainfall-runoff with the surface soil during runoff). On the other hand, that same adsorption is what causes the relative concentrations in subsurface drainage, both relative to what is in soil water, and between NH_4-N and NO_3-N, to be lower for NH_4-N. The ratios of NH_4-N and organic-N concentrations for sediment compared to their respective values for in-place soil are over unity which is due to the selective erosion process where the more chemically active, smaller, and less dense (with greater organic matter content) soil particles are preferentially transported. Organic-N in runoff water is usually less than 2 mg/L.

As shown for P in soil water, and in surface runoff and subsurface drainage, reactive-P (dissolved inorganic or molybdenum-reactive-P, sometimes termed PO_4-P or ortho-P) generally makes up more than 60% of the total soluble P. In the soil, total (organic plus inorganic) P dominates over what is classified as plant “available” P determined by one of several soil P tests (in this case a Bray-1 or Mehlich-3 extractant). As with NH_4-N, reactive-P is somewhat trapped on the soil surface, so runoff concentrations may only be reduced three fold over that in soil water, but concentrations are much lower in subsurface drainage because of adsorption/precipitation of reactive-P in generally P-deficient subsoils. As with N, P concentrations in sediment are greater than the in-place soil because of the selective erosion process. Given the very high adsorption and low solubility for total P, and realizing the ratio of the mass of surface runoff water to sediment can be as small as 100 to 1 for some rainfall-runoff events, P loss for row-cropped fields is often dominated by that lost with sediment (depending on the degree of erosion).

Nutrient concentration-time relationships and watershed losses

Monitoring activities for 1999, 2000, and 2001 were performed on the Upper Maquoketa River and three intrabasin sites in northeast Iowa (see Figure 5). At the four sites, measurements of flow and N, P, chemical oxygen demand (COD), and suspended sediment concentrations were performed. The site for flow measurement/sampling for the whole basin is just above Backbone State Park, with a drainage area of 39,260 ac (in 1998, 40% corn, 27% soybeans, 11% oats/hay/alfalfa, 10% pasture, and 9% forest). The three intrabasin sites range from 570 ac (designated 2; 82% corn, 12 soybeans, and 5% pasture) to 1315 ha (designated 3; 57% corn, 26% soybeans, 13% oats/hay/alfalfa, and 2% pasture) to 4280 ac (designated 1; 44% corn, 40% soybeans 10% oats/hay/alfalfa, and 4% pasture).

Figure 6, as an example, shows flow and suspended sediment concentration data for three rainfall-surface runoff events in a two-week period in May, 2001 for the whole basin site (number 4). These three events, preceded and separated by flow periods of only subsurface drainage, were caused by rainfall amounts of 30 to 40 mm, and are representative of growing-season events. Figures 7, 8, and 9 show NO_3-N, NH_4-N, and total-N (including N associated with sediment) concentrations versus time for the same period. Figures 10 and 11 show reactive-P and total-P (including P associated with sediment) concentrations versus time; and Figure 12 shows COD concentrations versus time, again for the same period. In agreement with the previous discussion, NO_3-N concentrations decrease during a surface runoff event, while all other concentrations increase.

Tables 2, 3, and 4 show total annual precipitation, flow, and losses of sediment and nutrients for each of the four sites for 1999, 2000, and 2001, respectively. Nutrient losses (kg/ha) are given for both soluble forms and N and P lost with sediment. As shown in the Tables, the N losses were dominated by NO_3-N, which ranged from 20 to 65 kg/ha. Ammonium-nitrogen losses were less that 1 kg/ha, and soluble organic N loss (organic-N minus NH_4-N) and N lost with sediment were about the same, in the range of 1 to 13 kg/ha. As a percent of total N lost in all forms, that lost as NO_3-N was at least 80% of the total for all four sites. As shown in the tables, total soluble P losses were less than 1 kg/ha, with reactive-P in solution making up at least 60% of the total soluble P. The amount of P lost with sediment ranged from about half to more than twice that of total soluble P.

