Analysis of modern and Pleistocene hydrologic exchange between Saginaw Bay (Lake Huron) and the Saginaw Lowlands area

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ABSTRACT

Two numerical models, one simulating present groundwater flow conditions and one simulating ice-induced hydraulic loading from the Port Huron ice advance, were used to characterize both modern and Pleistocene groundwater exchange between the Michigan Basin and near-surface water systems of Saginaw Bay (Lake Huron) and the surrounding Saginaw Lowlands area. These models were further used to constrain the origin of saline, isotopically light groundwater, and porewater from the study area. Output from the groundwater-flow model indicates that, at present conditions, head in the Marshall aquifer beneath Saginaw Bay exceeds the modern lake elevation by as much as 21 m. Despite this potential for flow, simulated groundwater discharge through the Saginaw Bay floor constitutes only 0.028 m^3 s^{-1} (~1 cfs). Bedrock lithology appears to regulate the rate of groundwater discharge, as the portion of the Saginaw Bay floor underlain by the Michigan confining unit exhibits an order of magnitude lower flux than the portion underlain by the Saginaw aquifer. The calculated shoreline discharge of groundwater to Saginaw Bay is also relatively small (1.13 m^3 s^{-1} or ~40 cfs) because of low gradients across the Saginaw Lowlands area and the low hydraulic conductivities of lodgement tills and glacial-lake clays surrounding the bay.

In contrast to the present groundwater flow conditions, the Port Huron ice-induced hydraulic-loading model generates a groundwater-flow reversal that is localized to the region of a Pleistocene ice sheet and proglacial lake. This area of reversed vertical gradient is largely commensurate with the distribution of isotopically light groundwater presently found in the study area. Mixing scenarios, constrained by chloride concentrations and δ^{18}O values in porewater samples, demonstrate that a mixing event involving subglacial recharge could have produced the groundwater chemistry currently observed in the Saginaw Lowlands area. The combination of models and mixing scenarios indicates that structural control is a major influence on both the present and Pleistocene flow systems.

Keywords: Saginaw Bay, Port Huron, glacier, Michigan Basin, chloride, and groundwater.

INTRODUCTION

The exchange of water and solutes between the Michigan Basin and the large, freshwater lakes of the Great Lakes region warrants investigation because the juxtaposition of these entities gives rise to one of the highest known salinity gradients (Fig. 4.7 *in* Hanor, 1979). We present a numerical analysis of groundwater flow under both modern and Pleistocene conditions to determine temporal variations in the exchange of fluids between the Michigan Basin and Saginaw Bay (Lake Huron). Saline water has been documented near the sediment-water interface in Lake Michigan (Callender, 1969), Lake Ontario (Drimmie et al., 1992), and in Saginaw Bay (Lake Huron) (Kolak et al., 1999), although the rate of exchange between these saline waters and the overlying water column remains unknown. Previous studies of groundwater/large-lake interactions in the Great Lakes region have shown the potential for significant discharge of groundwater to the Great Lakes (Cartwright et al., 1979; Grannemann et al., 2000; Hoaglund et al., 2002a). Cartwright et al. (1979) estimated that direct groundwater discharge to Lake Michigan may constitute as much as 10% of the total hydrologic budget for the lake. Grannemann et al. (2000) reduced the direct groundwater discharge estimate to ~3% but summarized that groundwater discharge indirectly entering Lake Michigan via streams accounted for 31% of the total hydrologic input to the lake. If this groundwater discharge is derived from formations containing saline water or brine, which are known to occur at relatively shallow depths in the Michigan Basin (Westjohn and Weaver, 1998), groundwater could play a significant role in regulating geochemical cycles in the adjacent large lakes.

In addition to the occurrence of saline water and brine at relatively shallow depths, portions of the Michigan Basin also contain groundwater with a stable isotopic composition that is significantly lighter than modern meteoric recharge (Clayton et al., 1966; Long et al., 1988; Meissner et al., 1996; Wahrer et

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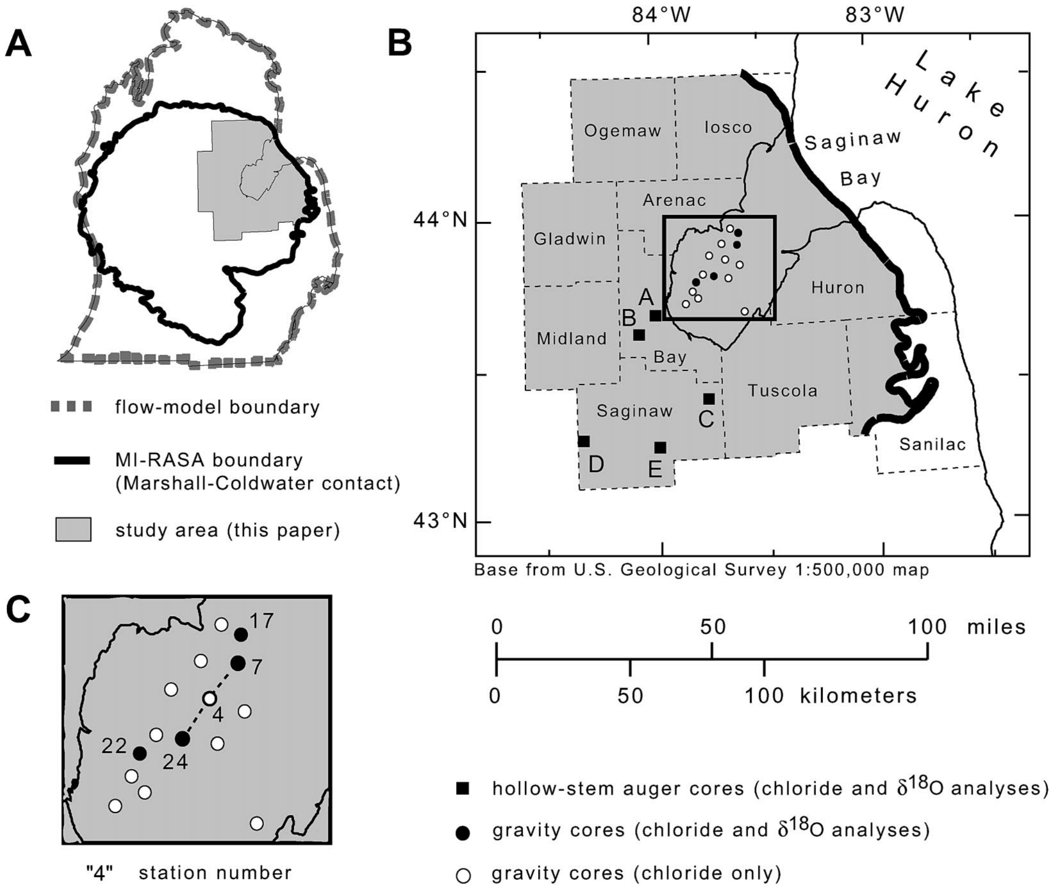


Figure 1. (A) Map of lower peninsula of Michigan showing extent of flow model, MI-RASA investigation, and study area. (B) Map of study area (county boundaries denoted by dashed lines) depicting locations from which sediment cores were previously collected. (C) Close-up view of Saginaw Bay area identifying selected coring stations.

al., 1996; Ging et al., 1996), indicating the preservation of a paleorecharge signal emplaced when the climate was significantly cooler than today. Attempts to address fluid transport within the Michigan Basin must account for the distribution of the salinity and stable isotope signatures; each signature has a different origin. An extensive study of the hydrogeology, geochemistry, and paleohydrology of the Michigan Basin has been conducted as part of the U.S. Geological Survey Regional Aquifer System Analysis (RASA) initiative (e.g., Mandle and Westjohn, 1989; Westjohn et al., 1994; Westjohn and Weaver, 1996a, b, c; Holtschlag, 1996, 1997; Ging et al., 1996; Meissner et al., 1996; Wahrer et al., 1996; Hoaglund et al., 2002b).

