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Agricultural Drainage Tiles: An Overview of their Use, Benefits, and effect on Hydrology and Water Quality

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Abstract

Agricultural drainage tiles (ADTs) have become an integral part of the Midwest's economy by their ability to transform fine-grained, poorly drained soils into highly productive farmland. Because of their design and function, they also pose a number of detrimental consequences related to water quality, stream bank erosion, a loss of wetland areas, increased baseflows, and flooding intensity. This research paper explores how ADTs contribute to the agricultural pollutant loading problem experienced in Midwest streams. It also identifies new practices and technologies being pursued to mitigate their impact.

ADTs provide unique field-to-water pathways for a number of agricultural pollutants, the most critical of which are nutrients. Since ADTs bypass traditional conservation practices used to mitigate the environmental impact of row crop agriculture, contaminants often reach streams with very little, if any, attenuation. ADTs also represent a major alteration in the Midwest's hydrology as they greatly enhance the connectivity between fields and streams. As a result, natural storage areas that once occupied the landscape and gradually released water to streams have been lost, water tables have been lowered, and baseflows have increased. Because of their profound effect on contaminant transport and hydrology, it's now realized that ADTs play a significant role in nutrient loading of Midwest streams and rivers. To mitigate the negative effect of ADTs on water quality, a strategic combination of targeted management practices and new technologies is needed. These include traditional soil conservation practices, new regulations, constructed wetlands, bioreactors, controlled drainage management, and re-routing tile drainage as sub-surface flow across riparian buffers.

Introduction

Row crop agriculture has transformed the Midwest from a landscape of perennial plants and abundant wetland areas to one engineered for the purpose of intensive production of annual crops. One method of altering the landscape for this purpose consists of installing subsurface agricultural drainage tiles (ADTs), a practice that began over a century ago to create an environment more suitable for crop production. ADT systems have since become an integral part of the Midwest's agricultural economy by transforming fine-grained, poorly drained soils into highly productive farmland.[1,2,3]

Use of Drainage Tiles in Agriculture

ADTs have been used to alter the drainage of natural landscapes since European settlement in the late 1800s.[4] Rather than clearing forested slopes, early settlers favored draining floodplains and gently sloping wetland areas for farm ground. Early ADTs were typically constructed of four to six inch diameter clay, concrete, and, sometimes wood tiles approximately one foot in length. Trenches for tile installations were completed by hand or horse drawn trenching machines at depths of approximately 1.5 to 3 feet.[5] Tile segments were then placed end-to-end, allowing water to infiltrate at their joints.

In the 1960s and 1970s, clay and concrete tile gave way to the use of corrugated plastic tubing (CPT). CPT consists of high-density polyethylene that is perforated to allow for water infiltration. Typically, CPT is four inches in diameter, and installation depths range from two to six feet.[4,5] In many instances, ADT systems include inlet risers that extend to the surface for the purpose of draining standing water in field depressions or prairie potholes. Although dependant on site specific conditions such as soil permeability, crop types, desired degree of drainage, and slope, spacings between ADT runs are typically 30 to 90 feet. Outlets are typically 3 to 5 feet below field grade and discharge to a drainage ditch or stream. ADT installation is now more easily accomplished through the use of equipment specifically designed to complete the trenching, CPT placement, and backfilling in a continuous operation. Some sophisticated installation equipment is also fitted with global positioning system receivers to monitor and record tile placement.

To prevent crop stress and damage, ADT systems are designed to remove excess water from a field within 24 to 48 hours following a heavy rain. They are also designed to move water at a velocity that scours the tile conveyance system, keeping it clear of sediment. Desired flow velocities range from 0.5 feet per second (ft/s) in stable, clay-rich soils to 1.4 ft/s in fine sands and silts.[6]

In the past, ADTs were used to drain only portions of fields prone to ponding. The practice has since evolved to pattern tiling where the intent is to lower the water table throughout an entire field, even in more steeply sloped landscapes.[4] In some instances, tile drainage may be responsible for lowering water tables by approximately six feet, representing a significant decrease in subsurface water storage (Figure 1).[7]