Flow-weighted annual average NO_3-N concentrations ranged from 9.6 to 17.5 mg/L for the three years. The maximum contaminant level (MCL) for NO_3-N is 10 mg/L, which was exceeded much of the time at all four sites. NH_4-N concentrations, which when above 2 mg/L can be harmful to fishes, never exceeded 1 mg/L and averaged less than 0.25 mg/L. Total N concentrations including NO_3-N as well as NH_4-N, soluble organic-N, and sediment-N were all above 10 mg/L, which is more than four times higher than a proposed regional water quality standard of 2.2 mg/L. Soluble P concentrations averaged about 0.15 mg/L, and when sediment P was added, total P concentrations in stream flow averaged from 0.25 to 0.50 mg/L. These concentrations are three to seven times higher than a proposed regional water quality standard of 0.076 mg/L.

Management Practices/Systems

In discussion of nutrient losses, and practices/systems to reduce them, the term "excess nutrients is often used with the implication that if there were no excess nutrients, there would be no losses. There are two problems with applying that logic to Corn-Belt row-crop agriculture; one, under the conditions and assumptions of mass balances being made by Corn Belt states for the corn-soybean rotation, there are no "excess nutrients," and two, in order that sufficient nutrients are available to the plants to obtain economic optimum crop yields, nutrients must be present in significant amounts during the growing season, and therefore are susceptible to loss with rainfall-runoff and subsurface drainage events that can and do happen at any time.

Corn N needs can be used as an example, where between grain, roots, and stover, at least 180 lb N/ac need to be taken up with about 18 inches of transpiring water (about 4 million lb/ac) to produce 165 bu/acre; therefore, the ratio of NO_3-N to water is 45 mg/L. Even if only half the N was taken up passively with water, the average concentration in soil water available to corn roots during the growing season would have to be over 22 mg/L to obtain economically viable yields.

Management practices/systems for the nearly flat, tile-drained areas of Iowa need to be more focused on N because of NO_3-N leaching losses (Baker, 2001 and 2003). Management practices/systems for rolling hills, with well-developed surface drainage, need to be more focused on P because of greater potential surface runoff volumes and sediment losses (Baker and Laflen,1983 and Baker, 1987). The Iowa P index addresses this issue (Mallarino et al., 2002).

In summary, discussion to follow in this workshop on current technology in the way of in-field best management practices/systems (including fertilizer and manure management and erosion control) will show there is potential but also limitations in terms of how much reduction in nutrient losses can be achieved for row-crops. Off-site practices such as wetlands (for reduction in NO_3-N transport) and vegetated filter/buffer strips (for reduction in sediment and sediment-P transport) will be discussed relative to their considerable potential to add to in-field practices/systems. Predictions that alternative cropping, in the way of small grains and more and longer sod-based rotations (including cover crops), if more economically feasible, could have a major impact on reducing nutrient losses will be made. The benefits of using field- and watershed-scale tools to design more efficient systems of practices based on site-specific conditions will be presented. And the difficult problem of how to assess the reduction in nutrient losses of implementing new practices/systems will be addressed. The questions now (and possibly for a future workshop) are how much reduction is necessary, and who should pay for the implementation of alternative practices when they do not pay for themselves.

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Table 1. Example concentrations of the nutrient forms in soil or soil water, and in surface runoff, subsurface drainage, and sediment from a corn-soybean rotation in the Corn Belt.

Nitrogen (N)

<u>soluble</u>

	Soil[1] water	surface runoff	subsurface drainage
	mg/L		
NH_4-N	1.0	0.5	0.1
NO_3-N	50.0	4.0	15.0

<u>solid/adsorbed</u>

	Soil[1]	sediment
	ppm	
NH_4-N	15	20
NO_3-N	0	0
organic-N	1500	2000

Phosphorus (P)

<u>soluble</u>

	Soil[1] water	surface runoff	subsurface drainage
	mg/L		
Reactive-P	0.6	0.2	0.050
total-P	0.9	0.3	0.075

<u>solid/adsorbed</u>

	Soil[1]	sediment
	ppm	
available-P	30	40
total-P	600	800

[1]Top 12 inches of soil; 3% organic matter.

Table 2. Total rainfall, runoff, and losses (kg/ha) of suspended sediments and nutrients for the Upper Maquoketa Watershed in 1999.

Watershed/site	1	2	3	4
Rainfall (mm)	853	853	847	847
Runoff (mm)	429	276	499	396
NH_4-N	0.9	0.4	0.6	0.2
NO_3-N	44.9	39.2	65.4	40.7
Organic-N	2.8	1.5	2.5	2.0
Reactive-P	0.5	0.3	0.4	0.4
Total soluble P	0.8	0.4	0.6	0.7
Sediments	406	666	1,539	440
N with sediments	2.3	5.8	13.2	1.7
P with sediments	0.4	0.8	3.5	0.4

Table 3. Total rainfall, runoff and losses (kg/ha) of suspended sediments and nutrients for the Upper Maquoketa Watershed in 2000.