The Michigan RASA study led to the development of a regional groundwater-flow model (Mandle and Westjohn, 1989; Hoaglund et al., 2002b) using modern groundwater-flow boundaries (Fig. 1) and an estimate of steady-state recharge. Stream discharge accounts for over 90% of the overall water budget in the RASA model, and groundwater heads are sensitive to local streams (Hoaglund et al., 2002a). As a result, transport modeling coupled to the local flow systems of the RASA model indicates that groundwater residence times along the water table-to-discharge flow paths are relatively short. The Younger Dryas, which is the last climatic event cold enough to produce paleorecharge with a light isotopic composition similar to that measured in groundwater from the study area, occurred prior to 10 ka. Both the number and extent of flowpaths greater than 10 ka in residence time are insufficient for the paleorecharge and subsequent transport of isotopically light water from the water table to the Saginaw Lowlands area. Given the relatively short groundwater residence time, a mechanism other than paleorecharge during ice-free conditions is needed to emplace the isotopically light groundwater (Hoaglund, 1996).

An alternative hypothesis for the origin of the isotopically light water in the study area is that subglacial recharge, defined here as the transmission of water from the glacial system to the groundwater system, introduced isotopically light water into the underlying aquifers. Recharge of glacial meltwater could have been induced either directly by the ice or indirectly by high proglacial lake stands. The glacial stratigraphy in Michigan's lower peninsula records four main late Wisconsinan Laurentide ice sheet advances from 21 to 10 ka: the Nissouri (maximum 18 ka), the Port Bruce (maximum 14.8 ka), the Port Huron (maximum 13 ka), and the Onaway (maximum 11.8 ka) (Eschman, 1985; Karrow et al., 2000). During these advances, loading from the ice sheet may have propagated through several bedrock units in the Michigan Basin and reversed groundwater-flow directions. For example, Bahr et al. (1994) attributed modern overpressures and a head reversal between the Middle Ordovician St. Peter Sandstone and the Glenwood Formation, which underlie the Michigan RASA study area, to the load stemming from the overriding ice sheet. The perturbations in these deeper units demonstrate

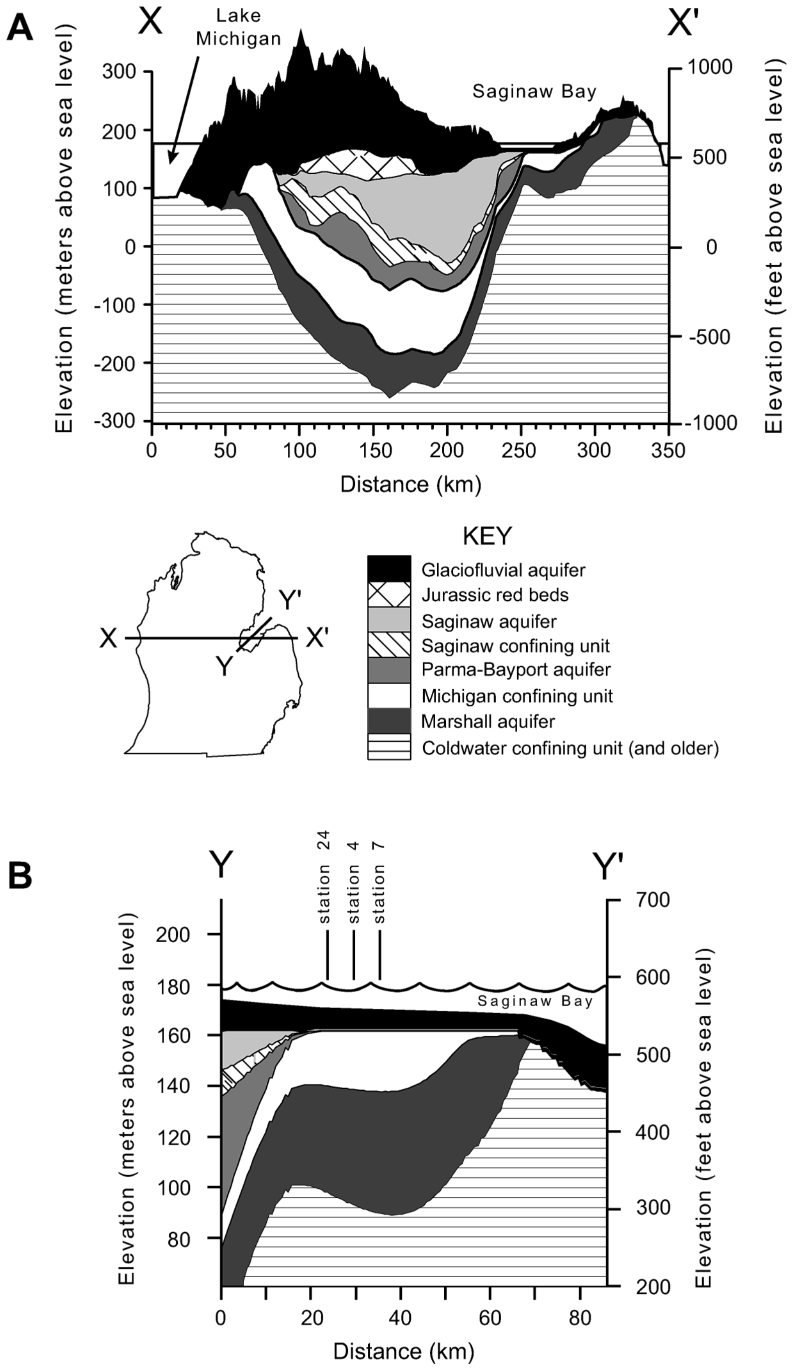


Figure 2. (A) Model-generated cross-section of Michigan Basin, depicting stratigraphic relations among primary hydrogeologic units of interest. (B) Model-generated cross-section through long axis of Saginaw Bay. Locations of Saginaw Bay sediment cores 24, 4, and 7 (cores with highest porewater chloride concentrations) are projected onto cross section.

the ability of the ice sheet to reverse hydraulic gradients, but these units are sufficiently removed from the ice sheet that no subglacial recharge would have occurred. However, the shallower aquifers of the Michigan RASA study could have received isotopically light recharge resulting from a hydraulic connection between the ice sheet, meltwater, and the groundwater beneath the ice sheet. Similar hydraulic connections have been invoked to account for the distribution of isotopically light water elsewhere in the Michigan Basin (Weaver et al., 1995) and in other studies (McGinnis, 1968; Filley and Parizek, 1983; Siegel and Mandle, 1984; Downey, 1986; Dannemiller and Badalementi, 1988; Siegel, 1991; Carlson, 1994; Stueber and Walter, 1994; Clark et al., 2000).

