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ORIGIN AND HYDROGEOLOGIC SIGNIFICANCE OF WETLANDS IN THE INTERLOBATE REGION OF NORTHWESTERN ALLEN COUNTY, INDIANA

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ABSTRACT Northwestern Allen County is characterized by a hummocky landscape that resulted from the melting of large blocks of ice from the Saginaw Lobe that were buried in their own outwash and by subsequent deposition of the clayey tills of the Erie Lobe Surface drainage is poorly integrated within this region, which is situated astride the eastern continental drainage divide Large parts of this interlobate landscape are internally drained and host a variety of depressional wetlands that range in size from small, hydraulically isolated bogs perched on thick clayey till to extensive peatlands situated within a hydraulically and geochemically defined recharge area for a regionally significant glaciofluvial aquifer system Many of the peatlands are underlain by thick, permeable outwash fan deposits, whereas surrounding hummocks are composed chiefly of low-permeability, clayey till that contributes abundant surface runoff to adjacent peatlands Groundwater flow patterns appear to be influenced by the accumulation of surface runoff in depressional wetlands during late winter and early spring. Dissipation of resulting water table mounds via leakage through the bottoms and sides of the wetlands leads to seasonally dependent recharge of the underlying aquifer system

A similar mechanism of landscape development probably affected much of northeastern Indiana Consequently, abundant wetlands in the region are expected to be of generally similar origin and to be situated in a variety of hydrogeologic settings *A priori* assumptions concerning the recharge-discharge functions of these wetlands are likely to be misleading unless constrained by information concerning their local and regional hydrogeologic settings Long-term impacts on groundwater quality and quantity resulting from artificial drainage of numerous wetlands in this region are poorly understood

KEYWORDS Groundwater recharge, northeastern Indiana, wetland hydrogeology, wetlands

INTRODUCTION

Geologists have recognized the relationship between the hummocky landscape of northeastern and north-central Indiana and the abundance of lakes and wetlands in the region for more than 100 years (Dryer, 1889, 1894; Leverett, 1902; Leverett and Taylor, 1915, Bleuer and Moore, 1974). This relationship is clearly reflected in the name classically applied to this physiographic region — the Steuben Morainal Lakes Area (Figure 1). The origins and nature of glacial sequences below this landscape have been debated by geologists for more than a century, but most investigators have generally attributed the coincidence of these landforms with the presumed extent of the Saginaw Lobe (for a summary, see Bleuer and Moore, 1974) The greatest concentration of lakes and wetlands in

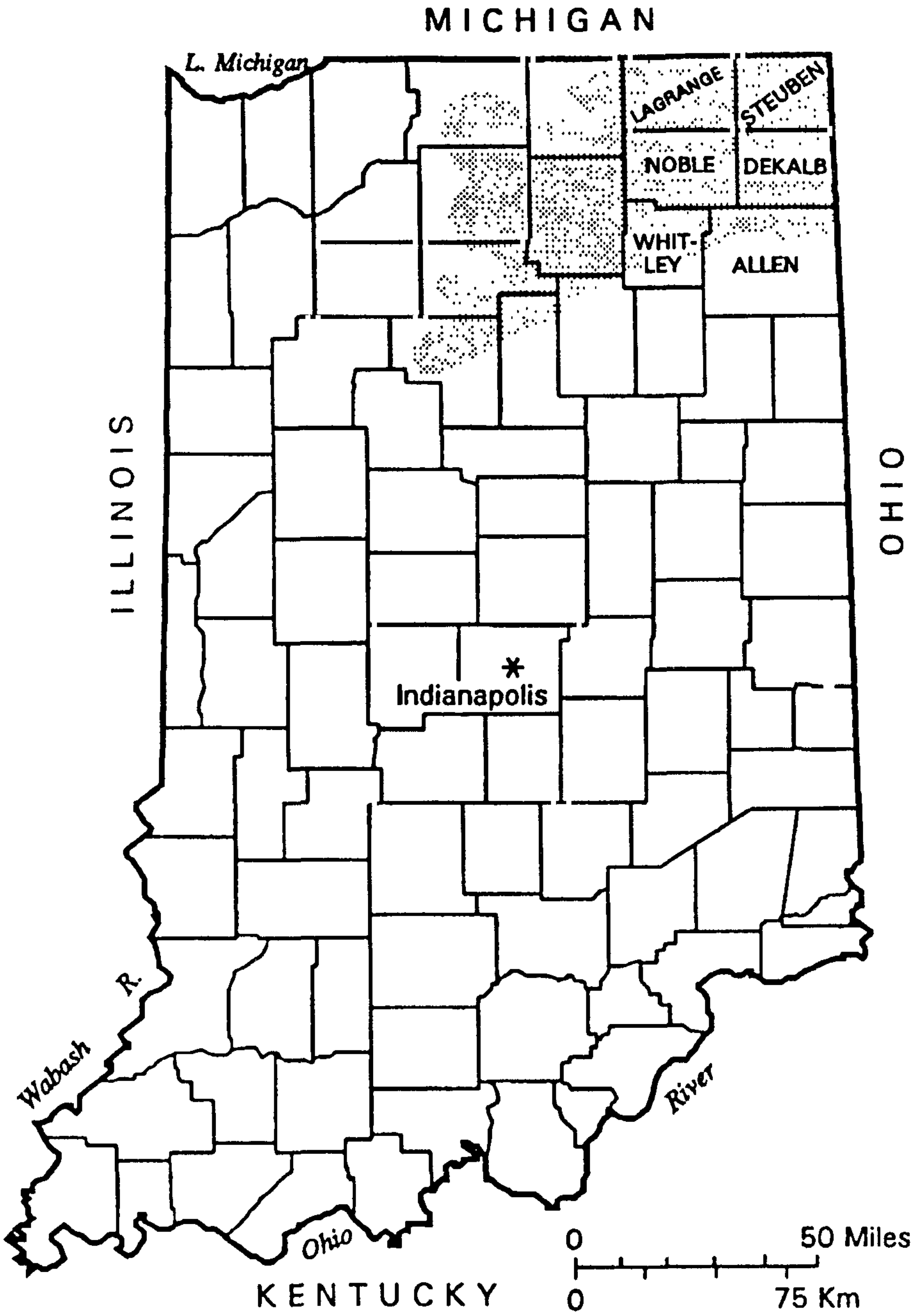

Figure 1. A map of Indiana showing the locations of the northeastern counties. The shaded area corresponds to the Steuben Morainal Lake Area (Malott, 1922; Schneider, 1966), the physiographic unit in which the majority of lakes and wetlands in Indiana are concentrated.