Watershed/site	1	2	3	4
Rainfall (mm)	790	790	830	830
Runoff (mm)	293	201	325	315
NH_4-N	0.4	0.2	0.7	0.3
NO_3-N	38.7	34.9	54.7	38.2
Organic-N	2.8	1.3	3.1	2.0
Reactive-P	0.5	0.3	0.3	0.4
Total soluble P	0.7	0.3	0.5	0.5
Sediments	136	149	2,410	884
N with sediments	0.9	0.7	5.9	1. 8
P with sediments	0.8	0.3	3.1	0.8

Table 4. Total rainfall, runoff, and losses (kg/ha) of suspended sediments and nutrients for the Upper Maquoketa Watershed, 2001.

Watershed/site	1	2	3	4
Rainfall (mm)	889	889	890	890
Runoff (mm)	226	138	210	332
NH_4-N	0.5	0.1	0.3	0.4
NO_3-N	25.4	19. 8	36.8	36.2
Organic-N	2.1	0.6	1.3	36.2
Reactive-P	0.4	0.2	0.2	0.4
Total soluble P	0.5	0.2	0.2	0.6
Sediments	41	44	266	326
N with sediments	0.1	0.4	1.5	2.1
P with sediments	0.0	0.7	0.4	0.5

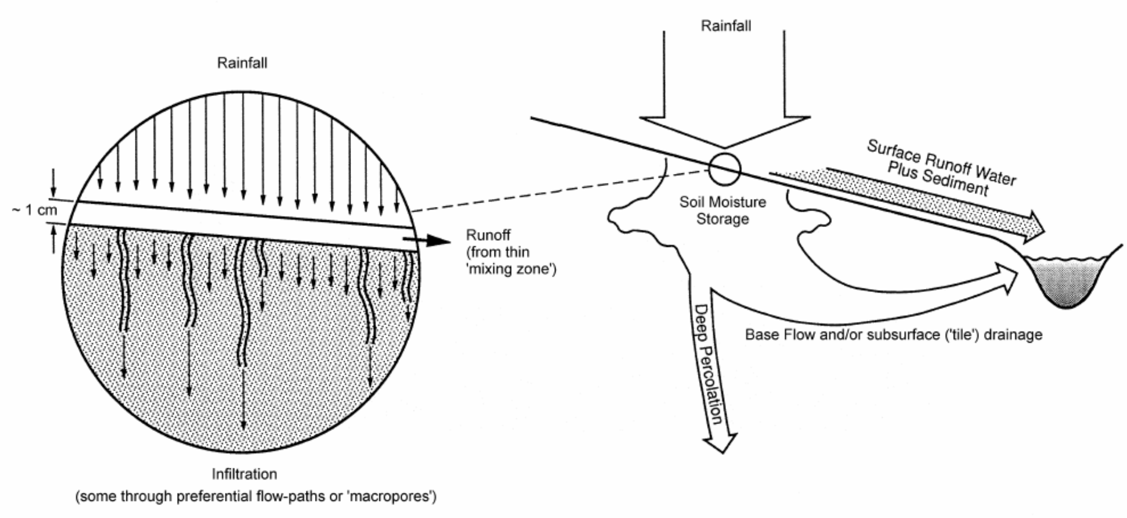

Figure 1. Schematic of transport processes and the "thin mixing zone."