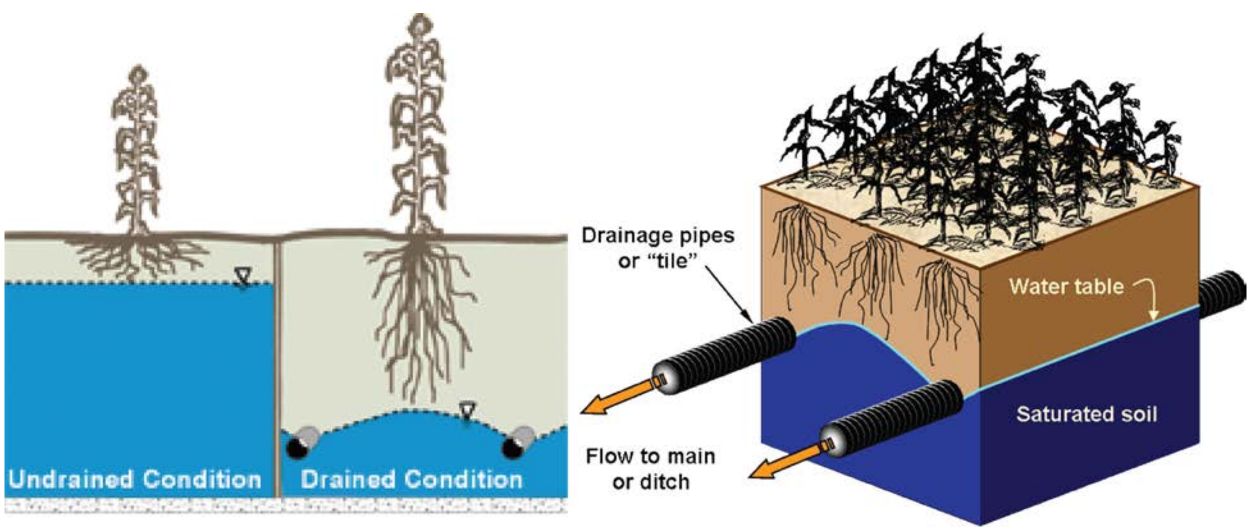

Figure 1. The effect of ADT installations on the water table and subsurface water storage.[4]

Intensity of Use

Over 80 percent of the land in the Midwest is used for agriculture production. A substantial portion of this, up to 80% in some catchment basins, may be artificially drained by networks of surface and subsurface conveyance systems.[4] It's been estimated that ADTs influence the drainage of approximately 37% of the Midwest's agricultural land by routing upland drainage water directly to main river channels.[8] Much of the existing subsurface drainage infrastructure was constructed from 1870 to 1920 and again from 1945 to 1960. Consequently, only broad estimates on the geographical extent of ADT systems exist because of a lack of recordkeeping and governing oversight during these time periods.[2,5,9] 1985 survey estimates reported the states of Illinois, Indiana, Iowa, Ohio, Minnesota, Michigan, Missouri, and Wisconsin had approximately 31 million acres (nearly the size of Iowa) containing subsurface drainage systems.[5] Estimates of subsurface drainage for the entire Mississippi River Basin (MRB) range from 40 to 70 million acres, roughly 5 to 9.5% of the MRB area.[4] An extensive amount of ADT has been installed since 1985 and continues with great fervor today.[3] Oftentimes, ADT installation activity is triggered by a previous wet year or the need to replace aging systems.[4] It's estimated that 25 to 35% of Iowa's cropland is artificially drained while other states may exceed 50%.[7]

Some improvements in recordkeeping and oversight have occurred in the Midwest through the establishment of state drainage districts or drainage associations. For example, Iowa has established over 3,000 drainage districts that cover approximately six million acres. These are largely concentrated within the heavily drained Des Moines Lobe ecoregion of the state.[10] The extent of these drainage districts is illustrated in Figure 2. Drainage districts own, operate, and maintain drainage networks which are financed by the landowners they benefit. They are governed through a board, typically a county board of supervisors or an elected board of landowners. These engineered systems serve entire watersheds and are generally based on plans with construction specifications.