The goal of this study is to link the RASA groundwater-flow model with the ice-induced hydraulic-loading model of Hoaglund (1996) to determine the extent of ice sheet/groundwater/large-lake interactions in Saginaw Bay (Lake Huron) and the adjacent Saginaw Lowlands area. The ice-induced hydraulic-loading model is used to investigate the plausibility of subglacial recharge as a mechanism for the emplacement of isotopically light water during the Pleistocene. Porewater chemistry data from a previous study of Saginaw Bay and the Saginaw Lowlands area (Kolak et al., 1999; sample locations shown in Fig. 1, B and C) are used here to further constrain fluid transport by identifying possible mixing scenarios. From the results of these numerical simulations and mixing scenarios, we draw inferences regarding the geologic controls on ice sheet/ground-water/large-lake interactions in the study area.

METHODS

Groundwater-flow Model Construction

A groundwater-flow model of the Michigan Basin was constructed using 1-km grid cells to simulate modern groundwater flow in the Glaciofluvial, Saginaw, Parma-Bayport, and Marshall aquifers (Fig. 2) as part of the Michigan RASA study. The Great Lakes shorelines and Saginaw Bay were used as specified-head boundaries for the Glaciofluvial aquifer, while bedrock aquifers were modeled to their subcrop extent. The steady-state model used independently estimated recharge rates while groundwater flow discharged to both an internal river network and external Great Lake boundaries. The model was regionally calibrated by trial-and-error and then with ModflowP (Hill, 1992) for a sensitivity analysis. The model construction and calibration are discussed in greater detail elsewhere (Hoaglund et al., 2002a, 2002b). Groundwater flow was simulated assuming negligible variations in fluid density. This assumption is reasonable for the relatively dilute waters of the Glaciofluvial and Saginaw aquifers and the unconfined subcrop portions of the Marshall aquifer, although this approach does not adequately represent fluid transport in the portions of the Michigan Basin where the Marshall aquifer is confined and known to contain brine.

The composite geologic structure of the aquifer system and confining units was digitally reproduced from structure contour maps and isopach maps provided in the original RASA reports (Westjohn and Weaver, 1998). No data were available for the region underneath Saginaw Bay, but the configuration of the aquifer system was completed by: (1) drawing interpreted contacts across Saginaw Bay for each aquifer and confining unit; (2) interpolating an isopach map for each aquifer and confining unit under Saginaw Bay from known thicknesses bordering Saginaw Bay to zero-thickness at the interpreted contacts; and (3) reconstructing the surface of each layer by subtracting each successive isopach map, starting with an interpreted topmost layer of 162 m (530 ft) above sea level, the assumed base of glacial deposits beneath Saginaw Bay. The reconstructed surfaces are therefore linear interpolations and linear projections between known mapped and interpreted contacts, assuming conservation of mass and an angular unconformity at the base of glacial deposits below Saginaw Bay.

The reconstructed Marshall aquifer exhibits an anticlinal structure underneath Saginaw Bay (Fig. 2, A and B). This anticline might be an artifact of the chosen reconstruction method, which assumes conservation of mass and neglects the possible influence of faults. However, this reconstruction is consistent with the oil and gas charts of Cohee et al. (1951) and plates by Lane and Hubbard (1895, nos. 1 and 2), where anticlinal structures observed on land are interpreted to extend under Saginaw Bay. A southwest-to-northeast cross section along the axis of Saginaw Bay shows that in the inner portion of the bay, the Saginaw and Parma-Bayport aquifer occur below the base of glaciofluvial deposits (Fig. 2B). These two aquifers pinch out against the Michigan confining unit, which underlies glaciofluvial deposits for most of the rest of Saginaw Bay.

Timing of Ice Advances and Position of Subglacial Meltwater

The completion of the modern hydrologic model domain allowed for an analysis of paleohydrologic conditions under the influence of glacial ice. The timing of ice advances and the position of subglacial meltwaters relative to the margins of the ice were evaluated to conceive a model whereby the original model domain was subglacially recharged. Three of four Late Wisconsinan ice advances, the Nissouri, Port Bruce, and Port Huron phases (Karrow et al., 2000), could have subglacially recharged the aquifer systems in the vicinity of the Saginaw Lowlands area and Saginaw Bay. During the Onaway phase (Karrow et al., 2000), however, the ice did not advance far enough to recharge the study area. The Nissouri ice advance completely covered the lower peninsula of Michigan, and the Port Bruce ice advance established a maximum advance at the Tekonsha moraine in southern Michigan. Both ice advances provided opportunity for subglacial recharge of isotopically light water, derived from ablation, on a statewide basis. Unlike these two earlier events, the Port Huron ice advance established a moraine paralleling the current inland shorelines of Lake Huron and the northern half of Lake Michigan (Eschman, 1985). Subglacial recharge of isotopically light meltwater derived from the Port Huron ice would have been relegated to areas up ice flow from the proximal ice margin and proglacial lakes bordering the distal ice margin, including the Saginaw Lowlands area and Saginaw Bay.

Proglacial lakes can inhibit the formation of permafrost (Cutler et al., 2000), resulting in a geologic substrate that is more receptive to subglacial recharge. The earliest stratigraphic record that documents proglacial lakes occupying the Great Lakes basins corresponds to the retreat of the Nissouri phase (Karrow et al., 2000; Larson and Schaetzl, 2001). The Port Bruce ice probably advanced over a proglacial lake in the Huron basin (Karrow, 1984) and established glacial Lake Arkona upon retreat (Larson and Schaetzl, 2001). The Port Huron ice advanced over proglacial Lake Saginaw in the Huron basin and Lake Whittlesey in the Erie basin (Larson and Schaetzl, 2001). The presence of proglacial Lake Saginaw existing prior to and after the establishment of the Port Huron moraine provided a substrate receptive to subglacial recharge from meltwater collecting under the ice behind the proximal ice margin.

Abundant glacial meltwater was trapped at the base of the Laurentide ice sheet behind a frozen ice margin in a zone of ice with mixed frozen-bed and wet-bed conditions, giving rise to drumlin fields commonly associated with eskers (Stanford and Mickelson, 1985). The mixed frozen-bed and wet-bed zone most likely corresponded to a region of overridden permafrost extending 60–200 km upstream from the glacial margin that gradually began to thaw, releasing stored subglacial water (Cutler et al., 2000). If permafrost conditions were minimized due to the presence of proglacial lakes prior to the ice advance, wet-bed conditions would prevail soon after a frozen ice margin was established. For much of the Laurentide ice sheet, the ice margin within ~5 km of the ice edge experienced a frozen-bed condition because the glacier bed experienced diminished insulation from the thinning ice; localized tunnel channels and eskers tapped the meltwater zone up-ice (Colgan, 1999). The zone of meltwater behind the frozen ice margin would have been limited to areas where the ice was thick enough to insulate the base, yet thin enough to allow surface meltwaters to seasonally reach the base of the ice through crevasses and/or moulins. All three late Wisconsinan ice advances known to cover the study area would have brought this frozen-bed margin/zone of meltwater through the Saginaw Lowlands area during advance; however, only the Port Huron ice advance established a moraine in the area, indicating that the zone of meltwater was in position long enough to subglacially recharge the Saginaw Bay and Saginaw Lowlands area groundwater system.