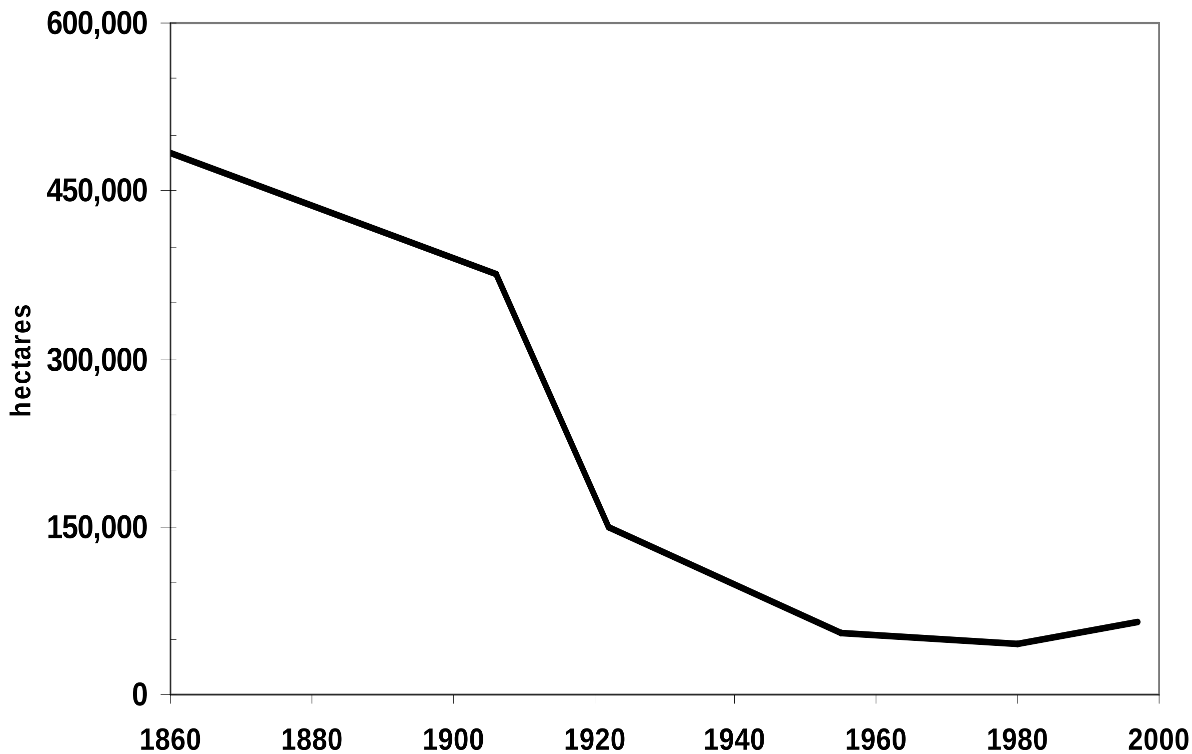

Figure 2. Trends in total wetland area in Iowa with time.