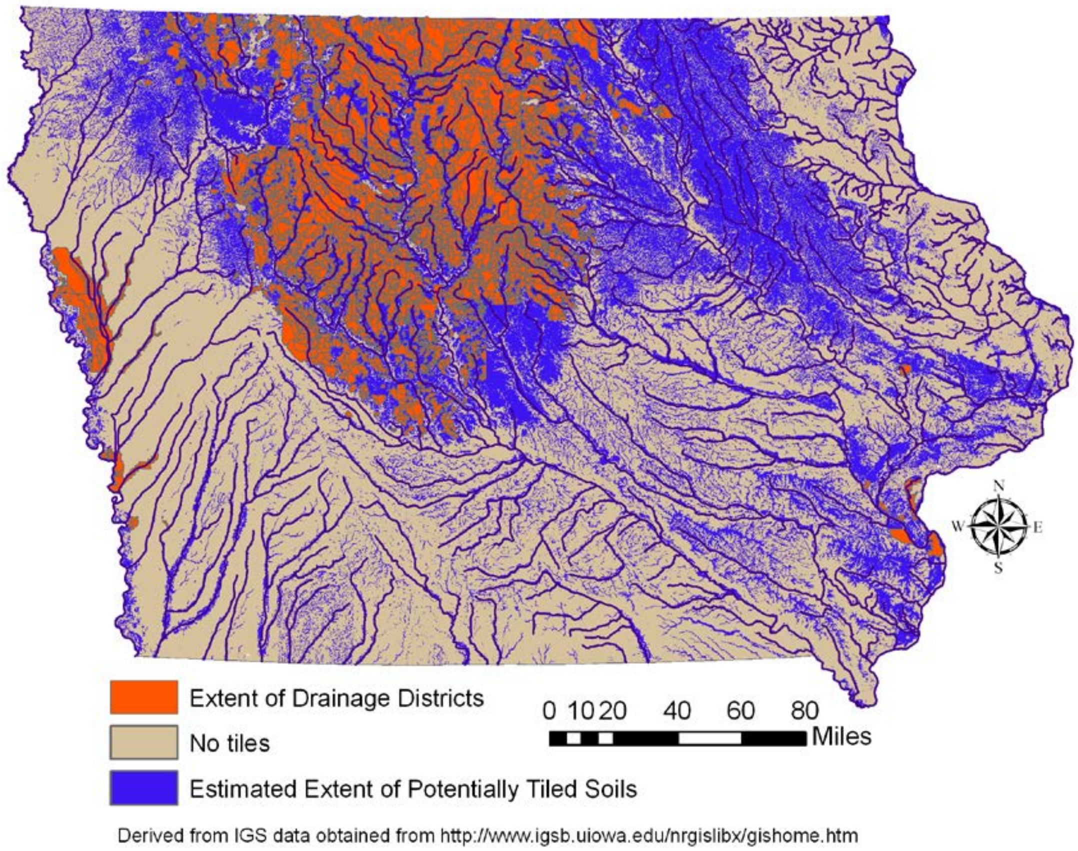

Figure 2. Extent of Iowa's drainage districts with respect to the estimated extent of soils potentially benfited from ADTs.

Another less structured class of ADTs also exists in Iowa. It consists of privately-owned, in-field ADT systems installed by landowners. If located within a district, privately owned systems may outlet to district mains and laterals. Otherwise, they outlet to whatever stream or waterway exists. As many of these ADT systems were installed decades ago, their exact numbers and locations are often unknown because records are poor to nonexistent. ADT installations are also common to regions outside the Des Moines Lobe ecoregion. These considerations, along with the widespread extent of soils suitable for ADT installations (Figure 2), suggest the amount of Iowa farmland underlain by ADTs is likely greater than published estimates.

Benefits and Detriments of ADT Systems

ADT systems provide a number of crop production benefits. Most importantly they: 1) facilitate field access for Spring planting and Fall harvest; 2) create a subsurface environment that enhances soil aeration and root development; and 3) significantly increase crop yield. Drained areas in the Midwest may realize yield increases of 10 to 45 bushels per acre for corn and 4 to 15 bushels per acre for soybeans.[6] ADT installation investments of $300 to $600 per acre can improve crop yields by 5 to 25%.[4] ADT systems also provide some environmental benefit by promoting infiltration, thus decreasing surface runoff.[4,10] Reduced surface runoff correlates to less soil erosion from fields. This, in turn, inhibits the transport of agricultural pollutants that tend to adsorb to soil particles such as total phosphorus (TP) and certain pesticides.[11]

ADT installations also produce some undesirable environmental consequences, most notably their impact on wetlands, loss of wildlife habitat, and water quality degradation. It's estimated that the 45 million acres of wetlands that once occupied the MRB prior to settlement have been reduced to approximately 19 million acres today.[4]

Historically, the impact of agriculture on surface water quality has received considerable attention because of nutrients, soil erosion, and pesticide nonpoint pollution. Early efforts to address these issues focused on surface runoff and soil conservation practices. More recently, however, ADTs have seen greater scrutiny due to their extensive use and profound effect on pollutant transport, surface water quality, and surface water hydrology.[1,4] Although tiling has been used for decades to create an agricultural landscape conducive to increased crop production, it's largely an unregulated, unmonitored, and widespread practice that continues with great fervor today. To effectively mitigate the detrimental effects of ADTs, a better understanding of these systems and their significance in regard to pollutant transport and hydrology is needed. The following highlights their impact on landscape hydrology, pollutant transport, and pollutant loading. It also identifies practices and technologies being investigated to mitigate their impact.

ADT Contributions to Agricultural Pollutant Loadings

The Midwest has experienced a dramatic rise in fertilizer and pesticide use since the mid-20th century. When combined with landscape drainage modifications for crop production, an environment described as "leaky" with respect to agrochemical transport has been created.[8,12,13] As a result, Midwest surface waters now boast some of the highest agrochemical loadings in the country. It's estimated that 25% to 50% of the fertilizer nitrogen applied to row crops may be lost to drainage water as nitrate.[3,12]

Consequences of Agricultural Pollutant Loading

Gulf of Mexico Hypoxia. Nutrient (i.e., nitrate-nitrogen [NO_3-N] and phosphorus [P]) export from agricultural fields is one of the most ubiquitous and serious water quality issues faced in many regions of the world.[4,13,14,15] Perhaps the most well know consequence of nutrient pollution is occurring in the Gulf of Mexico. Nutrients originating from Midwest agricultural watersheds have received a great deal of attention due to their significant contribution to Gulf of Mexico hypoxia.[1,4,7,8,16,17] Tile-drained agricultural lands of the Midwest are identified as a leading source of NO_3-N and P loads to the MRB.[1,8,18] Figure 3 illustrates the extent of the Gulf's hypoxic (oxygen depleted) zone and nutrient loads from 1985 to 2005. As shown, unfavorable trends continue despite decades of efforts to mitigate the problem. The Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (2008) suggests the Upper MRB is the responsible for 39% of the nitrogen loading to the Gulf of Mexico. However, conservative estimates are even higher, suggesting the Midwest is responsible for contributing one million metric tons of nitrogen (primarily in the form of NO_3-N) to the Mississippi River each year.[8]