Conditions for Subglacial Recharge: The Ice Profile

Subglacial recharge is usually accompanied by an increase in head resulting either from hydraulic loading or from a glacial ice-supported rise in the water table. With hydraulic loading, a portion of the total ice-loading stress is borne by the pore fluids. The increase in head occurs relatively instantaneously with the ice load. In their transient model of ice-induced hydraulic loading, Provost et al. (1998) apportioned the total ice load between the substrate and the subsurface fluids using a loading efficiency term. A loading efficiency term of 1.0 corresponds to 100% transmission of the ice load into a hydraulic load, with a corresponding increase in head equivalent to 91% of the ice thickness. Breemer et al. (2002) point out that the effective pressure, i.e., the difference between the ice load and the hydraulic load, must be greater than zero to prevent ice flotation. An effective pressure close to zero implies that the hydraulic loading is close to the total ice load. Breemer et al. (2002) showed that for the Michigan lobe of the Laurentide ice sheet, excess fluid pressures were relieved through a subglacial drainage system and that for thin ice, effective pressure was close to zero even when the effects of subglacial drainage were maximized. Hydraulic loading can occur without subglacial recharge and vice versa. However, the Laurentide ice sheet most likely supported a water table that rose from the ice margin as a function of the englacial hydraulic properties of the ice-aquifer system and leakance of the

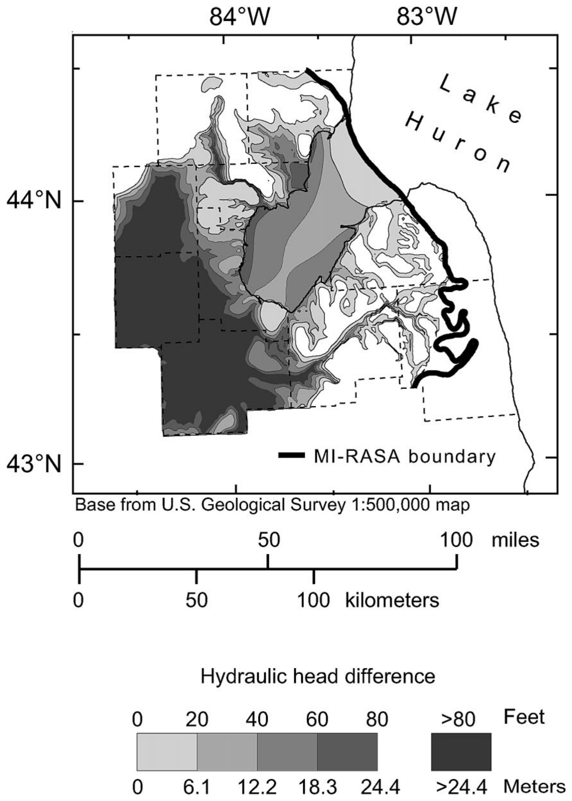


Figure 3. Distribution of hydraulic head difference between Glaciofluvial and Marshall aquifers (modern flow conditions). Positive values (shaded areas) denote areas where head in the Marshall aquifer unit exceeds head in the Glaciofluvial aquifer unit.

base of the ice into the substrate. An increase in the substrate head propagates by pressure diffusion and eventually reaches a steady state. Breemer et al. (2002) showed that subglacial aquifers under the Lake Michigan lobe equilibrated to steady state relatively quickly, taking 1000 yr to achieve 97% of steady state but 500 yr or less to achieve 80%. For both hydraulic loading and/or a raised water table supported by the glacial ice, an increase in head is applied to the substrate with the subglacial recharge. The increase in head is a function of the ice thickness.

The extent of hydraulic loading resulting from the overriding ice sheet depends upon conditions of the ice profile. When ice is present and actively flowing with a condition of constant basal shear stress, τ, the Nye equation (Nye, 1952) is used to solve for the ice profile assuming small ice slopes. The ice profile is described by a quadratic equation given in the following relation (Nye, 1952; Mathews, 1974):

$$y = \left(\frac{2\tau}{\rho g}x\right)^{1/2} = Ax^{1/2},$$

where x is the minimum distance from the ice margin to the profile point (in meters), y is the thickness (in meters), and A is an ice-profiling coefficient (in square root meters; $m^{1/2}$). Assuming a constant basal shear stress, τ, of 100 kPa, i.e., the condition of perfect plasticity for the ice, the coefficient A has a value of 4.7 $m^{1/2}$, which fits observed portions of both the Greenland ice cap and the Antarctic ice sheet (Nye, 1952).

The magnitude of A varies from glacier to glacier (Mathews, 1974). The greater the value (approaching 4.7 $m^{1/2}$), the more the ice profile matches the expected value for ice deformation without basal sliding. Ice deformation in the absence of basal sliding implies the presence of frozen-bed conditions that can halt meltwater production at the base of the ice sheet, thereby limiting the amount of water available for ice-to-groundwater recharge (Paterson, 1981). Frozen bed conditions might also prevent recharge to the underlying aquifers by inhibiting communication with local meteoric water (Beyerle et al., 1998). The value of A is generally lesser for warmer ice where enhanced basal sliding, from excess meltwater at the base of the ice, modifies the ice profile.

The ice-profiling coefficient (A) for the Pleistocene Laurentide ice sheet varied regionally from 0.32 to 4.1 (Mathews, 1974). Hughes et al. (1981) modeled the Nissouri ice advance (maximum 18 ka) using a thick ice sheet reconstruction, whereas subsequent studies invoked a thin ice sheet reconstruction (Boulton et al., 1985; Fisher et al., 1985). Using the thickness of the center of each reconstruction at the same point from the ice margin (15°, or 1665 km), the thick and thin reconstructions yield values of 2.7 $m^{1/2}$ and 1.8 $m^{1/2}$, respectively, for the ice-profiling coefficient. The deviation of these values from the frozen-bed condition of 4.7 $m^{1/2}$ suggests there was enhanced basal sliding and lowering of the ice profile because of an ample water supply at the base of the ice sheet. Modeling glacio-isostatic rebound, Clark et al. (1994) found that the thin ice reconstruction resulted in the best fit between isostatic rebound modeling results and observed lake outlet and shoreline chronologies, although the thin reconstruction slightly underestimated the amount of tilting.

Ice-induced Hydraulic Loading Model Construction

The Port Huron ice advance was modeled hydrologically using MODFLOW (McDonald and Harbaugh, 1988), the existing RASA model, and an ice-sheet reconstruction to evaluate the effect of ice-induced hydraulic loading on the Saginaw Lowlands area and Saginaw Bay. The paleohydrologic model used the same grid, grid extent, and aquifer properties as the original RASA model. The position of the Port Huron moraine was digitized to reconstruct the ice sheet and simulate the effects of the Port Huron ice advance (Hoaglund, 1996). The minimum distance from the nodal center to the moraine was calculated for each cell in the RASA model. For the ice-covered nodes, the ice thickness was calculated using the quadratic relation of Mathews (1974). The thin ice reconstruction was used to generate ice thicknesses of the Port Huron advance that were consistent with the findings of Clark et al. (1994) and to apply a conservatively small load to the hydrologic system. The equivalent hydraulic load was determined from the product of the ice thicknesses and the ice density (0.91). This hydraulic load was added to modern land-surface elevations, including 177 m (580 ft) for the Great Lakes, to calculate the equivalent hydraulic loading head, assuming a loading efficiency of 100%.