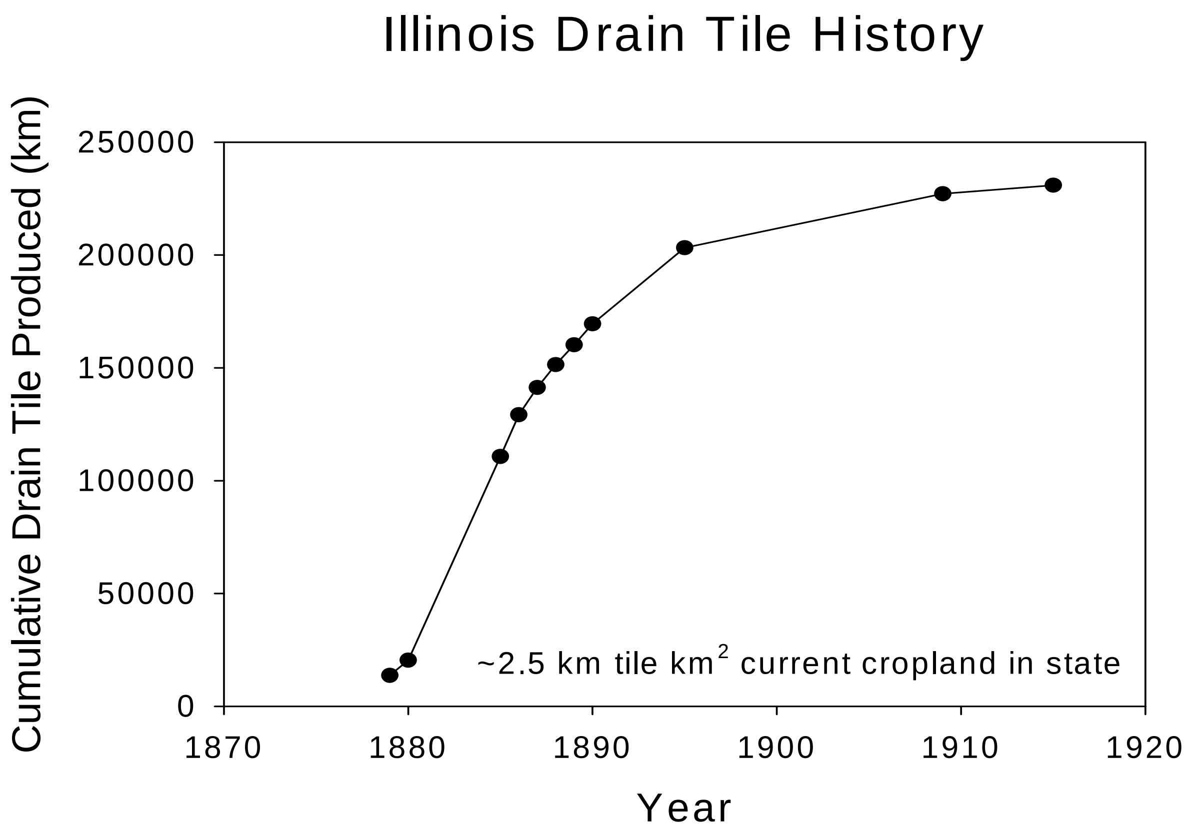

Figure 3. Trends of drain tile produced with time for the state of Illinois (most of Illinois was tiled during the 1880s, and records of tile produced were not kept after 1913, because so little was being produced).

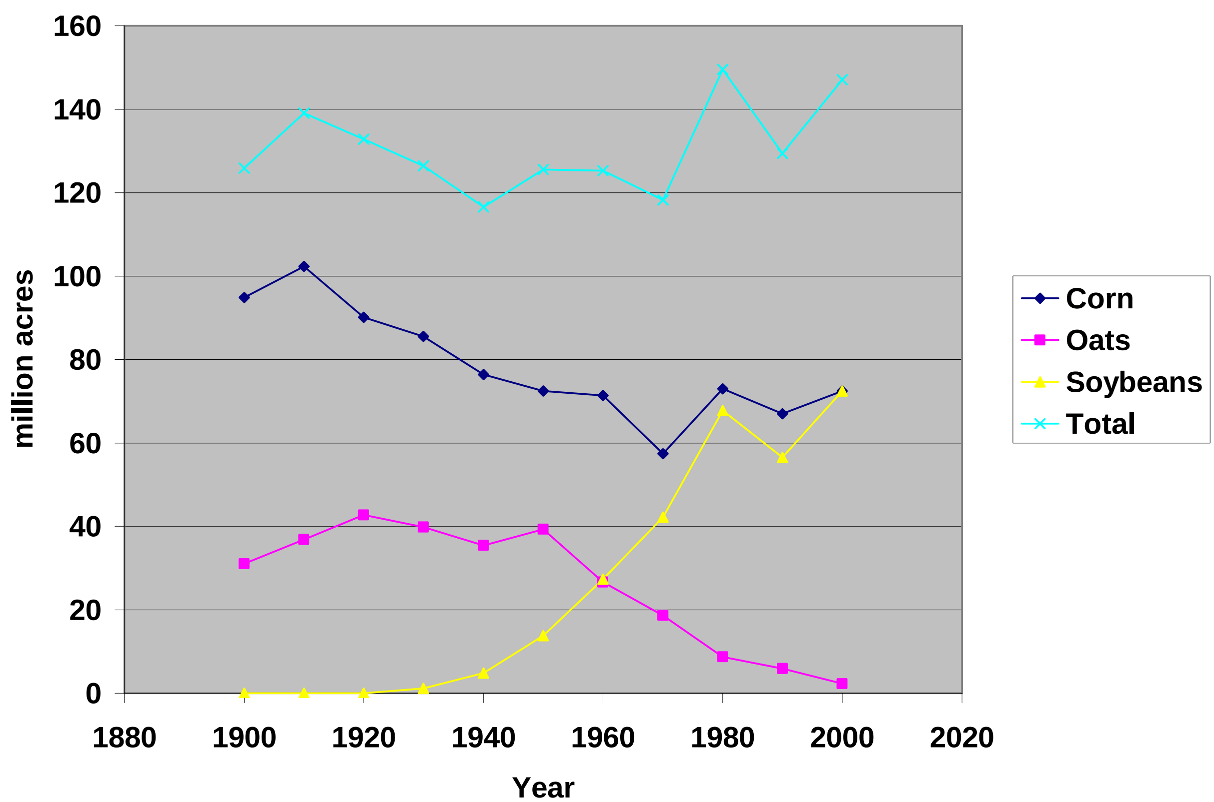

Figure 4. Trends in annual harvested acres in the U.S. (total equals corn plus soybeans plus oats).