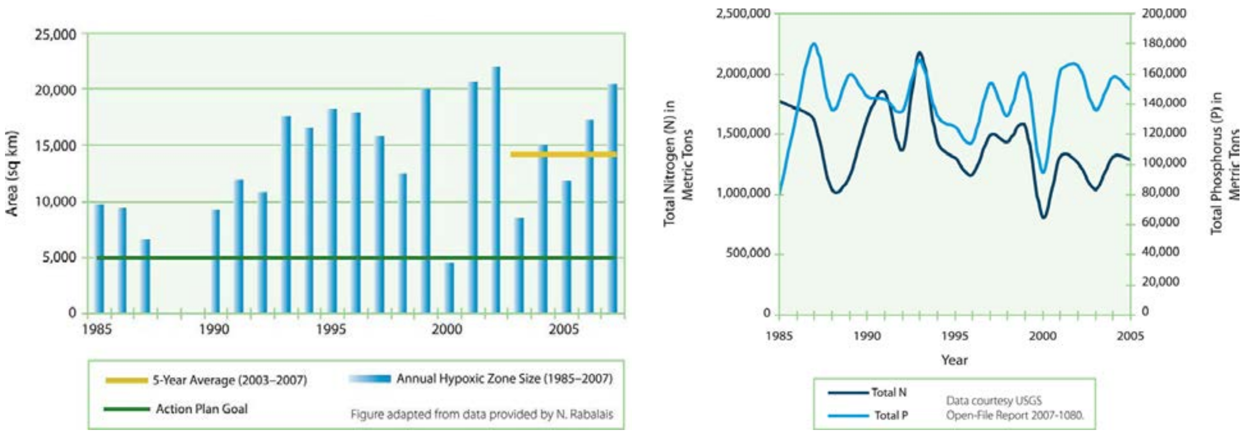

Figure 3. Extent of the hypoxic zone and nutrient loading trends in the Gulf of Mexico 1985 – 2005.[18]

Western US Irrigation Drainage. In North America, problems with agricultural drainage and associated pollutants are hardly limited to the Gulf of Mexico or nutrients. Lemly (1993) points out that subsurface drainage associated with irrigated land in the western United States has created a host of surface water quality issues in this region.[19] Salinity, high concentrations of trace elements (e.g., selenium, arsenic, boron, chromium, and molybdenum), pesticides, and nitrogen have degraded surface water and groundwater quality in addition to creating toxic environments for fish and wildlife.

Mass loading of agricultural pollutants (also commonly referred to as flux or pollutant loading) is a direct function of discharge rate and contaminant concentration. In agricultural landscapes, pollutant pathways to streams include surface runoff (SRO), ADT flow, soil erosion, and groundwater discharge.[17,20] SRO is a short-term response event to precipitation or snowmelt and is commonly referred to as stormflow. Baseflow represents a more steady-state component of streamflow that occurs between storm events. Consequently, baseflow is dominated and more reflective of groundwater and, if present, ADT inputs.

Due to their design and purpose, ADT systems have significant implications in regard to contaminant transport and landscape hydrology. However, because of limited information on their location, density, and interconnectedness, characterizing and separating the impact of ADT systems on surface water quality and watershed hydrology is complex.[2,21]

Hydrologic Impact of ADTs

Converting 80% of the landscape to row crop agriculture has clearly played a significant role in altering the hydrological characteristics of Midwest streams and rivers.[4,22] Intensive row-crop agriculture coupled with artificial drainage (i.e., surface and subsurface drainage) and stream channelization has lead to loss of natural water storage capacities, deeply incised streams, more flashy hydrograph responses to storm events, increased need for downstream flood management, decreased evapotranspiration rates, and greater stream bank erosion.[1,4]

True to form, ADTs have a significant influence on the Midwest's hydrology. Through their connectivity and construction, they readily convey water from areas that was once acted as natural, slow release storage reservoirs (e.g., subsurface soil storage and wetlands) to ditches, streams and rivers.[4] This increase in hydraulic connectivity and loss of natural storage capacity is reflected in increased stream baseflows, amplified hydrograph responses to precipitation events, and more frequent and downstream flooding events. Others have noted that tiled landscapes are similar to karst terrains in regard to hydrological characteristics.[21]

It's generally accepted that ADT discharge accounts for a majority of baseflow in extensively tiled watersheds.[4] In many studies, researchers treat ADT discharge as a surrogate for stream baseflow, particularly during late spring to early summer months.[4,7,23] Research of an agricultural watershed in central Iowa found 71% of the watershed's total discharge was attributable to tile flow while the groundwater input was negligible.[4,23] To avoid over-generalizing, however, it's important to note that ADT discharge is quite variable depending on the season. Although ADT peak discharge rates may range from 200 to 1,080 m^3/day, rates less than 50 m^3/day are more common.[16] High flow rates typically occur from late spring to early summer. Tomer and others (2008) determined that 70% of tile discharge occurred from spring to early summer, a time frame coincident with seasonal precipitation and low water uptake by crops.[23] In some studies, ADTs were found to run dry during late summer - early fall months.[8,24]

ADT systems have been implicated as a contributor to the increased baseflows observed for Midwestern rivers since intensification of row crop agriculture.[7,25] Similarly, Raymond and others (2008) identified tile drainage as a possible contributor to the Mississippi River's increased discharge, at average precipitation, during the latter half of the 20th century. In addition to increasing baseflow, ADT drainage is a suspected cause of increased peak flows of rivers and streams.[4] Over the last 25 years, annual peak flows resulting from one and two year precipitation events increased 20% to 206%.

