Carbonate Aquifer Recharge in Western Lucas County, Northwest Ohio[1]

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Abstract. **Because the carbonate aquifer in much of northwestern Ohio is the principal water resource, understanding the avenues of recharge and resulting pathways of solute transport are crucial to the assessment of water resource availability, water quality and contaminant transport. This study uses estimates of evapotranspiration, measurements of piezometric heads and calculations of groundwater fluxes to investigate carbonate aquifer recharge from a small basin within the carbonate aquifer recharge area 2 km south of Whitehouse, OH. Of the 0.240 m of soil moisture surplus, approximately 43% runs off by way of drain tiles, ditches, and streams leaving 0.135 m as potential recharge for the deeper carbonate aquifer. Direct recharge to the 2% of the carbonate aquifer that is covered by less than 2 m of overburden accounts for a small percentage of the total recharge. Large amounts of radial flow from this shallow bedrock area suggest contributions from sources other than direct recharge or shallow lateral flow. The only remaining possible source of excess recharge in the shallow bedrock area is recharge contributed by streams through vertical fracture zones. Even where the glacial till is thick and vertical permeability is low, large vertical gradients over large areas induce significant bedrock recharge. Because direct recharge is derived from soil moisture surplus and surface water contributions in the area of shallow bedrock, the aquifer is most susceptible to contamination from these sources during the wet seasons. Conversely, even though recharge through the glacial till is maintained throughout the year, threats of contamination due to this vertical recharge are diminished.**

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INTRODUCTION

Water resource usage in rural northwest Ohio parallels the usage nationwide and, as such, provides an example of the issues and concerns that face the nation with regard to overuse and contamination of groundwater resources. Water resources of urban northwest Ohio are largely provided by surface water, a resource that is vulnerable to direct contamination. The municipalities of Toledo and Bowling Green, for example, use surface water as the principle water resource. However, the rest of the northwest Ohio, which is predominantly rural, extracts groundwater as the primary water resource (Breen and Dumouchelle 1991). Although depletion and contamination of groundwater resources are less obvious, the issues are no less important. In effect, the pathways of recharge and contaminant transport to aquifers in northwest Ohio have been paid less attention due to the complexities and remoteness from common experience.

Two common threats that call attention to these inconspicuous groundwater resources are dropping water levels that cause wells to dry up and contaminant sources that pose health risks. These concerns are in part related to groundwater withdrawal by domestic and municipal supply wells. However, development of a thorough understanding of these water quantity and water quality issues requires an understanding of the pathways that provide the groundwater reservoirs with recharge and, consequently, transport dissolved contaminants to the subsurface (Dunne and Leopold 1978). For example, making informed decisions regarding the amounts of water that can be withdrawn from an aquifer without detrimentally lowering the static water level requires knowledge of the quantity, timing, and distribution of recharge to the groundwater reservoir. Water quality within an aquifer is controlled by both the source of recharge and the geological materials through which the recharge flows. Furthermore, understanding the avenues of groundwater recharge aids the design of programs that protect aquifers that are threatened by potential sources of contamination. Given the motivations of understanding the quantity, timing, and distribution of groundwater recharge, the objective of this study was to investigate possible pathways of recharge to the carbonate aquifer in western Lucas County, a key water resource for the rural residents.

METHODOLOGY

Investigating pathways of recharge to the carbonate aquifer requires estimates of the water budget within a drainage basin that lies within recharge area of the carbonate aquifer. The Mosquito Creek basin was selected because of the variety of recharge pathways to the carbonate aquifer (see Fig. 1 and Fig. 2) including: 1) direct recharge where the overburden is thin, 2) direct recharge from losing streams, 3) lateral flow within the shallow unconfined aquifer to these areas of shallow bedrock, and 4) regional vertical recharge through the aquitard. Given measurements of precipitation and temperature from the Toledo Express Airport 6 km to the north, the Thornthwaite method (Dunne and Leopold 1978) provided an estimate of the amount of evapotranspiration (Table 1a). Subsequently, these estimates were used to calculate the soil moisture surplus available for either runoff in the streams or for recharge to the deeper