The ice-induced hydraulic loading heads were introduced to the model as a layer 1 source bed; nodes were active in the region of the ice sheet with heads specified to the loading heads. Nodes were inactive in the ice-free region. The Glaciofluvial aquifer (layer 1 in the RASA model for present-day conditions) became layer 2. In the upper active layer, recharge of the RASA model was specified to layer 1 in the ice-sheet region of specified heads, where it was ''neutralized'' as part of the specified head, and to layer 2 in the ice-free region. Active nodes, the outer edges of which were automatically bounded by MODFLOW with no-flow boundaries, replaced the Glaciofluvial aquifer specified-head boundaries in the region overlain by ice. The Glaciofluvial aquifer-specified heads in the ice-free region remained unchanged at 177 m (580 ft) along the current Great Lakes shoreline.

In the RASA groundwater-flow model, modern Parma-Bayport heads closely match heads in the overlying Saginaw aquifer, and hydraulic communication between the Saginaw aquifer and the Marshall aquifer is controlled by the Michigan confining unit (below the Parma-Bayport) rather than by the Saginaw confining unit (above the Parma-Bayport). The Parma-Bayport aquifer was therefore eliminated to simplify groundwater flow simulations during the Pleistocene. The ice-induced hydraulic load was placed directly on the substrate, assuming that leakance was defined by the vertical hydraulic properties of the subglacial Glaciofluvial aquifer. All other vertical communications between the respective ice-induced, hydraulic-loading model layers were considered the same as in the original RASA model, except that the elimination of the Parma-Bayport aquifer required a new definition of the vertical communication between the Saginaw aquifer and the Marshall aquifer. In the ice-induced hydraulic-loading model, the vertical communication between the Saginaw and Marshall aquifers was controlled by the properties of the least hydraulically conductive unit in series, i.e., the Michigan confining unit.

RESULTS

Flow-model Results: Modern Hydrologic System

The groundwater model was calibrated to a statewide data set of Glaciofluvial, Saginaw, and Marshall aquifer heads and river flows (Hoaglund et al., 2002b). Discharge into Saginaw Bay is largely controlled by Glaciofluvial and Marshall aquifer heads while the interbedded Saginaw aquifer pinches out close to shore. Thus, Glaciofluvial and Marshall aquifer heads within the study area were analyzed to assess model reliability in the Saginaw Lowlands discharge area. Forty head targets within the Glaciofluvial aquifer had average and root mean square residuals of −7.6 m and 14.6 m, respectively, for heads ranging from 177 m to 381 m. Twenty-six head targets within the Marshall aquifer had average and root mean square residuals of −7.0 m and 18.9 m, respectively, for heads ranging from 610 to 1175 ft. The negative residual averages reflect a regional bias in the model where simulated head in the regional discharge areas is higher than measured head because the recharge estimation did not take into account gains from deep seepage (Hoaglund et al., 2002a).

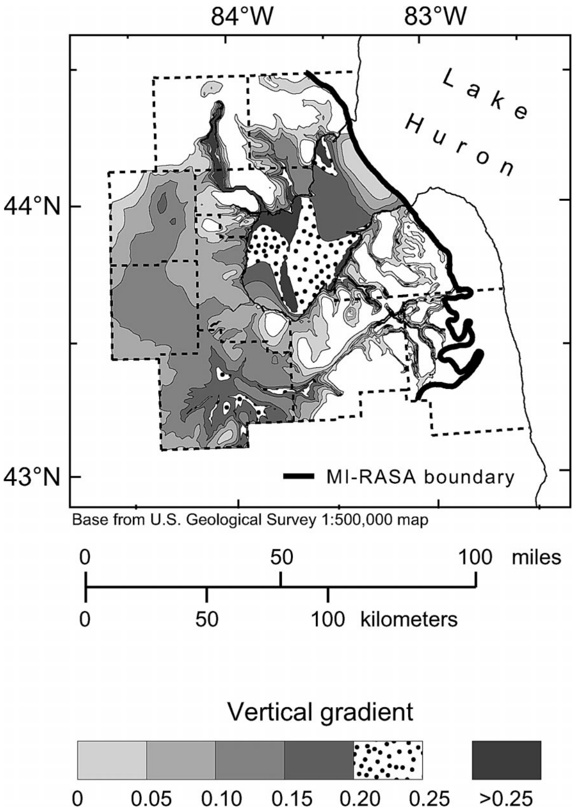


Figure 4. Distribution of vertical hydraulic gradients between Glaciofluvial and Marshall aquifer units (modern flow conditions). Positive vertical gradients (shaded areas) correspond to regions of upward groundwater flow.

After model calibration, the simulated heads in the Glaciofluvial aquifer were subtracted from those in the Marshall aquifer to produce a difference-in-head map of the study area (Fig. 3). The positive values of the plotted differences indicate that for most of the study area, including all of Saginaw Bay, the modern heads in the Marshall aquifer are greater than those in the Glaciofluvial aquifer. The unshaded portion of the study area denotes locations where negative differences were obtained, indicating that simulated heads in the Marshall aquifer were less than those in the Glaciofluvial aquifer. In the groundwater-flow model, heads in the portion of the Glaciofluvial aquifer bounded by Saginaw Bay were specified equal to the present elevation of Saginaw Bay (177 m; 580 ft), while simulated Marshall aquifer heads are ~3 m (10 ft) to as much as 21 m (70 ft) higher than the modern lake elevation. This disparity indicates the potential for upward groundwater flow from the Marshall aquifer into Saginaw Bay. Within Saginaw Bay, the smallest, positive difference-in-head values are found in a trough extending northeast to southwest along the bay axis.

The difference-in-head map does not take into account the depth to the Marshall aquifer, which shallows considerably over the crest of the presumed anticline. The driving force for groundwater flow is therefore better represented by the vertical gradient, which incorporates these changes in stratigraphic elevation between the Marshall and Glaciofluvial

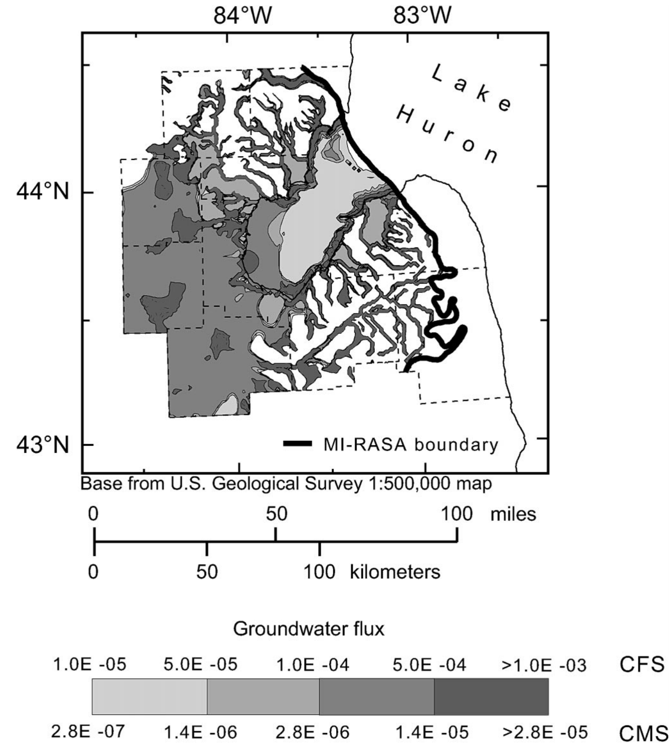


Figure 5. Spatial variation in groundwater flux from bedrock aquifers into the Glaciofluvial aquifer (modern flow conditions). CFS—cubic feet per second; CMS—cubic meters per second.