Contaminant Fate and Transport via Drainage Tiles

The impact of agrochemicals on water quality has been problematic for decades. NO_3-N, P, sediment, pesticides, and pathogens are the agricultural contaminants of greatest concern in the Midwest.[1,23,26] Generally, sediment and contaminants that tend to adsorb to soil particles (e.g., total P [TP] and certain pesticides) are most readily transported via SRO. SRO is also indentified as the dominant transport mechanism for bacteria.[1,23] As ADT installations promote water infiltration and decrease SRO, highly mobile, water soluble contaminants such as NO_3-N and dissolved phosphorus (DP) tend to be of most concern with subsurface drainage.[27]

Recent investigations have confirmed that extensive ADT systems exacerbate agricultural water quality problems, particularly with respect to NO_3-N and DP.[3,4,7] Inherent to their design, ADTs accelerate water transport to streams and, quite often, this water is laden with ag-related pollutants.[2] Water conveyed by ADTs also circumvents natural processes and land stewardship practices that would otherwise attenuate contaminant concentrations through denitrification, dispersion, or biodegradation.[1,16]

Like surface waters, contaminant transport via ADTs is dependent on a number of variables including: contaminant characteristics; landuse patterns; farming practices; timing of chemical application; timing and intensity of precipitation events; and antecedent soil moisture content. Other variables more specific to ADTs include tile spacing density, depth, and construction design. The following highlights some specific findings in regard to pollutant fate and transport via ADTs.

Nitrate-Nitrogen (NO_3-N). Because of its water solubility and high mobility in the environment, NO_3-N is the most problematic and widely studied contaminant associated with ADTs. In general, studies have found that extensively tiled watersheds have significantly greater NO_3-N exports than watersheds free of ADTs.[16,24] Additionally, NO_3-N concentrations quite often easily exceed its maximum contaminant level of 10 mg/L, particularly during spring and summer months.[3,16,17,23,28]

Extensively tiled watersheds offer little opportunity for denitrification as they readily intercept NO_3-N laden water as it leaches through the soil profile, quickly whisking it away to surface water discharge points.[22] Consequently, tile flow represents a significant NO_3-N input to streams and rivers. In a study on a heavily tiled watershed in eastern Illinois, researchers observed that a majority of river NO_3-N was exported when tile drainage was occurring while a cessation in tile flow was accompanied by a rapid decrease in riverine NO_3-N.[22]

NO_3-N losses from ADTs are typically greatest from early spring through early summer when crops are not present or in their infancy stage.[1,7,23] This is also the time of year when ADT discharge comprises a substantial portion of stream baseflow. In their study on a heavily tiled watershed in central Iowa, Schilling and Helmers (2008) found that NO_3-N concentrations decreased with increased ADT discharge in response to a storm event. Figure 4 illustrates the NO_3-N concentration fluctuation in tile flow discharge following a June 2005 storm event. As suggested by Figure 4, higher baseflow NO_3-N concentrations were diluted by rainfall. NO_3-N concentrations then returned to pre-storm baseflow levels following hydrograph peak flow. Similar stormflow discharge – NO_3-N concentration patterns were also noted for rivers and in a tile effluent response from a September 2006 storm event.[7,26]

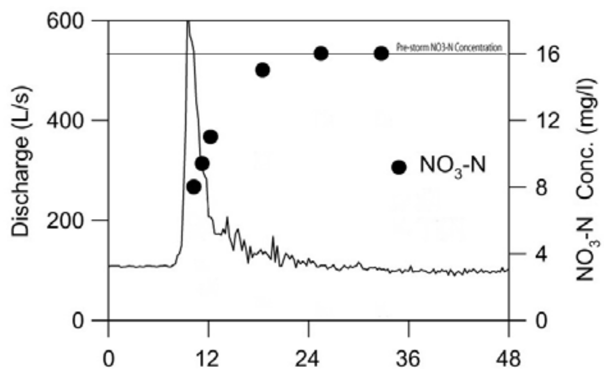

Figure 4. Hydrograph and NO_3-N concentration response to a June 2005 precipitation event within a heavily tiled watershed in central Iowa.[7]

Phosphorus (P). Although the primary means of P transport from agricultural landscapes is via overland flow, it is now realized that subsurface drainage also provides a significant field-to-stream pathway, primarily for DP.[11,24,29] In a long term study on P transport in the upper reaches of three heavily tiled watersheds in east-central Illinois, drainage tiles were found to provide a transport conduit for DP and TP.[22] Unlike NO_3-N, monitoring revealed that DP and TP concentrations in tile effluent paralleled the tile discharge hydrograph response following precipitation events.   DP flow-weighted concentrations in tile effluent ranged from 0.027 mg/L to 0.314 mg/L while TP ranged from 0.068 to 0.406 mg/L. Particulate P (i.e., TP minus DP) concentrations were greatest during high tile discharge rates, suggesting clay particles had flushed through the ADT system from tile inlets or preferential flow pathways (i.e., soil macropores). Similar findings were obtained for heavily tiled watersheds in the Des Moines Lobe ecoregion of central Iowa.[7,23,26]   TP commonly exceeded 0.1 mg/L, a concentration threshold associated with eutrophication. Although both DP and TP are conveyed through tiles, DP tended to be the dominant form. Gentry and others (2007) concluded that tile discharge was a significant contributor of DP from late fall through early summer.