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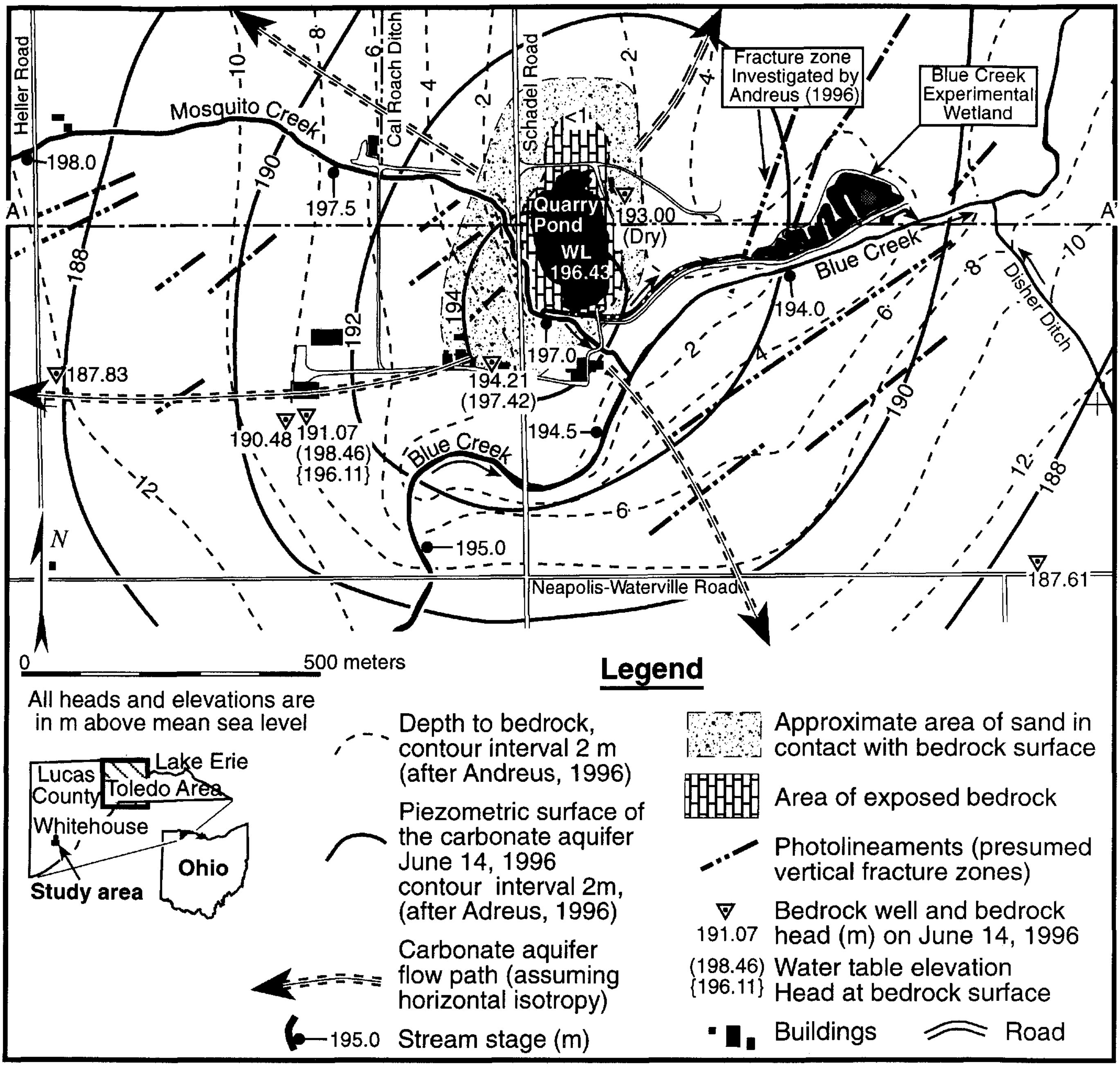

FIGURE 1. Location and hydrogeological features of the Quarry Pond Farm study area.

groundwater system. Cumulative stream flow measured during 1997 at the discharge of the Mosquito Creek basin allowed the estimation of the amount of soil water surplus remaining for recharge of the carbonate aquifer (Table 1a). Ultimately, the percentages of soil moisture surplus were used to estimate the amount of recharge available on average (Table 1b).