Indiana is found north of a line extending roughly from northern Allen County to Rochester in central Fulton County (Gray, 1989; Johnson and Keller, 1972). The appearance of abundant lakes and wetlands along the southern margin of this region coincides with a fundamental change in landscape from the typically flat, low-relief plain of central Indiana to the pronounced knob-and-kettle topography so distinctive of northeastern Indiana. This relationship suggests that the origin of the lakes and wetlands may be closely tied to a fundamental difference in glacial dynamics that created this dichotomy in landscapes during the latter part of the Late Wisconsin glaciation.

The hydrogeologic settings of wetlands are difficult to determine from land resource maps (e.g., wetland inventories, soil surveys, drainage maps, surficial geologic maps), which are typically the only sources of information available to wetland managers (Kusler, 1988). The recharge-discharge functions of wetlands are an important factor to be considered for purposes of wetland classification and for a variety of management activities (Born, *et al.*, 1979). Groundwater flow patterns and geochemical characteristics within individual wetlands and lake-wetland systems and their immediate geological surroundings have been described in a variety of studies (e.g., Boelter, 1972; Winter, 1976, 1978; Anderson and Munter, 1981; Siegel, 1988a, 1988b). However, the potential significance of the recharge-discharge function for a particular wetland system depends not only on internal hydrologic characteristics, but also on the setting of the wetland within the larger regional hydrogeologic system. The latter component has been integrated into relatively few wetland studies, presumably because of a lack of detailed information concerning the three-dimensional geologic framework and its relation to the regional groundwater system. Consequently, the significance of the recharge-discharge function commonly is overlooked or may be regarded only in the most local terms. In some cases, wetlands are thought of only as local groundwater discharge areas (Kusler, 1988; Beranek and Van Frank, 1994). No published studies exist dealing specifically with the hydrogeologic settings of wetlands in northeastern Indiana, which is surprising given their particular abundance in the region.

The transition from a relatively subdued till plain to a hummocky, internally drained landscape dotted with wetlands is exemplified in northwestern Allen County. A recent investigation of the geology and hydrogeology of that County (Fleming, 1994) documented the geologic structure of this landscape and outlined a mechanism for its origin. Although the hydrology of individual wetlands was not directly investigated during this study, several lines of evidence suggest that wetlands in certain parts of northwestern Allen County play a significant role in the larger hydrogeologic regime, notably in the recharge of a regionally extensive glaciofluvial aquifer system. The geologic origin and regional hydrogeologic settings of these wetlands are summarized in this paper, and the long-term hydrogeologic implications of extensive artificial drainage of wetlands in the study area are also discussed.

GEOLOGIC SETTING

The modern landscape of northwestern Allen County (Figure 2) is primarily the product of the latest advances of two ice lobes — the Saginaw Lobe, which

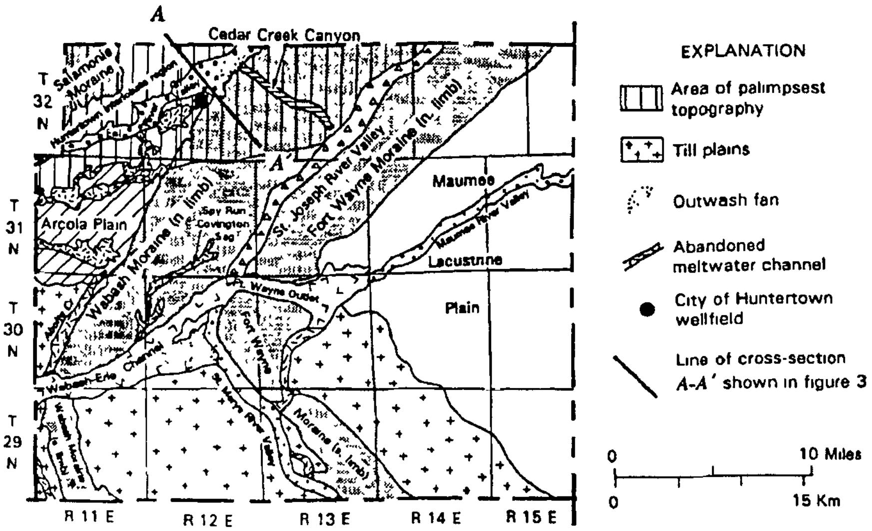

Figure 2. A map of Allen County showing the glacial terrain regions, the line of the cross section shown in Figure 3, and the location of the city of Huntertown's wellfield.

advanced from the north out of southern Michigan, and the Erie Lobe, which advanced shortly thereafter from the southeast out of the Lake Erie Basin. The ages of these latest glacial episodes are not well constrained but are generally believed to be less than about 17,000 years before present (ybp) (Fleming, 1994) — in other words, not long before the close of Late Wisconsin glacial activity in Indiana The presence of the two ice lobes has commonly led to the use of the term "interlobate" to describe the region that includes northwestern Allen County. It is not certain that both lobes were active simultaneously, but it is abundantly clear that the behavior of one lobe strongly affected the other, and that this interaction had a profound influence on the evolution of the modern landscape.

Although a Saginaw Lobe influence in northern Allen County and the adjoining counties to the north has been inferred by many workers, Bleuer and Moore (1974) were the first to provide direct evidence of a sandy, northern-source till and associated sand and gravel units in the near-subsurface in this area. Fleming (1994) attributed these units to a widespread Saginaw Lobe depositional sequence that underlies most of northern Allen County and includes a large volume of glaciolacustrine deposits in addition to abundant outwash, till-like sediment, and ice-contact fans. In northwestern Allen County, the sequence ranges in thickness to 30 m or more and typically includes an extensive basal outwash apron, thin to thick till and debris flow units at about mid-depth, and an upper complex of ablation deposits that typically contains abundant ice-contact sand and gravel Ice-contact outwash fans deposited along various ice-margin positions during the general collapse of the ice sheet are locally embedded in the upper part of the sequence, notably in the Eel River Valley (Figure 2) and adjacent areas At some places, the ice-contact fans have coalesced with the basal outwash, resulting in the entire sequence being composed of sand and gravel as much as 30-40 m thick.

The upper surface of the Saginaw Lobe sequence is highly irregular in many parts of northwestern Allen County, a characteristic that suggests the ablation complex and its associated outwash fans were deposited on, in, and against very large (100-10,000 m^2) blocks of stagnant ice. These blocks of dead ice were evidently still present when the Erie Lobe advanced into northern Allen County, and they were subsequently buried further by the ice and clayey till of that lobe during at least one event north of the Eel River Valley and probably on several occasions south of the valley. Melting of the buried ice caused the overlying sediment to collapse, resulting in the characteristic knob-and-kettle topography that marks the distribution of most of the Saginaw Lobe sequence.