Pesticides. As many pesticides adsorb to soil particles (i.e., clay and organic matter), SRO is viewed as their dominant mode of transport.[4,11] Blann and others (2008) report that pesticide loss in subsurface drainage tends to be minor, less than 0.5% of applied amounts. However, ADTs are also recognized as potentially significant pathways, particularly for dissolved pesticides and their degradates.[4,11] In general, pesticide detection in ADT effluent appears largely dependent on timing, with the highest concentrations occurring after field application and precipitation events. These occurrences, however, are short-lived.

Sediment. Although intense, episodic precipitation events may cause some sediment transport via ADT systems with surface intakes, sediment loss in ADT watersheds is typically negligible due to reduced SRO. ADT discharge, however, is believed to be an indirect contributor to accelerated erosion rates and increased sediment transport.[4] Channel incision and stream bank erosion are likely exacerbated downstream of ADT discharge points because of the kinetic energy input represented by the velocity and volume of relatively sediment-free water delivered to streams. As bank erosion may represent over 50% of a stream's sediment load, it's reasonable that ADT discharge plays a role in continued problems with sediment transport.[30] As indicated by Blann and others (2009), sediment transport in many agricultural Midwest streams remains an order of magnitude greater than pre-settlement estimates.

Pathogens. Because of manure land application practices, ADTs are a potentially significant field-to-surface water pathway for variety of pathogens.[1,4,26,31] As with surface water, Escherichia coli (E-coli) is often used as a pathogen indicator for tile discharge. Following land application of liquid dairy manure to tiled fields in southeastern Michigan, Haack and Durin (2008) found that very few tile drainage samples exceeded the EPA recreational water quality limit of 235 colony forming units per 100 mL for E-coli. In contrast, others have found E-coli in tile discharge to be significant, accounting for roughly 30% of a watershed's E-coli load.[26] Like TP, Tomer and others (2010) found that E-coli concentrations increased with the rising limb of an ADT hydrograph following a storm event, suggesting surface intakes and/or preferential flow pathways (e.g., soil macropores, cracks) play a role in transport. It's also important to note that ADTs frequently oblige as unintentional conduits that route manure spills and mis-managed land spreading operations directly to surface waters. Consequently, streams are periodically subject to manure slug loading, representing significant but short-lived events rich in E-coli as well as ammonia, nutrients, and high biological oxygen demand waste.

Potential Mitigation Practices and Technologies

A number of mitigation practices and technologies exist or are being proposed to address the negative hydrological and water quality effects of subsurface drainage systems. In some instances, the true efficacy of these practices and technologies is either unknown or quite variable. The following identifies a number of mitigation approaches that may be used to address negative effects of subsurface drainage.

Mitigation Practices

Improved management. Improving management practices (e.g., chemical application rates, application timing, and management/implementation of traditional in-field conservation practices) is often promoted as a means of reducing agricultural impacts to surface waters. However, the efficacy of this approach has drawn increased criticism and doubt. Although viewed as important, a number of researchers now agree that management practices alone are incapable of resolving water quality issues faced in agricultural areas, particularly when ADTs are present.[1,3,12,16,32,33] Many conservation practices address SRO pollutant transport rather than tile drainage. The efficacy of conservation practices is also in doubt, suggesting the value has plateaued. As Blann and others (2009) point out, erosion rates of U.S. cropland remain high in spite of soil conservation improvements. Other management problems include determining what application rates effectively reduce ADT NO_3-N loading and the lack of strategic targeting in regard to implementing conservation practices.[1,8,27]

Increased regulation. Traditionally, agricultural pollutants and soil erosion have been addressed through voluntary state and federal programs. These programs typically offer landowners incentives to implement management and structural practices aimed at reducing agricultural pollutant transport to surface waters.[1] However, the efficacy of this approach is under scrutiny due to low landowner participation, mixed results, and questionable functionality.[34] In response, increased regulation is often identified as a necessary evil toward progress in addressing water quality issues. In a review of agricultural drainage issues experienced in the western U.S., it has been argued that EPA has the authority and responsibility to regulate drainage systems under the Clean Water Act.[19] As described by Lemly (1993), agricultural drainage regulated through the National Pollutant Discharge Elimination System permitting program would provide a much needed mechanism for preventing agricultural water quality degradation.

Mitigation Technologies

Strategically Placed Constructed Wetlands. A number of researchers believe that strategically constructed wetlands offer great promise for reducing NO_3-N export from tile-drained landscapes.[8,12,27,33] These systems are touted as an economical, effective, and pragmatic long-term approach to mitigate NO_3-N loading of streams and rivers. They would also begin to replace some of the wildlife habitat lost in the past.