The contributions of the 4 different avenues of recharge were estimated using heads from monitoring wells to calculate vertical gradients and unused bedrock wells (some of which are not shown on Fig. 1) to map out the piezometric surface within the carbonate aquifer. The vertical hydraulic conductivities of the glacial till, sand and bedrock were measured using falling head permeameters, slug tests and municipal well pump tests, respectively. These hydraulic conductivities and gradients were then used in a pseudo-steady-state manner to calculate groundwater fluxes assuming the transient effects were averaged over the monthly periods investigated. Finally, the stratigraphy of the area was characterized using field observations and samples taken during monitoring well installation.

GEOLOGY AND GENERAL HYDROGEOLOGY

Because this study focuses on groundwater recharge to the bedrock aquifer in western Lucas County, investigations concentrate on an area that is shallow to bedrock and has received minimal hydrologic modification due to pumping or drainage. An area 2 km south of the Village of Whitehouse, OH (Fig. 1), known as the Quarry Pond Farm has been identified as a recharge area

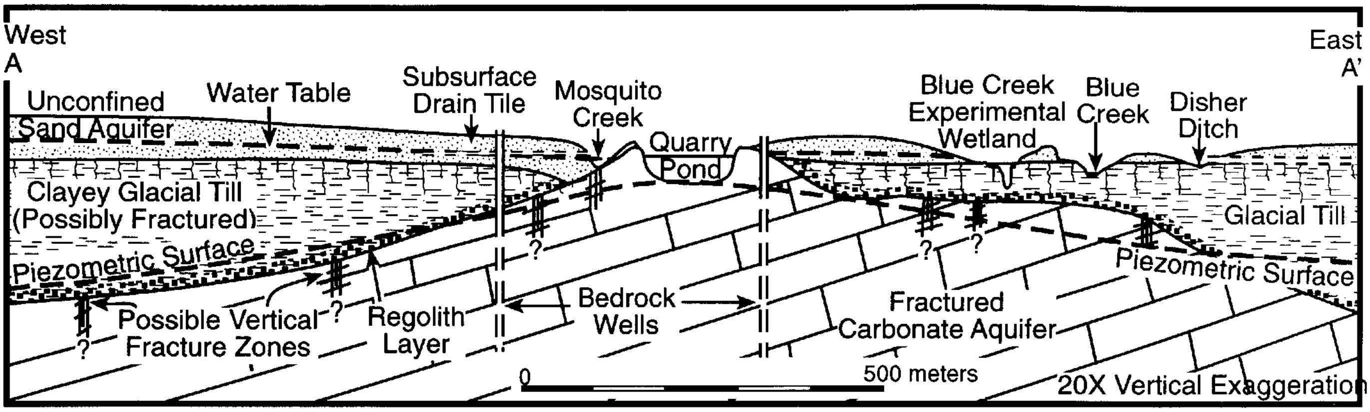

FIGURE 2. Cross section of the Quarry Pond Farm study area hydrogeological features

for the carbonate aquifer (Breen and Dumouchelle 1991; Raab and Haiker 1995). An area with minimal hydrologic modification was sought in order to investigate natural avenues of recharge with few complicating anthropogenic influences. Because the quarry was excavated by hand it is shallow and exhibits no hydraulic interaction with the underlying aquifer (Andreus 1996). Furthermore, none of the wells at the site is being pumped and the study area lies outside the zone of influence for the Whitehouse municipal supply well 1.5 km to the northeast. Consequently, this area is an example of relatively undisturbed hydrogeological conditions and provides a representative area to perform investigations of natural recharge to the bedrock aquifer in western Lucas County.

Groundwater recharge typically occurs where permeable units are exposed to direct infiltration at the surface or where ample vertical flow is supplied from overlying units. In western Lucas County the major water bearing units are predominantly confined Silurian and Devonian limestones and dolomites often referred to collectively as the carbonate aquifer (Andreus 1996; Breen and Dumouchelle 1991; Bugliosi 1990). Although the

TABLE 1

Estimations of runoff and recharge, (a) 1997 and (b) Average values.