This landscape exhibits numerous features, referred to as palimpsest topography, that are inherited from one or more older surfaces buried at depth. Topographic lineaments and other trends generally have little relation to the surface tills or direction of movement of the Erie Lobe, but instead reflect structural patterns on the surface of the underlying Saginaw Lobe deposits. Palimpsest topography is most pronounced northwest of the Wabash Moraine (Figure 2), where buried ice blocks appear to have been large and numerous and where overlying Erie Lobe deposits are thinnest. Palimpsest topography is more subtle in and south of the moraine, where several Erie Lobe advances deposited a thick sequence of clayey till that helps to mask the buried topography on the underlying sequence.

The Eel River Valley originated as a fan-marginal channel during the retreat of the Saginaw Lobe but was an active meltwater conduit during subsequent Erie Lobe events as well. The most significant event in terms of the evolution of the modern landscape occurred relatively late in the glacial history, when the Erie Lobe stood at the Wabash Moraine along the south edge of the valley in Allen and DeKalb Counties. Deposition of large amounts of outwash, especially at the mouth of Cedar Creek Canyon, filled the valley and ultimately led to its blockage when the ice front retreated to the southeast. Drainage from the upper part of the valley was subsequently diverted southward down Cedar Creek and into the incipient Great Lakes drainage, leaving the Eel River beheaded. Today, this area lies at the very headwaters of the Eel, astride the eastern continental divide that separates the Great Lakes drainage from the Mississippi River drainage. The term "Eel River" is thus something of a misnomer insofar as this part of the valley contains virtually no integrated surface drainage, instead being a broad wetland within a larger, internally drained landscape.

The relationships between surface landforms and the sequences of sediments that constitute those forms are expressed in the idea of glacial terrains. Glacial terrains are composed of two main elements: 1) a vertical sequence, representing deposition of sediment under a particular range of environmental conditions; and 2) a landscape or group of associated landscapes whose configuration is a manifestation of the particular types of depositional and erosional processes that created the sequences and operated subsequent to glaciation. Three glacial terrains are important in the history and hydrogeologic regime of northwestern Allen County (Figure 2) The first is the Wabash Moraine, a strongly rolling to hummocky, ridged upland composed of a thick stack of clayey Erie Lobe tills and related sediments. The second is the Huntertown interlobate area, a mostly internally drained landscape with numerous closed depressions, small to large hummocks, and abandoned meltwater channels. The present topography of this terrain closely reflects the collapsed surface of the buried Saginaw Lobe ice-contact deposits rather than the thin, discontinuous veneer of the Erie Lobe till that caps many hummocks. The final glacial terrain is the Eel River Valley, a largely abandoned, high-level glacial sluiceway underlain by a thick, complicated outwash sequence deposited episodically by both ice lobes.

DISTRIBUTION AND CHARACTER OF WETLANDS

A large number of wetlands in Allen County and elsewhere in northeastern Indiana have been partially or totally altered by drainage projects, peat mining, and other activities that have disturbed the natural hydrologic regime. Consequently, areas described as "wetlands" on modern land resource surveys generally represent only a small portion of what existed prior to European settlement. In northwestern Allen County, there are numerous areas underlain by peat or mineral soils having hydric characteristics that are now largely drained and have thus lost most or all of their natural wetland qualities. Therefore, the term "wetland" is used somewhat loosely herein and refers to both existing and former wetlands.

Wetlands occur in all of the glacial terrains in northwestern Allen County; however, the distributions of different wetland types show a strong relationship to local geologic setting. These wetlands can be grouped into three general categories based on their settings:

1. **Depressional Wetlands on Thick Clayey Till.** These wetlands may be either mineral- or peat-based. Many of them appear to be bogs that result mainly from the extremely low hydraulic conductivity of the underlying till, which causes surface water and shallow groundwater to be perched. Some may be fed by shallow groundwater discharge from fractured till and small sand lenses within, but they appear to be largely disconnected from the larger, regional groundwater flow system. Most of these wetlands are concentrated along the Wabash Moraine and in other upland areas underlain by thick Erie Lobe till.
2. **Flow-Through Wetlands Developed on Sand and Gravel.** These wetlands appear to be largely mineral-based and occur in depressions and small channels below the water table. Almost all of them are found in and near the Eel River Valley. They are thought to be maintained by groundwater that enters on the upgradient side of the wetland and exits on the downgradient side. Some of these wetlands are located in channels that are integrated with the headwaters of the Eel River in far western Allen County and may be predominantly groundwater discharge areas (fens).

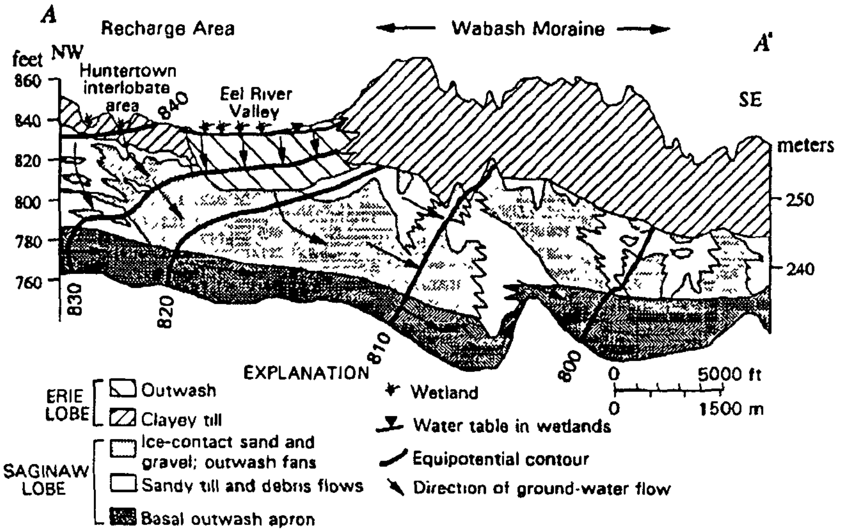

Figure 3. A hydrogeologic cross section showing configuration of aquifers, confining units, equipotential contours, and inferred groundwater flow patterns of the Huntertown aquifer system in the three major glacial terrain regions of northwestern Allen County. The basal outwash apron, ice-contact units, and outwash fans of the Saginaw Lobe as well as the outwash of the Erie Lobe constitute aquifers, whereas the clayey and sandy tills are confining units.