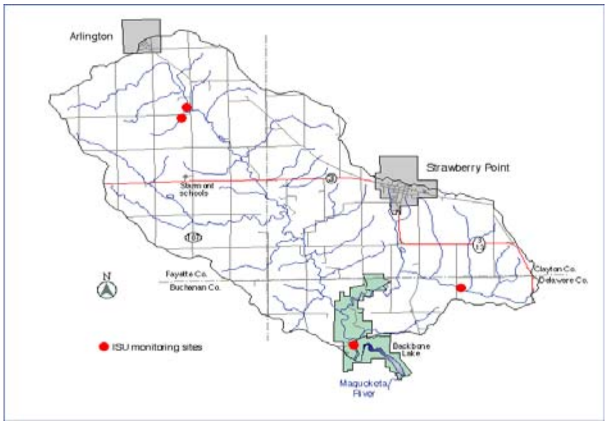

Figure 5. Maquoketa watershed monitoring locations.

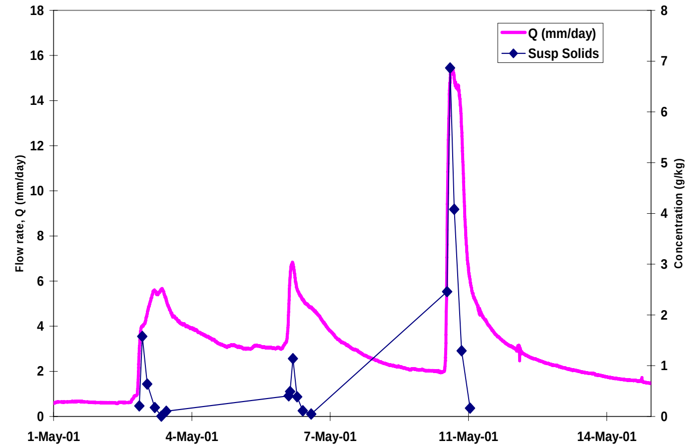

Figure 6. Suspended solids at Site 4.

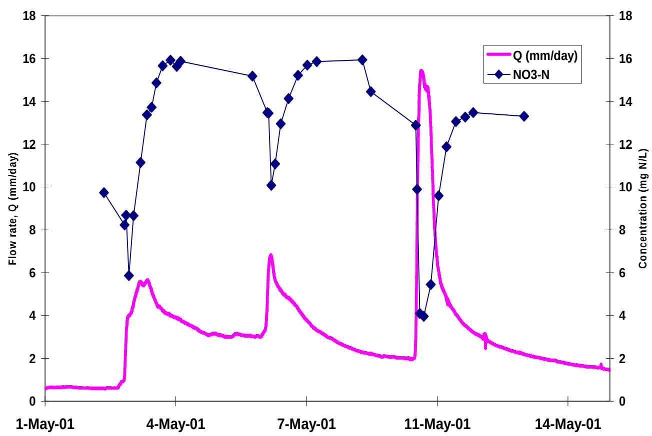

Figure 7. Nitrate-nitrogen at Site 4.

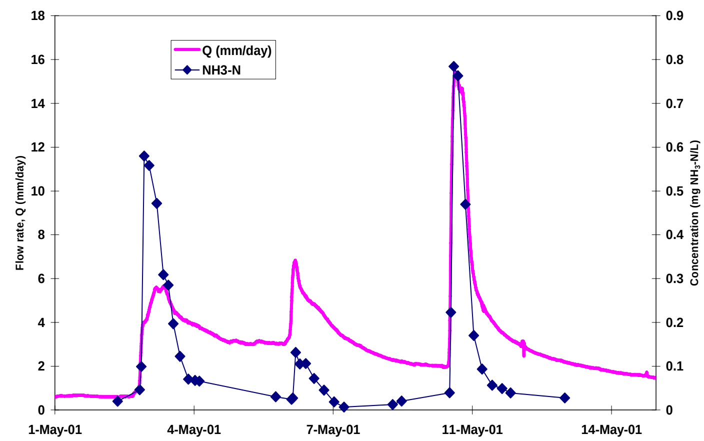

Figure 8. Ammonia-nitrogen at Site 4.