	T (°C)	ETp	Ppt	Ppt-ETp	ETa	D	S	Roc (m³)	RO (m³)	$\frac{RO}{A}$	$\frac{RO}{A\,S}$	Rch
a) 1997												
Jan	-5.6	0	62	62	0	0	62		*44,770	26	0.43	36
Feb	-0.6	0	108	108	0	0	108	69,371	69,371	41	0.38	67
Mar	3.9	14	65	51	14	0	51	110,519	41,148	24	0.48	27
Apr	8.3	38	39	1.4	38	0	1.4	114,112	3,593	2.1	~1.5	0
May	11.1	60	171	111	60	0	111	195,928	81,816	48	0.43	63
Jun	20.6	126	111	-15	113	13	0	198,313	2,385	1	0	0
Jul-Nov	–	404	250	-154	301	104	0	198,313	0	0	0	0
Dec	-0.6	0	83	83	0	0	30		*21,984	13	0.43	17
Annual Totals			889				363			155	0.43	210
b) Averages												
Jan	-5.6	0	44	44	0	0	44			*19	0.43	25
Feb	-3.9	0	44	44	0	0	44			17	0.38	27
Mar	2.2	7	67	60	7	0	60			28	0.48	31
Apr	8.9	41	74	33	41	0	33			14	0.43	19
May	15.0	86	73	-13	75	11	0			0	–	0
Jun-Nov	–	513	462	-51	475	38	0			0	–	0
Dec	-2.2	0	74	74	0	0	59			26	0.43	33
Annual Totals			838		598		240		*176,592	*104		135

All values are in millimeters unless otherwise indicated. T: average monthly temperature; ETp: potential evapotranspiration; Ppt: monthly precipitation; ETa: actual evaporation estimated using the Thornthwaite method; D: soil moisture deficit; S: soil water surplus; ROc: measured cumulative runoff from the Mosquito Creek basin with area A = 1.698 x 10^6 m^2; RO: monthly runoff; * runoff estimated from average RO/S ratios; ~ overestimate due to contribution of runoff from previous month; Rch: recharge estimated as S-ROe.

permeability due to primary porosity is low within the carbonates, the secondary porosity due to bedding plane parting and solution cavities results in the horizontal permeabilities that are responsible for transmitting groundwater regionally. Vertical fractures are concentrated in fracture zones (Armstrong 1976) and act to transmit groundwater vertically from the shallower recharge zones into the deeper groundwater flow regimes (Breen and Dumouchelle 1991). Linear discolorations in the overlying soil, which are observed on aerial photographs of the study site, indicate possible locations of these vertical fracture zones near the top of the carbonate aquifer (see photolineaments shown on Fig. 1). These features, often referred to as photolineaments, represent locations of enhanced recharge to the deeper aquifer (Breen and Dumouchelle 1991).

Western Lucas County is located on the western limb of the Findlay Arch, a broad anticlinal structure that exposes Silurian and Devonian carbonates along its axis. Subcrops and outcrops of these carbonates form a broad band that covers much of western Ohio. In western Lucas County the carbonates dip less than 7° to the west-northwest where they are overlain by the Upper Devonian – Lower Mississippian Ohio Shale. Where these shales overlie the carbonate aquifer, 12 km to the north-northwest of the study site, they act as the upper confining unit. Before the Wisconsinan glaciation the bedrock was incised by the ancestral Maumee River system which left a valley 2.5 km to the northwest of the site (Bush 1966). A ridge in the bedrock surface runs through the study area and continues to the north-northeast, roughly parallel to the strike of the bedrock units, presumably along a resistant formation (Forsyth 1968). Due to the relatively flat topography of the region, this bedrock ridge results in areas of shallow bedrock that are covered by permeable sand or less than 1 m of glacial till. These areas of shallow bedrock are exposed to direct recharge from the overlying unconfined aquifer and from surface water bodies by way of vertical fractures and fracture zones. An example of a shallow bedrock area, as defined in this study, is shown near the center of Fig. 1 where the bedrock is either in contact with sand or covered by less than 1 m of glacial till. These areas of shallow bedrock comprise less than 2% of the carbonate aquifer in Lucas County.