By berming lowland areas adjacent to streams and re-routing tile lines to discharge onto the land surface, constructed wetlands have an opportunity intercept and treat tile effluent. As water flows through the wetland, NO_3-N and DP are reduced through microbial denitrification and plant uptake. A wetland's quiescent environment also acts as a sediment trap for TP reduction. Once it passes through the wetland, treated water is released to a stream through a controlled outlet or ground seepage.

The ability of wetlands to reduce nutrient loadings to surface waters has been recognized for several decades.[35] However, the degree of nutrient removal is quite variable depending upon site specific conditions.[27] In a case study review of wetland nutrient removal performance, Woltermade (2000) reported NO_3-N and P removal efficiencies ranging from 20% to 85% and 20% to 43%, respectively. Through influent and effluent sampling, Kovacic and others (2009) found that two constructed wetlands in Illinois reduced NO_3-N loadings by 16% and 43%. In addition, DP loadings dropped by 33% and 86% while a 42% and 76% drop in TP loadings were realized. Table 1 summarizes the conditions and findings of the 21-month study.[8]

Table 1
Summary of Constructed Wetland Water Quality Study

	Wetland 1	**Wetland 2**
Average Depth (m)	**0.48**	**0.52**
Volume (m^3)	**660**	**1,780**
Surface area:Volume	**2.42**	**2.25**
Tile Flow (as % of Total Flow)	**43%**	**30%**
Tile Drainage Area (ha)	**2.17**	**12.1**
Surface Watershed Area (ha)	**3.76**	**12.3**
Wetland Area (ha)	**0.16**	**0.4**
Wetland Area:Tile Drainage Area	**0.07**	**0.03**
Wetland Area:Surface Drainage Area	**0.04**	**0.03**
NO_3-N Removal	**16%**	**43%**
DP Removal	**86%**	**33%**
TP Removal	**79%**	**40%**

A total of 850 kg of NO_3-N entered the two wetlands from tile drainage and overland flow over the 21-month study period. Of this, approximately 88% was attributed to ADT loading. DP and TP ADT loadings were approximately 36% and 28% of the total DP and TP loadings, respectively.

A number of researchers have emphasized the importance of using a watershed-scale approach for constructed wetland site selection.[12,27] This approach relies on situating wetlands in geographic locations where they intercept 50% or more of a watershed's drainage before stream discharge. In contrast, conventional constructed wetlands are typically placed at the end of small sub-basins within a watershed, resulting in an average drainage area to wetland area ratio of approximately 4:1.[12,27] As a result, these conventional wetland sites receive only a small percentage of a watershed's drainage (roughly 4%) and offer little improvement in NO_3-N loading. Based on modeling simulations for a given wetland area, Crumpton (2002) found that watershed-scale siting would result in a 35% decrease in NO_3-N loading while traditional siting practices had a negligible effect. However, as Woltemade (2000) notes, water retention times are critical in regard to performance and this depends on precipitation events. At least one to two week retention times are needed for greatest nutrient removal.[27] Development of watershed-scale wetlands also faces siting limitations imposed by voluntary landowner participation.

Bioreactors. Similar to constructed wetlands, bioreactors (also called biocells or denitrification walls) essentially funnel drainage water to an underground chamber filled with a carbon source (e.g., wood chips, tree bark, saw dust, leaf compost) to enhance denitrification.[16] Bioreactors have been found to reduce NO_3–N concentrations in subsurface drainage water (averaging 22 mg/L) to concentrations below 10 mg/L.[37] In bench-scale laboratory studies, bioreactors were shown to be capable of removing 30 to 100% of influent NO_3–N concentrations, with removal efficiency decreasing at higher influent flow rates.[16] Although this technology holds some promise, it is relatively new in concept. As a result, a number of uncertainties exist in regard to optimal design criteria, long term efficacy, and maintenance requirements. Other barriers to implementation include cost and landowner adoption.

Managed Drainage Systems. Managed drainage systems (also referred to as Smart Drainage) represent yet another potential technology for reducing agricultural pollutant loadings from ADTs.[36]. Managed drainage systems simply consist of ADT systems equipped with water control structures that allow landowners to control the timing and degree of subsurface drainage. Figure 5 illustrates the operation of an ADT water control structure and its effect on field water retention. As shown, the control structure allows landowners to regulate field drainage depending on the season and desired effect. Following harvest, the structure is used to raise field water levels, thereby limiting ADT discharge and nutrient export. A few weeks prior to planting and harvest, the structure is lowered, allowing fields to drain for farming access. After planting, water levels are again raised but only to a degree that provides water and nutrients to crops. Although highly dependent on proper use, location, soil types, climate, and farming practices, controlled drainage has been found to reduce NO_3-N loading by 15 to 75%.[36]