3. **Depressional Wetlands on Sand, Gravel, and Sandy Till-Like Sediments.** Most of these wetlands are not directly connected to an integrated surface drainage system and are typically surrounded by hummocks and ridges of low-permeability clayey till from which they receive surface runoff. Nearly all of these are peatlands associated with the many depressions of the Huntertown interlobate area; however, a broad area (approximately 4 km^2) of peatlands in the Eel River Valley along the axis of the eastern continental divide is also included in this category, because it is disconnected from surface streams and receives runoff from adjacent areas. These depressional wetlands appear to play an important role in the regional groundwater flow system and are the focus of the remainder of this paper.

HYDROGEOLOGY

The Saginaw Lobe deposits contain numerous small to large sand and gravel aquifers and are thus a major source of groundwater for domestic, municipal, industrial, and agricultural water users in northern Allen County. Individual aquifers within this sequence of deposits tend to be hydraulically interconnected and function as a coherent, well-defined system termed the Huntertown aquifer system (Figure 3; Fleming, 1994). The extent of the aquifer system north of Allen County is uncertain, however, reconnaissance subsurface mapping suggests that the larger sand and gravel units become thin and ultimately disappear not far into DeKalb and Noble Counties. In those areas, the Saginaw Lobe sequence is

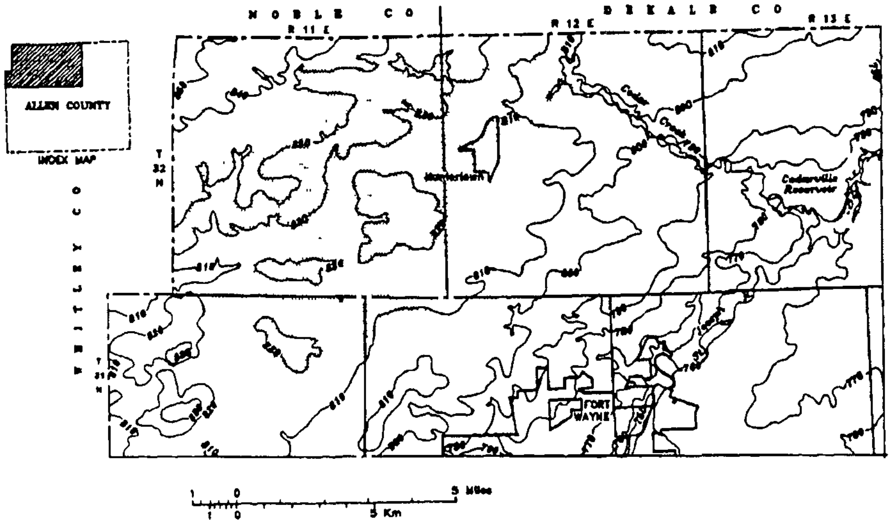

Figure 4. A map of northwestern Allen County showing the potentiometric surface of the Huntertown aquifer system. The contours primarily represent water levels in the basal outwash apron, the most widespread and most commonly used aquifer in the system. The dot pattern corresponds to the inferred recharge area in parts of the Eel River Valley and the Huntertown interlobate area, where the aquifer system is poorly confined.

generally much thinner and appears to contain only small, isolated lenses of sand and gravel enclosed within less permeable till.

The Huntertown aquifer system typically is well confined by clayey Erie Lobe tills and lake sediment over much of northern Allen County. The bulk hydraulic conductivity of the till confining sequence is typically less than 10^{-7} cm/sec, although greater values are known from the upper 5 to 7 m of the till, which are characteristically highly fractured (Ferguson, 1992; Ferguson, *et al.*, 1992; Fleming, 1994). The thickness of till confining units over the Huntertown aquifer system in northern Allen County is commonly much greater than the effective fracture depth and is inferred to restrict recharge to the aquifers below. Weathering of the till gives rise to soil series having very slow permeability (Kirschner and Zachary, 1969), which further inhibits recharge to underlying aquifers by increasing surface runoff and limiting infiltration. The major exception to the above conditions occurs in the Eel River Valley and Huntertown interlobate area, where the clayey tills are commonly thin (< 7 m), discontinuous, or absent altogether over sizable areas. Consequently, the top of the Huntertown aquifer system is generally at or near the land surface and is under water table conditions in parts of these terrains (Figure 3).

Water level data for the Huntertown aquifer system show a well-defined regional groundwater flow pattern (Figure 4; Fleming, 1994). Groundwater flow is generally from northwest to southeast under a relatively consistent horizontal hydraulic gradient of about 2 m per km. Somewhat steeper gradients occur in the extreme northwestern corner of the County near the inferred margin of the aquifer system, and near the St. Joseph River in north-central Allen County, a deeply entrenched valley that functions as the regional discharge area for the system. In contrast, the potentiometric surface is virtually flat over an area of about 250 km^2 in the Eel River Valley and adjacent parts of the Huntertown interlobate area; however, it exhibits several small- to medium-sized areas where water levels are somewhat higher than the prevailing potentiometric surface. Relatively pronounced downward gradients are also inferred to exist in this area based on the observation that the elevation of the water table is commonly 3 to 7 m greater than water levels in deeper parts of the system (Figure 3). Such hydraulic behavior is characteristic of recharge areas in general and is highly suggestive of a major recharge area in northwestern Allen County. The hydraulic characteristics are consistent with the unconfined to semiconfined condition of the aquifer system in this area, which also coincides with the highest concentration of peatlands in the County.

LANDSCAPE AND SURFACE DRAINAGE CHARACTERISTICS

Natural surface drainage within the Huntertown interlobate area is very poorly integrated. A few small, ephemeral surface streams lead to the Eel River Valley, but most of this terrain is internally drained via depressions or disjunct segments of small, abandoned meltwater channels. Most of these features are completely enclosed and range in size from less than 100 m^2 to about 0.1 km^2, although it is not uncommon to find areas where numerous smaller depressions have coalesced to create much larger (0.1 to 0.5+ km^2) enclosed or semi-enclosed low-lying areas. The larger coalesced depressions are typically associated with the heads of buried outwash fans and, thus, are underlain at shallow depth by sand and gravel. The bottoms of many depressional areas lie below the water table; consequently, the great majority of these contain wetlands, most of which are small- to medium-sized peatlands. Sparse data obtained from highway bridge borings, excavations, and other sources indicate peat thicknesses as great as 10 m, although thicknesses in the range of 1 to 5 m are probably more typical.