The material confining most of the carbonate aquifer in western Lucas County is clay-rich glacial till laid down during the Wisconsinan glacial stage (Forsyth 1968). The hydraulic conductivity of the unfractured glacial till measured for this study and by Andreus (1996) gave values as high as 2×10^{-5} m/s within 1 m of the surface and approaching 1×10^{-8} m/s beneath about 1.5 m of the surface. However, in some locations the glacial till may be fractured and possess substantially enhanced vertical permeability and recharge (deRoche and Breen 1989). The chances of fractures extending to the bedrock surface are greatest where the glacial till is the thinnest. Overlying the clay-rich glacial till throughout much of northwestern Lucas County is a layer of sand that ranges from 0 to 3 m thick at the Quarry Pond Farm study site (Fig. 2) to as much as 10 m thick 6.5 km to the northwest of the study site. This sand layer constitutes an unconfined aquifer that desaturates during the drier months within the study area but remains perennially saturated in areas to the northwest. As is typical of groundwater recharge areas, the piezometric surface of the confined aquifer is lower than the water table in the unconfined aquifer generating a downward hydraulic gradient which results in recharge to the confined aquifer.

RESULTS AND DISCUSSION

Potential Recharge

Because direct measurements of groundwater recharge are not possible, investigations of recharge require estimates of the amount of precipitation that is available for recharge of the deeper aquifer during various seasons. Before groundwater recharges the deeper aquifer it is either returned to the atmosphere by evapotranspiration or removed from the area by runoff in the ditches and streams. During the warmer drier months, that is between May and November, rates of evapotranspiration in this region tend to be greater than rates of precipitation (Table 1b). During these months, precipitation is taken up by evapotranspiration and by soil moisture deficits. This rapid depletion of soil moisture was demonstrated during the study period by desaturation of the unconfined aquifer, sharply diminished stream flows, and drying of the ditches in June of 1997 (Table 1a). The soil moisture deficit indicates that infiltration is not available to recharge the deeper aquifer and that the only water available for recharge during these drier months is surface water and those portions of the shallow aquifer that remain saturated.

During the winter months, temperatures are generally below freezing in this region and consequently evapotranspiration effectively ceases. However, precipitation often falls as snow and infiltration capacities are reduced due to frozen soils and, therefore, approximately 43% of this precipitation leaves the area as runoff. The amount of infiltration reaching the groundwater reservoirs can be estimated by subtracting the runoff, either measured (Table 1a) or estimated (Table 1b), from the soil moisture surplus. According to the estimates of evapotranspiration (ETa), on the average approximately 0.048 of the 0.303 m of precipitation (Ppt) that falls during the surplus months is returned to the atmosphere and 0.015 m is used to replenish soil moisture deficits. Runoff measurements taken at the discharge of the Mosquito Creek drainage basin during spring 1997 (RO/A in Table 1a) indicate that 43% of the soil moisture surplus leaves the basin as runoff. No monthly lag between infiltration and shallow groundwater discharge has been incorporated in the runoff analyses because the unconfined aquifer is very shallow (1 to 3 m thick) and well drained. This lack of lag is exhibited by the small amount of runoff remaining in June 1997 even after an atypically wet May. Because the piezometric surface within the carbonate aquifer in this region is always below the stream stage, the runoff is derived from the unconfined sand aquifer (and/or overland flow) and any difference between runoff and soil moisture surplus must recharge the carbonate aquifer. Thus, the amount of infiltrating precipitation remaining, a total of 0.135 m on average (total Rch in Table 1b), recharges the carbonate aquifer by one of the 4 avenues listed in the Methodology section and leaves the basin by underflow.