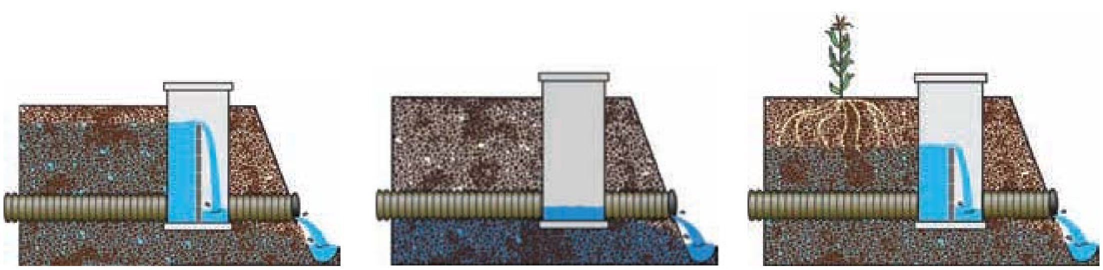

Figure 5. Use of an ADT water control structure following harvest (left), prior to planting or harvest (center) and after planting (right). [36]

Routing ADT Drainage as Subsurface Flow through a Riparian Buffer. A relatively new but simple approach for addressing nutrients in ADT drainage consists of re-routing ADT drainage as shallow subsurface flow beneath a riparian buffer strip.[38] Instead of discharging directly to a ditch or stream, ADT drainage is routed through a modified drainage control structure that redirects a portion of it to a perforated tile paralleling a riparian buffer. Routing drainage water as shallow subsurface flow beneath the riparian buffer allows NO_3-N to be removed through denitrification, plant uptake and microbial immobilization. Early results look promising, producing a significant NO_3-N loading reduction at a relatively low cost.

Discussion

ADTs clearly represent a significant and unabated field-to-surface water pathway for agricultural contaminants in the Midwest, the most critical of which are NO_3-N and DP. This, combined with their hydrologic significance and critical role in crop production, has resulted in ADTs becoming a major nutrient load export mechanism that is difficult to address.

Mitigation of Pollutant Loading

Gulf of Mexico hypoxia trends suggest a historic inability to adequately address agricultural pollutant loadings from the Midwest and other regions of North America, particularly with respect to ADTs. As noted by numerous researchers, a more holistic but targeted approach is needed. Although traditional management practices remain an important aspect of addressing pollutant loading, a multi-faceted approach comprised of new management practices and mitigation technologies is needed to achieve meaningful results. Many proposed efforts undoubtedly face significant barriers. For example, although the intent of increased regulation has unquestionable merit, implementation would face severe political and legal backlash from an industry generally unaccustomed to environmental regulation. The ability to craft simple yet effective and enforceable regulations for agricultural drainage is also a legitimate concern given the complexities and questionable value of many environmental regulations in place today.

Even though new mitigation technologies show potential, their actually efficacy in field applications will undoubtedly vary depending on site conditions and require some fine tuning. Additionally, an effective mitigation strategy likely calls for a broad-based, multi-faceted approach. One or more mitigation technologies complemented by improved management practices and effective regulation may prove most productive and cost effective in reducing nutrient loading to streams. Of the remediation technologies reviewed, constructed wetlands and re-routing subsurface drainage as shallow groundwater flow beneath a riparian buffer may be most promising because of their efficacy in nutrient removal and lower construction costs.[38] It's also anticipated that, over the long term, these technologies will require less maintenance, management, and monitoring needs than other remediation alternatives.

Successful implementation of any mitigation technology faces the same obstacles as experienced by past conservation practices, namely funding and landowner participation in voluntary programs. No matter how effective a new mitigation practice or technology proves to be, the ability to achieve meaningful results ultimately depends on large-scale landowner participation. Consequently, the ability to develop supporting policies and regulations that encourage landowner participation, uphold long term commitment, and provide attractive funding assistance are key to program achievement.

One of the more pressing and fundamental needs associated with ADTs consists of identifying their location. As indicated previously, records on ADT installations are spotty to nonexistent. Although researchers have used modeling and geographic information system software to assess geographical densities of subsurface drainage systems, these assessments are undoubtedly too generalized to be of any practical use when implementing mitigation strategies at the local level.[9] Consequently, more details on ADT installations are needed before any effective management or regulatory strategies can be put in place.

Conclusions

- ADTs present a significant dilemma in continuing efforts to address an old problem. They provide unique field-to-surface water conveyance systems for agricultural pollutants, allowing contaminants to reach streams and rivers with little, if any, attenuation. They are particularly suited for transporting water soluble nutrients such as NO_3-N and DP.

- ADTs have significantly altered the natural hydrology of the Midwest. Because of their design and function, ADTs have enhanced the hydraulic connectivity of the landscape, reduced or eliminated natural storage areas, and increased baseflows of Midwestern streams and rivers. When combined with their efficacy in removing excess water and nutrients from row crop fields, they become a formidable problem with respect to nutrient loading.

- Numerous management practices and technologies have been proposed to address the impact of ADTs on water quality. These include: Continued efforts with traditional management practices (e.g., chemical application rates, establishment of riparian vegetation buffers); Establishing regulations aimed at addressing ADT discharges (similar to NPDES permitting required for industrial discharges); Bioreactors; Strategically placed constructed wetlands; Drainage management systems; and Routing ADT drainage as shallow subsurface flow through a riparian buffer. Each show some degree of promise but it's clear that a combination of approaches is needed to produce cost-effective, meaningful results. These practices and technologies also face substantial implementation barriers in regard to landowner adoption, funding, and ADT unknowns.

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