The depressional areas are enclosed by hummocks of clayey till having markedly different physical properties. The hummocks are typically underlain by poorly permeable soils. Moderately steep side slopes in the range of 12 to 25 percent are common, although a few slopes are as steep as 50 percent (Kirschner and Zachary, 1969) Field permeabilities of the soils developed on the till are characteristically very slow. These properties retard the infiltration of precipitation and snowmelt into the hummocks and generate a considerable amount of surface runoff into adjacent depressional areas (Figure 5). Ponding of runoff in depressions was observed by the author on numerous occasions and appears to be largely a seasonal phenomenon. Standing water as much as a meter or more in depth was commonly present in depressions during late winter and spring but appeared to largely dissipate by early summer. Accumulation of runoff also was observed in some depressions following heavy summer storms, but the water generally dissipated within a few days Some surface runoff may also enter the peatlands in the Eel River Valley, either directly from adjacent hummocks or via small surface ravines and drainage ditches that enter this part of the valley.

Near-surface relations in the Eel River Valley differ only slightly, with up to 12 m of peat overlying thick outwash along the valley axis. Most of the valley

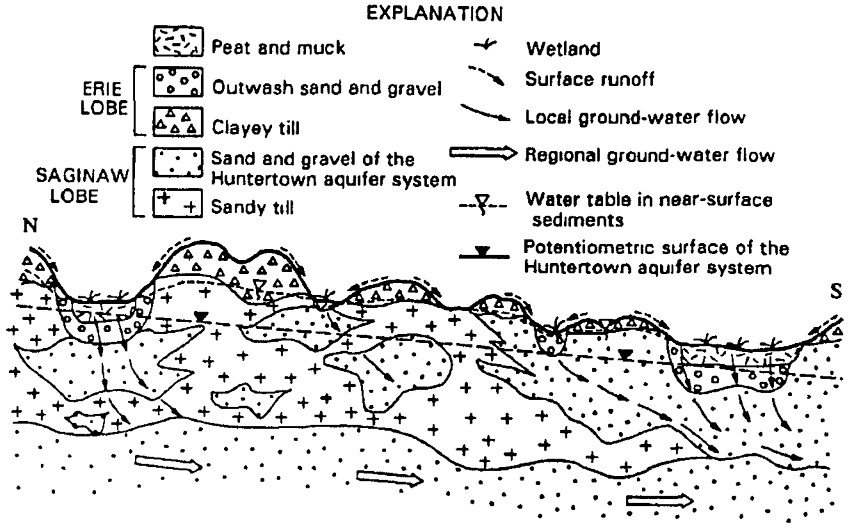

Figure 5. A schematic diagram illustrating the inferred surface hydrology and near-surface hydrogeology of the Huntertown interlobate area and the Eel River Valley. The low permeability and relatively steep side slopes of the hummocks generate runoff to adjacent depressional wetlands from where the water gradually leaks into the underlying aquifers. The largest amount of recharge is probably derived from wetlands having the thinnest peat and where sand and gravel is directly exposed to ponded surface water along the fringes of depressions.

floor is perfectly flat and there is no distinct stream channel evident where the valley crosses the eastern continental divide. A few parts of the valley are flanked by low-level outwash terraces, some of which are moderately pitted, but, for the most part, the valley is abruptly bounded by the knob-and-kettle topography of the adjacent Huntertown interlobate area. Soils developed on both peat and outwash exhibit some of the highest permeabilities of any in Allen County (Kirschner and Zachary, 1969).

RECHARGE-DISCHARGE FUNCTIONS OF WETLANDS

The peatlands in many parts of the Huntertown interlobate area and the Eel River Valley typically overlie highly permeable sand and gravel aquifers that constitute the top of the Huntertown aquifer system. Downward gradients also appear to exist between the water table at the surface of the peatlands and the aquifers lower in the system. The hydrogeologic setting of the peatlands is thus conducive to leakage into the underlying aquifers (Figure 5). The proportion of water that actually leaves the peatlands as groundwater recharge (versus evaporation) depends on the bulk permeability of the peat and on the geologic structure of any particular peatland. The permeability of the peatlands themselves is likely to vary widely according to the thickness and degree of decomposition of the organic matter. No hydraulic data are available for the peatlands in this area. Therefore, their properties must be inferred from limited observations of their physical properties and from studies of peat in other areas.

The hydraulic conductivity of peat is known to vary widely (e.g., Chason and Siegel, 1986; Siegel, 1988a; Boelter, 1965, 1972; Rycroft, *et al.*, 1975a). Some studies suggest that hydraulic conductivity generally decreases with depth in peat (e.g., Ingram, *et al.*, 1974), but other investigators have found little relationship to depth (e.g., Chason and Siegel, 1986; Siegel, 1988a). Hydraulic conductivity does appear to be affected by the degree of decomposition, with lower hydraulic conductivity values generally associated with greater humification, regardless of depth (Boelter, 1965, 1969, 1972; Rycroft, *et al.*, 1975a, 1975b).

Detailed physical profiles from outcrops or cores of peat in northwestern Allen County are generally lacking. Observations made by the author in a few small peat excavations and ditches and generalized descriptions available from records of geotechnical borings suggest the presence of two conditions that may significantly affect the nature of water movement through the peat. First, the overall degree of decomposition appears generally to increase with depth in the peat, although some horizons containing coarser and less decomposed material were observed or reported at a variety of depths. Second, a thin layer of sedimentary peat (highly decomposed, fine-grained material generally deposited on lake bottoms) appears to be commonly present along the interface with the underlying mineral soil.

The hydraulic conductivity of well-decomposed sapric peat, such as might be expected in the lower parts of the thickest peatlands, is commonly much less than that of sand and gravel. Likewise, the hydraulic conductivity of sedimentary peat may approach that of fine-grained till (Siegel, 1988a; Boelter, 1965, 1969). In contrast, the coarse, fibrous peat and sandy muck characteristic of the upper 1 to 3 m of many of these peatlands, as well as some deeper horizons, are highly permeable (Kirschner and Zachary, 1969). Based on these observations, it seems likely that permeability may in many cases decline with depth, because of the increasing proportion of sapric peat in the section as well as the presence of sedimentary peat. Widespread layers of the latter are especially likely to result in low bulk vertical hydraulic conductivity in some of the larger peatlands and may lead to a high ratio of horizontal to vertical bulk hydraulic conductivity. On the other hand, the distribution of horizontal hydraulic conductivity may be quite heterogeneous within parts of these peatlands, because localized zones of less decomposed (and thus more permeable) material may act as conduits for the lateral transmission of water.