Direct Recharge

The most direct avenue by which the recharge reaches the carbonate aquifer is by means of direct infiltration to the zone of shallow bedrock as defined previously (see Fig. 1 and Fig. 2) and flow into exposed vertical fractures. However, if this is the only area contributing recharge to the carbonate aquifer, the maximum possible volume of recharge would be the total soil moisture surplus (assuming runoff does not occur in this area) multiplied by the area of shallow bedrock which extends 2 km to the north of the site, $0.240\ \text{m/yr} \times 1.0 \times 10^6\ \text{m}^2 \approx 2.40 \times 10^5\ \text{m}^3/\text{yr}$. This amount can be compared to the amount being pumped from the municipal supply well for the Village of Whitehouse located 1.5 km to the northeast of the study site. Raab (1995) indicated that this well produces $4.81 \times 10^5\ \text{m}^3/\text{yr}$ from a zone of contribution (the area delineated by a groundwater divide) that encompasses approximately $1.29 \times 10^7\ \text{m}^2$, an area that includes half of the study site. The production well was found to exhibit only localized drawdown extending approximately 0.5 km toward the study site and is not contributing to declining heads in the long term, that is the system has come to a long term or pseudo-steady-state condition where the water withdrawn is compensated by recharge. However, if the only source of recharge was due to direct recharge in the area of shallow bedrock, the Whitehouse well would be causing regionally declining water levels. This demonstrates that recharge reaching the deeper aquifer is derived from a much larger area than the area underlain by shallow bedrock and is being transmitted by some avenue besides direct recharge to those areas.

Andreus (1996) provided further evidence that recharge from sources other than direct recharge must contribute to the zone of shallow bedrock and increase the flow relative to the rest of the region. This study assumed horizontally radial, steady state flow from the zone of shallow bedrock and used hydraulic head (h) measured as a function of radial distance (r) to calibrated a steady state radial flow model. The radial flow model was of the form $Q = 2\pi Kb(h_1 - h_2)/\ln(r_2/r_1)$, that is the Thiem equation (Todd 1980) where Q is the volumetric flow rate crossing any cylindrical surface concentric with the area of shallow bedrock and hence is equal to the recharge rate, K is the hydraulic conductivity of the carbonate aquifer taken as 1.4×10^{-4} m/s (Raab and Haiker 1995), b is the thickness of the aquifer over which the recharge is acting and is taken as 12 m (the thickness of bedrock penetrated by the bedrock wells), and h_1 and h_2 are hydraulic heads measured at radial distances (r_1 and r_2 respectively) from the center of the area of shallow bedrock. For example, the heads in June of 1996 at the bedrock wells to the southwest of Quarry Pond ($h_1 = 194.21$ m at $r_1 = 250$ m and $h_2 = 191.07$ m at $r_2 = 550$ m) represent an average gradient and suggest that $8.2 \times 10^5\ \text{m}^3/\text{yr}$ recharges the aquifer in the area of shallow bedrock. Dividing this recharge by the area of shallow bedrock at the center of the radial flow (Fig. 1), approximately $210{,}000\ \text{m}^2$, gives a value of 6.6 m of recharge which is more than an order of magnitude greater than the potential recharge available for direct recharge. Even if the hydraulic conductivity was overestimated by an order of magnitude due to a highly productive zone within the municipal supply well tested, the recharge would still be greater than the potential recharge.

This excess recharge at the site can be demonstrated qualitatively by examining the hydraulic gradients relative to the gradients in the rest of the region. The gradients throughout western Lucas County typically range from 0.001 to 0.002 m/m, whereas, the gradients adjacent to the area of shallow bedrock (Fig. 1) range from 0.007 to 0.01. Assuming relatively uniform transmissivities, the elevated hydraulic gradients indicate that volumetric fluxes in this area are 3 to 10 times those found elsewhere in western Lucas County. These analyses also indicate that as much as an order of magnitude more recharge is being contributed to the area of shallow bedrock than is available from direct recharge and must be transported laterally from other areas in the basin. Therefore, the next question to address is the source of this excess recharge.

Lateral Flow to Areas of Shallow Bedrock

One possible avenue of lateral flow to the area of shallow bedrock is horizontal flow towards the area of shallow bedrock within the unconfined sand aquifer (Fig. 2). The area surrounding the zone of shallow bedrock is mantled with a layer of fine sand with a thickness of generally less than 2 m. Subsurface drains and ditches within the unconfined sand aquifer limit the saturated thickness approximately 0.5 to 1 m or less. The hydraulic conductivity of the sand was approximately 1×10^{-5} m/s with a maximum horizontal hydraulic gradient of 0.003 directed toward the region of shallow bedrock. According to Darcy's Law, assuming a width of flow equal to the perimeter of the area of shallow bedrock (at most 6 km), the volumetric flow rate would be only $6 \times 10^3\ \text{m}^3/\text{yr}$. Even if the sand remained saturated year around, this amount is a small fraction of the potential recharge and can be neglected.