aquifers. The difference in depth between the geometric centers of the reconstructed aquifers was used to calculate the vertical gradients between these two aquifers (Fig. 4). The largest vertical gradients determined between the Marshall and Glaciofluvial aquifers ranged from 0.20 to 0.30. These vertical gradients are found along a crest coincident with the contact between the Saginaw and Parma-Bayport aquifers and the Michigan confining unit, and the associated anticlinal axis (Fig. 4). Thus, the drive for groundwater flow is actually greatest immediately underneath Saginaw Bay, where the anticline brings the Marshall aquifer close to the bottom of Saginaw Bay. Direct observations of vertical gradient were unavailable either for calibration or for evaluating model reliability. Furthermore, lacking vertical stresses in the regional calibration, the model was relatively insensitive to the vertical conductivity that greatly affects the calculation of vertical gradient. However, the magnitudes of the predicted vertical gradients compare favorably to gradients measured directly in benthic sediments elsewhere in the Great Lakes' region, including offshore Lake Michigan (0.180–0.350; Cartwright et al., 1979) and Hamilton Harbour, western Lake Ontario (0.430; Harvey et al., 2000).

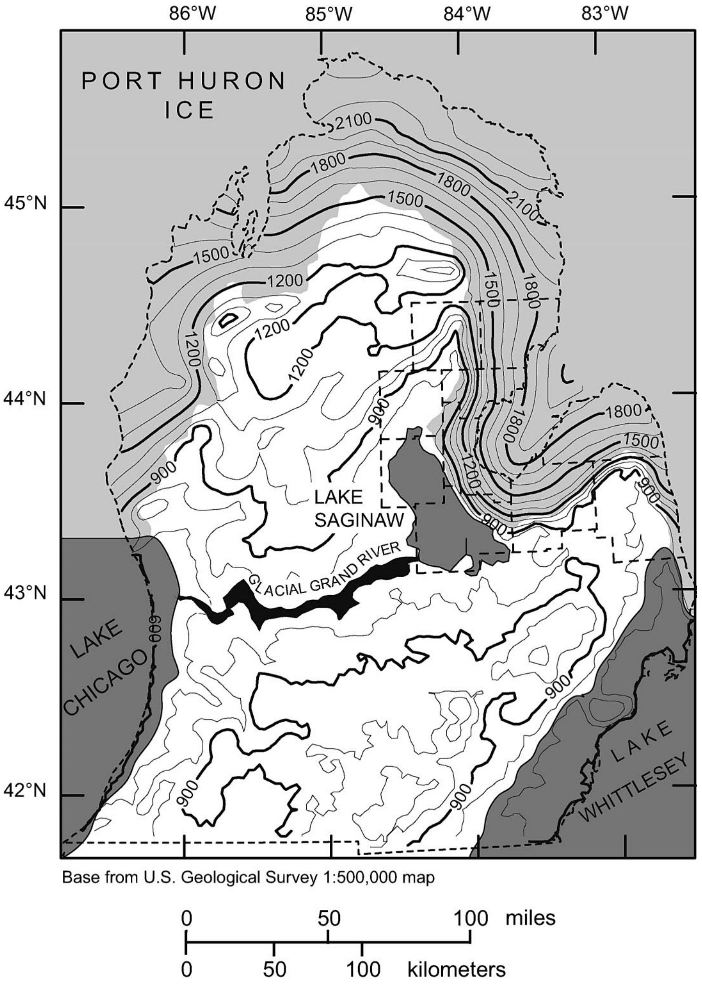
Model-calculated groundwater fluxes between the inner bay, corresponding to the subcrop of the Saginaw and Parma-Bayport aquifers, and the outer bay, corresponding to the subcrop of the Michigan confining unit and Marshall aquifer, vary by more than an order of magnitude (Fig. 5). This disparity in groundwater flux is due in part to the difference in the vertical hydraulic conductivity assigned to the Saginaw aquifer versus that assigned to the Michigan confining unit. The groundwater flux through bottom sediments up into Saginaw Bay can be approximated using the sum of the flux estimates to the base of the Glaciofluvial aquifer flooring the bay. The total calculated basal discharge from Saginaw Bay benthic sediments is ~0.028 m^3s^{-1} (~1 cfs). Solute transport in Saginaw Bay benthic sediments is likely dominated by diffusive rather than advective transport, given this modest groundwater flux. This supposition is consistent with findings from a previous study in which one-dimensional transport models indicated that diffusion alone could account for the observed gradients in porewater chemistry from Saginaw Bay sediments (Kolak et al., 1999).

In addition to groundwater discharge from the basal sediments to the floor of Saginaw Bay, groundwater discharge from the Glaciofluvial aquifer to the shoreline was calculated (Hoaglund et al., 2002a). Shoreline groundwater discharge to Saginaw Bay was estimated by summing the groundwater flux from the Glaciofluvial aquifer to the specified head cells peripheral to the bay. Using this procedure, the model estimate for shoreline groundwater discharge to the shoreline of the bay is on the order of 1.13 m^3s^{-1} (~40 cfs). The discharge per length of shoreline in Saginaw Bay is considerably smaller than the rest of the lower peninsula shoreline (Hoaglund et al., 2002a). Thus, despite that groundwater flow is generally focused toward embayments (Cherkauer and McKereghan, 1991) and that the Saginaw Bay area is generally regarded as a regional discharge area (Mandle and Westjohn, 1989; Hoaglund, 1996), the rate of groundwater discharge directly into Saginaw Bay is actually very small.

Modeling Results: Paleohydrologic System

The simulated heads in the Glaciofluvial aquifer (Fig. 6) show that the effect of ice-induced hydraulic loading is localized to the region of the ice sheet and its proglacial margin. In this region, model results indicate that groundwater flow during the Pleistocene Port Huron ice advance is reversed from the present condition. The 213 m (700 ft) head contour in the Glaciofluvial aquifer encloses a large region located southwest of Saginaw Bay that drained toward the ice (Fig. 6). Proglacial Lake Saginaw (slightly higher than 212 m, or 695 ft) was regulated by the Glacial Grand River outlet (Eschman and Karrow, 1985) and drained down the Glacial Grand River to the Glenwood level of Glacial Lake Chicago in the modern Lake Michigan Basin (Hansel et al., 1985).

In response to the ice-induced hydraulic load, the heads in both the Saginaw and Marshall bedrock aquifers increased in the areas overlain by the proglacial lake and the ice sheet. Heads in the Glaciofluvial aquifer, however, increased only in that area overridden by the ice sheet. Underneath Glacial Lake Saginaw, the heads in the two bedrock aquifers were considerably higher than those in the Glaciofluvial aquifer. Thus, in response to the ice-induced hydraulic loading, the vertical gradients between the Glaciofluvial and Marshall aquifers generally induced a strong, downward component of flow beneath the ice sheet (Fig. 7) and an upward component of flow into Glacial Lake Saginaw. However, there are two noteworthy exceptions to this



Base from U.S. Geological Survey 1:500,000 map

Figure 6. Hydraulic head distribution (feet above mean sea level) within Glaciofluvial aquifer in response to ice loading (ca. 13 ka). Dark gray shaded areas denote approximate boundaries of proglacial lakes.

general model result. First, a portion of the western ice margin, corresponding to the north-south–trending ice margin, experienced upward gradients under the ice. Secondly, downward gradients corresponding to modern regional recharge areas are visible in the northwest and southeast portions of the ice-free region of the study area.