Several inferences concerning water movement into and out of the peatlands can be made if it is assumed that the hydraulic characteristics outlined above are generally typical of wetlands in northwestern Allen County. Depressions characterized by thin, fibrous peat deposits of relatively high bulk permeability are likely to have substantially greater rates of leakage to underlying aquifers than those filled by thick, decomposed peat. In contrast, the low permeability of sapric and sedimentary peat is likely to greatly retard vertical leakage through the bottoms of the thicker peatlands, causing the water table within these peatlands to become perched above the true zone of saturation during dry periods. Consequently, the majority of groundwater recharge that does originate from thick peatlands is inferred to occur primarily through their sides during periods of high water levels. Observations noted earlier suggest that such periods are common and are associated with the high runoff that occurs during spring thaw and spring and early summer precipitation. Spring is also typically a period of high water levels in the underlying aquifer system; consequently, coincidental accumulation of runoff in enclosed depressions is likely to lead to the formation of groundwater mounds above the aquifer system. Dissipation of the mounds occurs by a combination of evaporation and groundwater recharge through the more permeable fibrous peat and granular sediment along the sides of the wetland. Recharge is also likely to be enhanced in peatlands of all sizes by irregularities and protuberances associated with the hummocky upper surface of the aquifer system, which create localized zones of direct hydraulic communication between the water ponded in the wetlands and subjacent aquifers.

Transient groundwater mounds have been observed under similar conditions elsewhere and are increasingly recognized as an important component of the water budget of some lakes and wetlands (e.g., Born, *et al.*, 1974; Anderson and Munter, 1981; Winter, 1981; Siegel, 1988c; Kusler, 1988). Similar to the wetlands of northwestern Allen County, groundwater mounds in nearly all of these other areas also developed mainly in the spring and generally were dissipated by summer. Their appearance and dissipation likewise were correlated with groundwater recharge events.

GEOCHEMICAL EVIDENCE FOR GROUNDWATER RECHARGE

Certain geochemical parameters are useful in many hydrogeologic settings for determining the relative age of groundwater, its position in the groundwater flow system, and (or) the environmental conditions under which it was recharged. In addition to major ion chemistry, tritium (^{3}H), deuterium (^{2}H), oxygen (^{18}O, ^{16}O), and carbon (^{13}C, ^{14}C) are among the environmental isotopes commonly employed for these purposes in groundwater studies (Hendry, 1988).

Tritium concentrations are represented in tritium units (T.U.), where one T.U. is equal to one atom of ^{3}H per 10^{18} atoms of hydrogen. Tritium is naturally present at very low levels (2 to 25 T.U.) in the atmosphere, where it is produced during the bombardment of nitrogen atoms by cosmic rays. The isotope is readily incorporated into water molecules and is removed from the atmosphere by precipitation. Massive amounts of tritium were introduced into the atmosphere as a consequence of above-ground nuclear testing. Atmospheric tritium concentrations peaked at several thousand tritium units (T.U.) in 1963 and have since declined to about 50 to 100 T.U. The half-life of tritium is only 12.35 years. Thus, groundwater recharged since the advent of above-ground bomb testing exhibits a measurable (1 T.U.) tritium content, whereas older groundwater does not. Consequently, tritium is an excellent tool for the identification of relatively young groundwater and for indicating the locations of groundwater recharge areas (Bradbury, 1991; Knott and Olimpio, 1986; Thatcher, 1962). Recent chemical analyses of groundwater from the Huntertown aquifer system (Fleming and Yarling, 1994) indicated the presence of tritiated groundwater at many places below the Huntertown interlobate area and the Eel River Valley. In other, better-confined parts of the aquifer system, however, tritium was below the detection limit of 0.8 T.U. Tritium concentrations up to 15 to 30 T.U. were found in shallow aquifers close to the large peatlands in the Eel River Valley and in areas of abundant large enclosed depressions, whereas somewhat lesser tritium values were typical at greater depths in this area.

The ratios of the stable isotopes of oxygen (^{18}O, ^{16}O) and hydrogen (^{2}H, ^{1}H) in the atmosphere are temperature sensitive, with the evaporation of the heavier isotopes of each element being favored by warmer conditions and retarded by cooler ones. Most precipitation originates by evaporation from the open ocean. Thus, the precipitation tends to exhibit a distinct isotopic signature that reflects the particular climatic conditions under which evaporation occurred. This relationship can be used to identify groundwater that was recharged under long-term climatic conditions significantly different from the modern situation (Drever, 1988). Various lines of evidence, such as analyses of ice cores from the Greenland Ice Sheet (Arnason, 1981), suggest that the precipitation that fell on the Northern Hemisphere during the Late Wisconsin glaciation was depleted significantly in the heavy isotopes of these elements relative to modern precipitation Several studies of groundwater chemistry from the Great Lakes region have found isotopically light groundwater at depth, some of which has apparent radiocarbon ages of 8,000 to 10,000 years (Desaulniers, *et al.*, 1981; Bradbury, *et al.*, 1985; Fritz, *et al.*, 1974). In contrast, isotopic values for oxygen and deuterium from wells throughout the Huntertown aquifer system were within a narrow range that is consistent with modern temperate precipitation in northern Indiana (Drever, 1988). This result is comparable to isotopic values found in groundwater from other glacial deposits further south in Allen County (Ferguson, 1992; Ferguson, *et al.*, 1992) and suggests that the aquifer system has been completely recharged by modern precipitation. Groundwater from many of the same wells that exhibited elevated tritium concentrations also showed a minor but systematic depletion of heavy isotopes relative to other parts of the aquifer system. The meaning of this pattern is not clear at this time, but the pattern could conceivably be related to the fractionation of these isotopes by vegetation, decomposition processes, or precipitation of carbonate minerals within the peatlands.

Other geochemical patterns also suggest the presence of relatively young groundwater below the inferred recharge area. Groundwater from wells in that area demonstrated slight to strong enrichment in ^{13}C relative to wells elsewhere. Analyses of the carbon cycle of this system are incomplete, but this characteristic probably corresponds to an increase in dissolved organic carbon, which in turn may be attributable to organic acids derived from the biodegradation of peat. The concentrations of total dissolved solids (TDS) are relatively low in groundwater below the recharge area (commonly 400 mg/l) and show a slow but progressive increase down-gradient to the southeast The down-gradient increase in TDS also coincides with a change from bicarbonate to sulfate as the predominant anion. Concentrations of iron and several trace metals also appear to be less in groundwater near the recharge area than in areas further down-gradient.

In summary, geochemical relations suggest that. 1) groundwater below the Eel River Valley and parts of the Huntertown interlobate area has experienced a shorter residence time than in other parts of the aquifer system; 2) a significant component of modern (tritiated) water is entering the regional flow system in this area, and 3) some of the modern water may be derived from peatlands. All of these relations lend additional support to the geologic and hydraulic evidence for a regional recharge area in northwestern Allen County.