The only other possible avenue of lateral flow to the area of shallow bedrock is by means of stream flow. On average, Blue Creek with a basin area of 96 km^2 carries approximately $1.0 \times 10^7\ \text{m}^3/\text{yr}$ and Mosquito Creek carries approximately $1.8 \times 10^5\ \text{m}^3/\text{yr}$. These volumetric discharges could contribute significantly to bedrock recharge even if only a fraction of the flow is available for recharge. Groundwater/surface-water interactions are demonstrated qualitatively by examining the relationship of the stream stage elevation (Fig. 1) to the piezometric surface in the carbonate aquifer and the elevation of the water table in the shallow sand aquifer (Fig. 2). Because the water table and, in some locations, the entire sand aquifer are above the stream stage, most of the runoff in the streams originates as discharge from the shallow aquifer by way of baseflow or drain tiles. Because the piezometric surface of the carbonate aquifer is typically beneath the stream stage, streams tend to be losing streams with respect to the deep aquifer in the area. In essence, the streams and ditches are effluent with respect to the unconfined sand aquifer and influent with respect to the bedrock aquifer.

Areas where Blue Creek and Mosquito Creek are most likely hydraulically connected to the bedrock surface are shown on Fig. 1 where the streams enter the area of shallow bedrock near the quarry pond. The surface water may either flow directly into exposed vertical fracture zones or flow along the bedrock surface to fracture zones. With regard to the latter, a regolith zone at the bedrock surface and a coarse sand and marle layer beneath the glacial till (extending laterally at least 1 km from the area of shallow bedrock) provide a permeable pathway to fracture zones farther from the area of direct recharge.

Recharge from streams is difficult to estimate due to the unreliability of streambed conductance estimates. However, in the areas where the streams flow over the surface of the bedrock, the stream bed sediments are either absent or coarse grained and the flow into the carbonate aquifer is probably controlled by vertical fractures in the streambed. Flow rates in fractures follow a cubic law of the form $Q = w \cdot L \cdot a^3 \cdot j$ (Marsily 1986) where w is a factor that depends on the kinematic viscosity of water ($w = 6.2\times10^5$ m^{-1}s^{-1} at 10° C), L is the length of the fracture, a is the aperture of the fracture and j is the hydraulic gradient. One kilometer north of the study site, a 200 m quarry excavation exposes approximately 10 to 15 fractures that extend 3 m or more beneath the surface. In addition to these major fractures, vertical fractures (60 per 200 m observed) that connect adjacent bedding plane fractures could contribute to vertical recharge as well. In the area where the stream is in contact with the bedrock the vertical distance across which the head difference acts is approximately equal to the head difference (stream stage minus the head in the carbonate aquifer) resulting in a hydraulic gradient is 1 m/m. Given a stream width of 2 m and an estimated 10 major fractures crossing Blue Creek in the area of shallow bedrock it is possible that 7.4×10^4 m^3/yr could be contributed to the carbonate aquifer. Photolineaments near the streams in the area of shallow bedrock indicate the possibility of fracture zones in the stream beds. If a fracture zone with multiple fractures of wider aperture crossed Blue Creek, the recharge amount could well be an order of magnitude larger. Furthermore, the radial flow calculations presented in the Direct Recharge section indicate that recharge must originate from some source other than direct recharge. The only likely alternate source is recharge from losing streams in the area of shallow bedrock.

Vertical Recharge Through the Glacial Till

Finally, a source of recharge to the carbonate aquifer that is often overlooked is vertical flow through the clayey glacial till that mantles much of the carbonate aquifer (Fig. 2). Although the glacial till in the area tends to have low hydraulic conductivities (between 1×10^{-8} and 1×10^{-6} m/s), large vertical hydraulic gradients are maintained throughout the year. These large vertical gradients result in continuous vertical recharge that is distributed over a large area. Andreus (1996) measured the vertical gradients within the glacial till aquitard in detail (see Fig. 1, 50 m northwest of the Blue Creek Experimental Wetland) and estimated a volumetric flux of between 0.53×10^{-8} and 1.38×10^{-8} m^3/s per m^2 or between 0.16 and 0.41 m/yr. These values are higher than the potential recharge probably because the till is thin in the area of that study and because of accentuated vertical gradients in the vicinity of the recharge area. Realizing that the potential recharge estimate is an average for the Mosquito Creek basin, if the vertical recharge is elevated in the region of shallow bedrock it is likely to decrease with distance from the recharge zone where till thickens. The study also indicated that recharge to a suspected fracture zone (near a photolineament) is a factor of 3 greater than the recharge through the glacial till elsewhere.