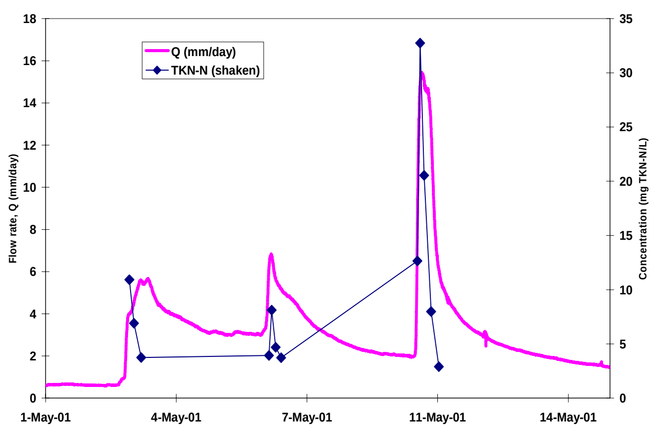

Figure 9. Organic nitrogen (shaken) at Site 4.

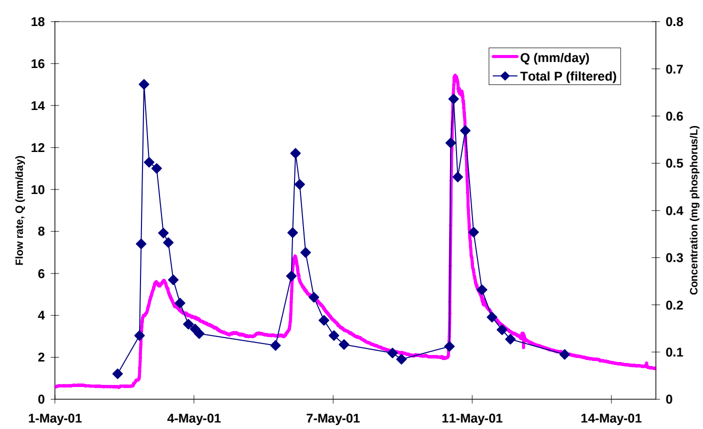

Figure 10. Total phosphorus (filtered) at Site 4.

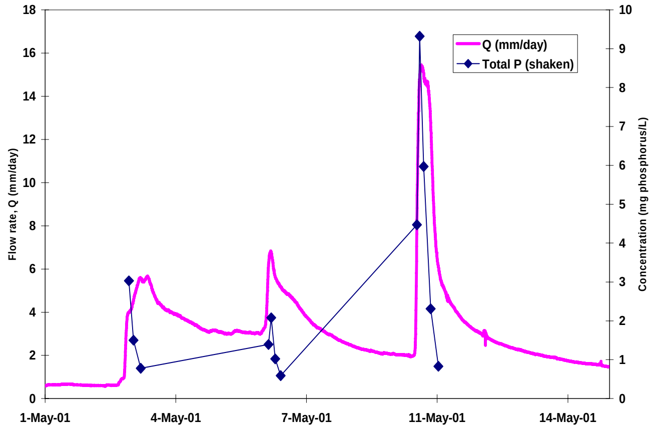

Figure 11. Total phosphorus (shaken) at Site 4.

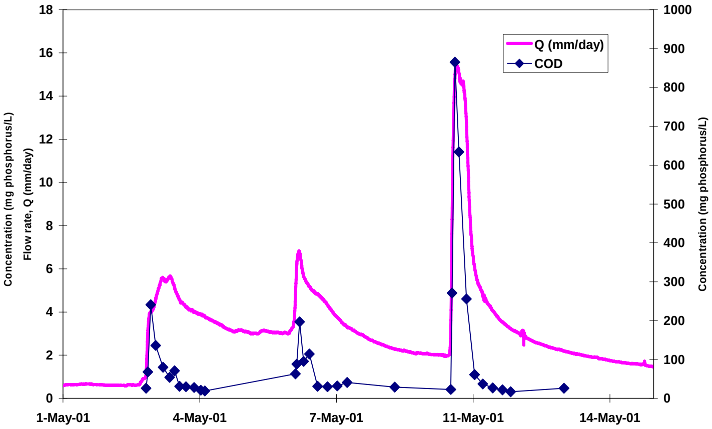

Figure 12. COD at Site 4.