DRAINAGE OF WETLANDS

As many as 75 percent of the original wetlands in northwestern Allen County have been drained via ditching of existing ravines and swales and by the installation of new ditches that connect previously isolated depressions. Drainage of these areas results in the loss of wetlands by lowering the water table, which allows the upper part of the peat to dry out and blow away, particularly during cultivation. The degree to which the wetlands have been dewatered depends on many factors: e.g., the depth, profiles, and spacing of the drainage ditches; the thickness of the peatland; and the hydraulic conductivity of the peat (Boelter, 1972). Undoubtedly, these factors vary from wetland to wetland and from place to place in a given wetland. The efficiency of ditches in dewatering wetlands is extremely sensitive to relatively small changes in the hydraulic conductivity of the underlying peat (Wertz, 1968; Boelter, 1972). The heterogeneous nature typical of many peat deposits and the relatively large spacing of drainage ditches in the peatlands of northwestern Allen County suggest that sizable parts of these drained wetlands are probably not completely dewatered. Rather, the artificial drainage has in many cases lowered the water table only slightly, but nonetheless sufficiently to facilitate cultivation of the uppermost part of the peat. The greatest impacts are probably in the smallest wetlands, where peat deposits are thin and underlain by highly permeable sand and gravel at very shallow depths.

The net effect of artificial drainage on groundwater recharge and water quality is even less understood. Runoff from uplands adjacent to drained areas may be carried away as surface water via the ditches, reducing the amount of standing water available to recharge subjacent aquifers. An incidental effect of artificial drainage is the dewatering of the top of the aquifer system, where segments of ditches are excavated into sand and gravel aquifers. Conversely, sections of some ditches may facilitate direct infiltration of surface water into the upper level of the aquifer system during periods of high surface runoff.

The ability of wetlands to trap suspended sediment and to remove certain dissolved constituents from both surface runoff and shallow groundwater is well known (e g., Hickok, 1979; Elder, 1988; Betts, *et al.*, 1994; Kehew, *et al.*, 1994). The loss of wetlands within the recharge area in northwestern Allen County is likely to diminish this ability. This loss could, in turn, cause long-term changes in the quality of water that enters the aquifer system, particularly where recharge is derived from runoff from agricultural areas on which large amounts of pesticides and fertilizers are applied. All these effects alter the hydrogeologic regime, but the long-term implications for both the quality and quantity of groundwater in the aquifer system may not become evident for decades.

STYLE OF DEGLACIATION AS A FACTOR IN WETLAND ORIGIN

Evidence from northwestern Allen County as well as from other parts of far northeastern Indiana suggests that formation of much of the knob-and-kettle topography may be related to the style of deglaciation, which is in turn reflected in the broader regional-scale pattern of glacial terrain. Known Saginaw Lobe deposits in northeastern Indiana consist chiefly of large outwash fans, hummocky morainal ridges, and irregular ablation complexes that outline several distinct ice-margin positions. These deposits constitute a succession of several distinct terrains that appear to be progressively inset into "holes" or depositional basins created by the collapse or retreat of the ice that deposited the immediately preceding terrain, and that become progressively younger to the northeast (Fleming, *et al.*, 1994). Consequently, the depositional sequences associated with each of these terrains tend to be geographically limited to relatively narrow, lobate tracts and are rarely traceable over more than a few miles in any direction.

This pattern indicates that the Saginaw Lobe experienced several distinct pulses. During each pulse, the ice advanced to a terminal position along which deposition was concentrated, and then abruptly downwasted *in situ.* This pattern is in contrast to a relatively uniform rate of backwasting characterized by deposition of a more uniform blanket of sediment along a well-defined, steadily retreating ice margin (e.g., the central till plain). Some, or perhaps all, of these pulses were probably closely spaced in time. Each successively younger advance was characterized by deposition among stagnant ice masses left by the earlier episodes. Abundant debris concentrated along and near the ice margin was deposited as extensive complexes of ice-contact sand and gravel mixed with a variety of thin tills, debris flows, and other ablation sediments. This style of deglaciation resulted in the burial of very large blocks of stagnant ice in their own debris. Abundant depressional wetlands, particularly peatlands, were the natural result of this depositional style, as the depressions rapidly filled with meltwater and became kettle lakes. The bottoms of many depressions extend below the modern water table, and the lack of regular flushing by surface water flows has enhanced the accumulation of peat, causing many of the smaller initial lakes to become peatlands. Radiocarbon ages from peatlands in Steuben County (Wayne, 1963) and from Pretty Lake in southeastern LaGrange County (Williams, 1974) indicate that significant amounts of organic sediment had already begun to accumulate by about 11,000 to 13,000 ybp.

In northwestern Allen County, the stagnant ice and ablation complex of the Saginaw Lobe were overridden by the Erie Lobe and partly buried beneath a veneer of clayey till. Melting of the buried ice blocks led to the development of a distinctive palimpsest topography whose features bear little relationship to the sequence of surface tills but are instead largely inherited from the hummocky surface of the Saginaw Lobe sequence below. The overlap of these latest Erie Lobe tills extends over a large part of northeastern Indiana that includes the massive morainal highland referred to as the Packerton Moraine (Dryer, 1894). The extent of strongly palimpsest topography beyond northern Allen County, derived either from the Saginaw Lobe or other sequences underlying the Erie Lobe tills, has not been systematically documented, but it appears to be significant in some places (Bleuer and Moore, 1974; Fleming, *et al.*, 1994).

Not all the wetlands associated with the hummocky landscapes of northeastern Indiana are developed on sand and gravel nor is their presence necessarily an indicator of outwash fans or ice-contact stratified deposits at shallow depths. Saginaw Lobe terrains constitute the modern land surface in parts of western Steuben, LaGrange, and northern Noble Counties, where the hummocky topography is more pronounced, because it is not veneered by younger Erie Lobe tills. All these areas contain numerous wetlands, but the sedimentary sequences commonly include abundant till-like and lacustrine sediments in addition to a variety of sand and gravel bodies. Furthermore, many peatlands along the massive Packerton Moraine in Noble, DeKalb, and eastern Steuben Counties are developed on extremely thick tills of varied source, and Saginaw Lobe deposits appear to be but a thin wedge at some places. Thus, although large outwash fans may represent the most efficient way to bury and preserve large blocks of stagnant ice, wetlands formed in ice-block depressions can be associated with a variety of glacial sedimentary environments.

HYDROGEOLOGIC IMPLICATIONS

An understanding of the role of wetlands in the larger hydrogeologic systems within which they occur is typically expensive and time-consuming to develop. Generalizations from one wetland to another are problematic, because, as suggested above, a wide range of depositional sequences and associated hydrogeologic settings are possible in glaciated terrains. Even though a number of hydrogeologic schemes have been developed to classify wetlands, the relationship of most wetlands to their larger hydrogeologic settings is very poorly understood (Kusler, 1988; Hollands, 1988a, 1988b). Because of this lack of information, wetlands are commonly (and often erroneously) presumed to be primarily groundwater discharge areas, when in reality their hydrogeologic relations may be much more complex and, in many cases, dominated by transient processes.