A similar groundwater-flow pattern would have developed between the Saginaw and Glaciofluvial aquifers. The groundwater flux between the Glaciofluvial and Saginaw aquifers, however, would have been considerably greater than that between the Glaciofluvial and Marshall aquifers, the latter of which is impeded by the Michigan confining unit. The simulation results demonstrate that ice-induced hydraulic loading would have been a very effective mechanism for introducing isotopically light meltwater from the ice sheet deep into the aquifer system.

DISCUSSION

Output from the ice-induced, hydraulic-loading model indicated that conditions during the Port Huron ice advance were favorable for the emplacement of isotopically light meltwater into the study area. This meltwater would have been recharged to the aquifer system directly under the ice (Saginaw Bay) and through to proglacial Lake Saginaw (Saginaw Lowlands area). Given that the Marshall aquifer likely contained saline water or brine at this time, some degree of mixing would have taken place. This mixing process could have produced a saline, isotopically light water similar in composition to that presently found within the subcrop of the Marshall aquifer. A similar process has been used previously to explain the distribution of saline, isotopically light water found elsewhere in the Michigan Basin (Weaver et al., 1995), the Illinois Basin (Steuber and Walter, 1994), and the Canadian Shield (Clark et al., 2000). Thus, the process for generating saline, isotopically light water in the present study area appears plausible, but further analysis is needed to address the timing and extent of this mechanism. The model results must be viewed in the context of both the present spatial variations in porewater and groundwater chemistry and the structural/stratigraphic relationships among the aquifers to further constrain the hydrologic evolution of this system.

Solute Sources: Mixing Scenarios

Model results for the modern hydrologic flow system indicate that water masses within the study area are relatively stagnant, particularly under Saginaw Bay. Thus, the geochemical signal retained in porewater samples may prove particularly useful in elucidating the extent of interaction between water masses. In this study, possible mixing relations between brine and three freshwater end members are constrained using chloride concentrations and δ^{18}O values (Fig. 8A and B), both of which are assumed to behave conservatively in this system. The brine end member composition is taken from a groundwater sample collected from the Marshall aquifer that contained 190,000 mg L^{-1} Cl^{-} and had a δ^{18}O value of −1.85‰ (Dannemiller and Baltusis, 1990; Midland County, well #14, p. 100–103). This brine end member is considered intermediate in terms of its chloride and δ^{18}O composition: δ^{18}O values in brines from the Marshall aquifer range from ~–5‰ to 1‰, and chloride concentrations can exceed 250,000 mg L^{-1} (Ging et al., 1996). All three freshwater end members were assigned a chloride concentration of 1 mg L^{-1}; however, each had a distinct δ^{18}O signature. The δ^{18}O values of −8 and −10‰ were used to bracket the range of values found in local, mean modern meteoric precipitation (Sheppard et al., 1969; Machavaram and Krishnamurthy, 1994). A δ^{18}O value of −20‰ was used to represent the isotopic composition of the glacial meltwater, although meltwater from the Laurentide ice sheet may have been significantly lighter (Dansgaard and Tauber, 1969).

From these end members, three curves were generated depicting the mixing relations between brine and freshwater (Fig. 8A). The combination of the three curves generally brackets all Saginaw Bay and Saginaw Lowlands area porewater samples, supporting the idea that brine and freshwater mixed to produce the observed geochemical variations among these samples. At lower chloride con-

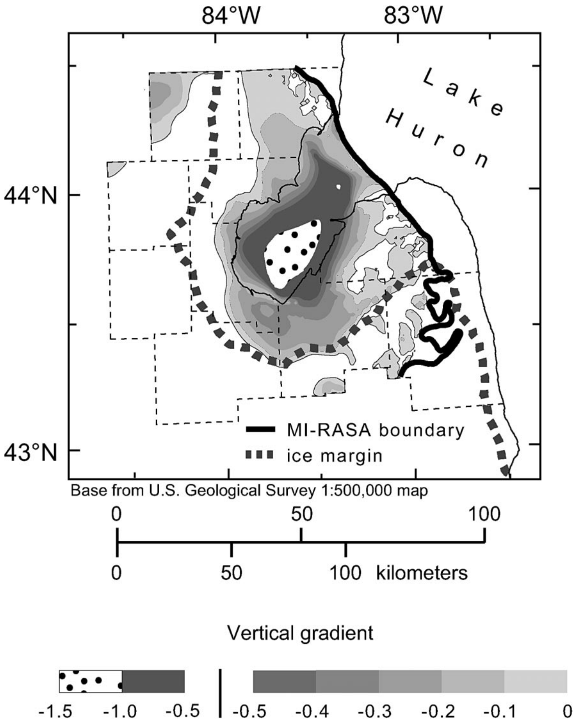


Figure 7. Vertical gradients between Glaciofluvial and Marshall aquifer units in response to ice loading. Negative values denote areas where flow direction is into the Marshall aquifer unit. The unshaded portions of the study area indicate locations where flow direction is from the Marshall aquifer unit up into shallower units.

centrations, the porewater samples and Saginaw Bay water column samples appear to overlap, implying that modern meteoric water is a common end member. The gray field (Fig. 8A) represents the geochemical variations among groundwater samples from the Glaciofluvial aquifer (Wahrer, 1993). As expected, this gray field also encompasses the porewater samples, which were obtained by squeezing core segments in a compressor, from the Saginaw Lowlands area cores. However, the porewater samples obtained from Saginaw Bay cores do not plot in this field. The porewater samples from the Saginaw Lowlands area and Saginaw Bay sediments do not appear to have followed the same mixing pathway, although a comparable process, i.e., mixing between freshwater and brine, may have affected the porewater samples from both sets of sediment cores.

The data in Figure 8A do not plot along the mixing curves, apparently precluding the scenario in which brine and freshwater mixed directly and produced the geochemical signature retained in porewater from Saginaw Lowlands area cores. A multiple-event mixing scenario was therefore investigated to better account for the observed variations in water chemistry. Previously, a multi-stage mixing model was used to explain groundwater chemistry variations within Devonian formations of the Michigan Basin (Weaver et al., 1995). In the present study, the mixing relations between the brine end member (B) and a subglacial recharge component (III) were modeled, producing three water masses (X, Y, and Z) of intermediate composition (Fig. 8B). Each intermediate water mass was subsequently mixed with a modern meteoric freshwater end member (I). The mixing relations generated from this secondary dilution are plotted as dashed curves (Fig. 8B). Porewater samples from Saginaw Lowlands area core C (Fig. 8B; bold squares) plot along one of the secondary dilution curves (mixing trend I-X). This finding indicates that the geochemical gradients observed in porewater samples collected from core C may be the result of a two-stage mixing process. Mixing between a saline, isotopically light water (X) and a modern meteoric freshwater (II) could account for the chemistry of the remaining Saginaw Lowlands area porewater samples.