These analyses support the hypothesis of significant potential recharge being transmitted to the carbonate aquifer through the low permeable tills even in the absence of vertical fractures. In the areas where the unconfined sand aquifer becomes desaturated, water continues to be slowly released from storage within the clay aquitard. Although the high storativities and low permeabilities will result in continued recharge from the aquitard, the vertical recharge is reduced because the head is no longer maintained by the overlying aquifer. However, 6 km to the northwest of the study site, the unconfined sand aquifer remains saturated during these drier months and consequently the vertical recharge is maintained.

SUMMARY AND CONCLUSIONS

Estimates of evapotranspiration indicate that, of the 0.838 m of precipitation that normally falls in the region, 0.240 m is available for recharge of the shallow, unconfined, sand aquifer. Of this amount, 43% runs off by way of shallow aquifer discharge, drain tiles, ditches, and streams leaving 0.135 m as potential recharge for the deeper carbonate aquifer by 4 possible avenues. The amounts of recharge that have been estimated for each of these hypothesized avenues within the Mosquito Creek basin are summarized in Table 2. Direct recharge to the deeper carbonate aquifer is inhibited by a clayey glacial till that acts as an aquitard covering 98% of the aquifer. Although direct recharge of as much as 0.240 m is possible in isolated areas of shallow bedrock, this only accounts for a small percentage of the total flow within the carbonate aquifer. Evidence suggests that streams contribute a significant component of recharge to the area of shallow bedrock by means of vertical fracture zones or a permeable regolith layer at the bedrock surface directly beneath the glacial till aquitard. However, accounting for the amounts of water being transmitted by the aquifer requires consideration of downward vertical flow through the glacial till aquitard. In the regions of the carbonate aquifer confined by glacial till large vertical hydraulic gradients over large areas result in significant, diffuse recharge to the deeper formation

TABLE 2

Summary of Mosquito Creek basin recharge estimates.

Avenues of Recharge	Recharge (m/yr)	Area over which the recharge acts	Area (km^2)	Volumetric Recharge (m^3/yr)
Potential Recharge	0.135 [a]	Whole Basin	1.70	2.30×10^5
Radial Flow from Shallow Bedrock	3.92	Shallow Bedrock [e]	0.21	8.24×10^5
(1) Direct Recharge	0.240 [b]	Shallow Bedrock	0.21	5.04×10^4
(2) Stream Contribution	0.352 [c]	Shallow Bedrock	0.21	7.40×10^4
(3) Lateral Flow from Unconfined Aquifer	0.004	Deep Bedrock [f]	1.49	6.00×10^3
Vertical Flow, Till (4)	0.29 [d]	Deep Bedrock	1.49	4.32×10^5

[a] 56% of soil moisture surplus; [b] total soil moisture surplus assuming no runoff in the area of shallow bedrock; [c] could be significantly higher if fracture zones are present; [d] probably lower farther from areas of shallow bedrock; [e] the area of shallow bedrock within the Mosquito Creek Basin; [f] area of the whole basin minus the area of shallow bedrock.

even though the clays possess a very low hydraulic conductivity. The most direct avenue of recharge, that is recharge to the area of shallow bedrock, is mainly contributed during the late fall, winter and spring when the streams are flowing and the sand aquifer is saturated. Consequently, the aquifer would be most susceptible to contamination at the surface due to road salt in the winter, agricultural chemical application in the spring, and contaminant spills. On the other hand, recharge through the glacial till is maintained throughout the year by slow leakage and storativity, especially where the unconfined sand aquifer remains saturated. Because the slow movement provides time for biotic and abiotic degradation of certain contaminants, this transport pathway is less likely to contribute contamination to the aquifer unless fractures in the aquitard extend to the bedrock surface.

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