The peatlands in northwestern Allen County, while not necessarily unique, are certainly unusual in being situated within a hydraulically defined recharge area for a major aquifer system and astride one of the major regional drainage divides in the eastern United States. Several lines of physical and geochemical evidence illustrate the historical function of some of these wetlands in groundwater recharge to the Huntertown aquifer system. The net effect of wetlands in maintaining the quality and quantity of groundwater recharge may be impossible to quantify, but one practical example may illustrate their potential value in the larger hydrogeologic setting.

The public wellfield for the city of Huntertown is situated in the southern part of the Huntertown interlobate area, less than 1 km south of the Eel River Valley (Figure 2). Groundwater is produced at a rate of approximately 1,000 gallons per minute from thick outwash in the lower part of the Huntertown aquifer system. Within the immediate zone of influence of the wellfield, the productive part of the aquifer system is relatively well confined by both a thin layer of clayey Erie Lobe till at the land surface and by one or more internal bodies of sandy Saginaw Lobe till (Figure 6). Consequently, direct recharge to the wellfield from the land surface above the zone of influence is inferred to be relatively limited. The zone of contribution for the wellfield extends a considerable distance upgradient, and parts of the five- and ten-year capture zones are estimated to lie beneath the wetlands in the Eel River Valley and adjoining parts of the Huntertown interlobate area. There, the aquifer system is composed almost entirely of thick sand and

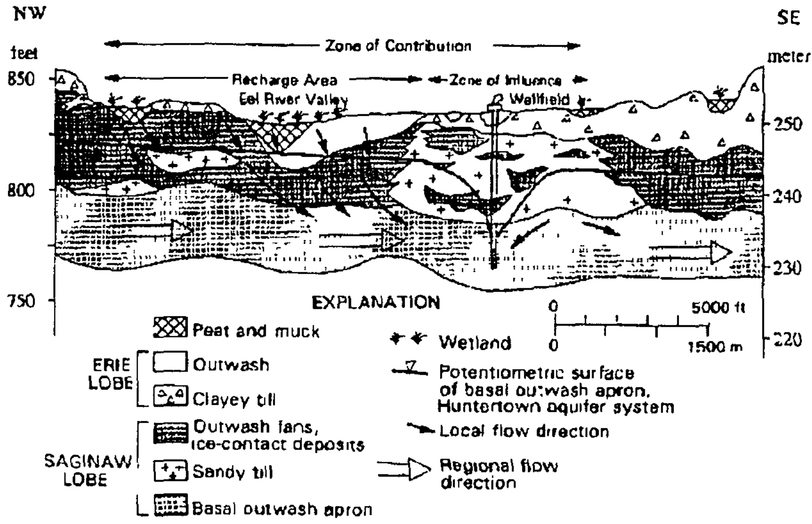

Figure 6. A generalized hydrogeologic cross section illustrating the subsurface geology and groundwater flow patterns in the vicinity of the Huntertown municipal wellfield.

gravel, is unconfined, and considerable recharge to deeper parts of the system is inferred to take place. These results imply that recharge from the wetlands northwest of the wellfield contributes an unknown but potentially significant component of the water budget of the wellfield, and that the fate of these wetlands may influence the quality of water produced by the wellfield over the long term.

CONCLUSIONS

The internally drained knob-and-kettle landscape of northwestern Allen County and its associated depressional wetlands appear to have resulted from the melting of large ice blocks buried during the chaotic style of deglaciation of the Saginaw Lobe. Surface topography is strongly palimpsest, reflecting the structure of the hummocky Saginaw Lobe sequence that is now mostly buried beneath younger Erie Lobe deposits. In Allen County, the largest concentration of depressional areas and associated peatlands are associated with thick buried outwash deposits that originated as ice-contact fans. Evidence for a similar style of deglaciation elsewhere in northeastern Indiana, where Saginaw Lobe deposits are prominent, suggests that this model of landscape and wetland formation may be applicable to the knob-and-kettle topography that characterizes some parts of Steuben, LaGrange, DeKalb, and Noble Counties to the north.

The wetlands in northwestern Allen County occur in at least three distinct geologic settings and thus have different relationships to the regional groundwater flow system:

1. **Bogs Perched on Thick, Clayey Till.** These wetlands may have some interaction with very localized flow systems within near-surface till, but they have essentially no relationship to the deeper regional flow system.

2. **Fens Situated on Saturated Sand and Gravel.** These wetlands are predominantly groundwater discharge areas or flow-through wetlands with respect to the upper part of the regional flow system.
3. **Depressional Wetlands Located Over a Regional Recharge Area.** These wetlands exhibit the most transient response, but they serve mainly to transfer surface runoff into the top of the underlying aquifer system.

This diversity of hydrogeologic settings within a small geographic area (relative to the whole of northeastern Indiana) suggests a wide range of possible interactions between wetlands and groundwater in glaciated terrains and its dependence on the regional geologic setting. This diversity also illustrates the potential dangers of making *a priori* assumptions about the recharge-discharge functions of wetlands.

The peatlands within the Eel River Valley and surrounding interlobate terrains of Allen County are characterized by an unusual combination of geologic history, regional hydrogeologic setting, and location on a major surface drainage divide. The convergence of these factors has created a situation in which the wetlands appear to have a significant recharge function for a regionally extensive and productive aquifer system. The geologic origin and general characteristics of these wetlands are similar to those in other parts of the Steuben Morainal Lake Area of northeastern Indiana. It seems reasonable, therefore, to expect that other wetlands in the region may be situated within groundwater recharge areas. However, the existence of a recharge function is meaningful only at places where significant aquifers are present directly beneath and are thus receiving recharge from the wetland. The existence of this condition is best identified through an understanding of the regional hydrogeologic setting. The results presented herein highlight the necessity of interpreting and classifying wetlands in terms of their total hydrogeologic setting — an undertaking that is commonly problematic in the absence of a relatively detailed and systematic study of subsurface geology and hydraulic head data.

The long-term impacts of the destruction of many wetlands resulting from drainage projects designed to "improve" land for agriculture and other purposes may ultimately represent the "law of unintended consequences." These modifications have probably altered the balance of surface water-groundwater interaction in the recharge area for the Huntertown aquifer system. The effects of these alterations on the quality or quantity of groundwater in this economically important groundwater resource are not likely to become evident for decades.

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