Several mixing scenarios could account for the variations in porewater geochemistry among the Saginaw Bay samples. For example, the geochemical signatures of the porewater samples could be described by mixing modern meteoric water with saline groundwater (Fig. 8B; mixing trend I-Y). Alternatively, Saginaw Bay porewater samples may be communicating with brine at depth (Fig. 8B; mixing trend I-Z). However, the chloride concentrations documented in groundwater from the Marshall aquifer (Ging et al., 1996) along either flank of Saginaw Bay generally are sufficiently low ($<$1,000 mg L^{-1} Cl) as to render unlikely a scenario that directly involves brine. Regardless, the data plotted in Figure 8B apparently indicate that distinct mixing trajectories are needed to produce the porewater chemistry documented in the Saginaw Bay cores and in the Saginaw Lowlands area cores.

At comparable chloride concentrations, Saginaw Bay porewaters have significantly heavier $\delta^{18}O$ values than porewaters from the Saginaw Lowlands area. This difference in $\delta^{18}O$ values may be an indication that glacial meltwater preferentially recharged the surrounding Saginaw Lowlands area relative to Saginaw Bay. If true, this finding is noteworthy given that the hydraulic gradient established during ice loading would have favored subglacial recharge through the Saginaw Bay floor. The disconnection between modeled hydraulic gradients and observed geochemical signals implies that regional geologic controls regulated the amount and distribution of recharge during the Port Huron ice advance.

Inferred Geologic Controls on Groundwater/Large-lake Interactions

Model results for the modern hydrologic system indicate that the rate of groundwater discharge to the bottom of Saginaw Bay is strongly influenced by subcrop lithology. For example, the vertical groundwater flux to the bottom of Saginaw Bay (Fig. 5) from the sandstone aquifers (Saginaw, Parma-Bayport, and Marshall aquifers) is significantly greater than from the Michigan confining unit. The Michigan confining unit, which overlies the Marshall aquifer and floors most of Saginaw Bay, is known to compartmentalize the major sandstone aquifers throughout the lower peninsula of Michigan. As a result, the Michigan confining unit plays a considerable role in the distribution of freshwater, saline water, and brine elsewhere in the basin. For example, the presence of brine in the Marshall sandstone aquifer corresponds to areas where the Michigan confining unit overlies the Marshall aquifer. Conversely, the Marshall aquifer generally contains freshwater in regions where the Michigan confining unit is absent and a direct hydraulic connection exists between the Mar-

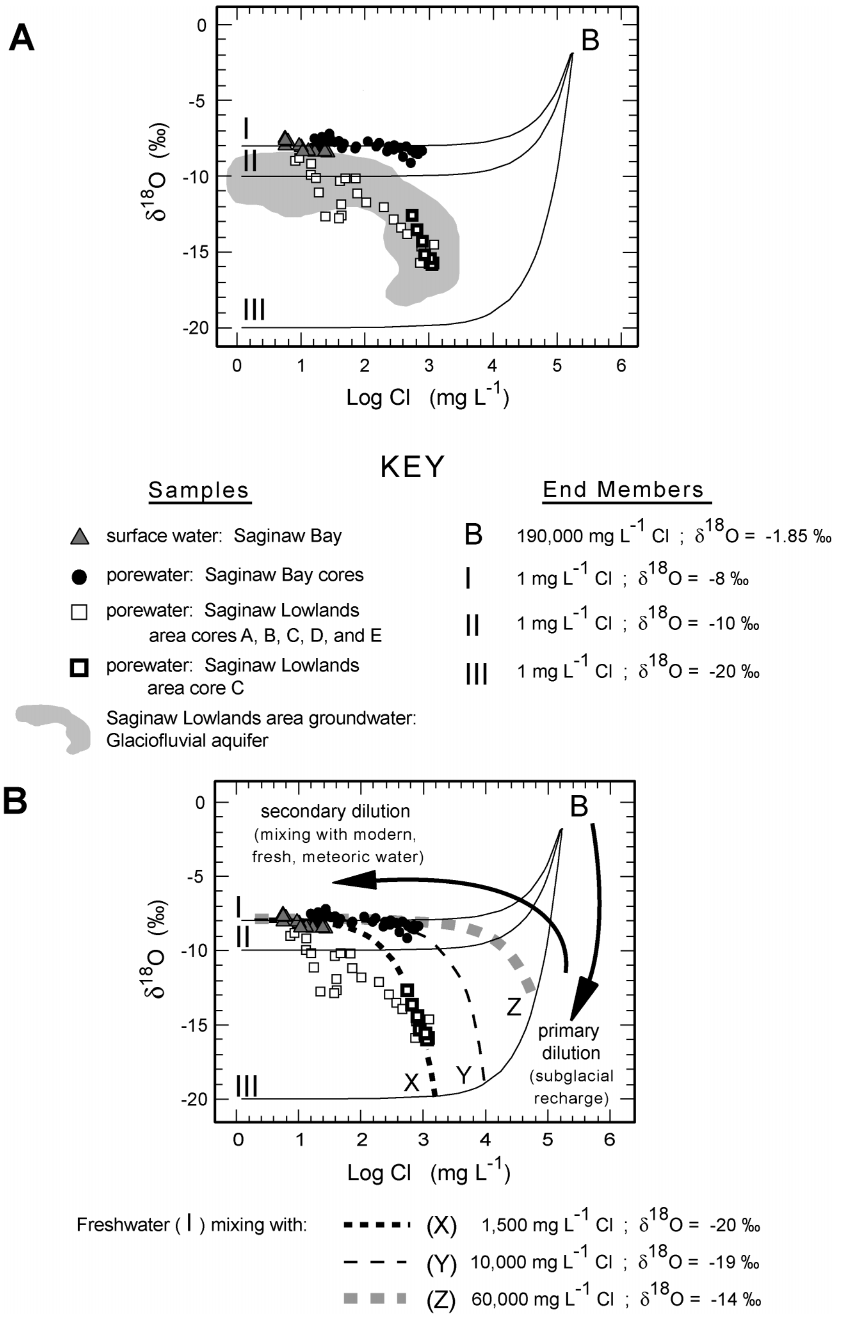


Figure 8. (A) Results of single-stage mixing event between Michigan Basin brine and dilute end members. (B) Results of multi-stage mixing scenario between Michigan Basin brine, intermediates, and dilute end members.

shall aquifer and Pleistocene glacial deposits (Westjohn and Weaver, 1996c). Westjohn and Weaver (1996c) also stated that the transition zone from freshwater to brine within the Marshall aquifer typically ranges from 24 to 80 km in width but can be significantly narrower, particularly down-dip along the limbs of anticlinal structures, where the transition zone ranges in width from 3.2 to 6.4 km.

Given the observations of Westjohn and Weaver (1996c), the presence of a northwest-trending anticline under Saginaw Bay would likely control the distribution of freshwater and brine in the Marshall aquifer below the bay. The anticlinal reconstruction assumed in the groundwater-flow model is coincident with extensions of anticlinal structures observed on land, as interpreted by Cohee et al. (1951) and Lane and Hubbard (1895). Cvancara and Melik (1961) do not explicitly mention the presence of an anticline under Saginaw Bay; however, one can infer the existence of such a feature from their reconstruction of the bedrock geology of Lake Huron.

Other interpretations of Saginaw Bay subsurface geology have been proposed, including a northeast-trending graben (Herman et al., 1991). The graben reconstruction includes Saginaw Bay and extends southwesterly through most of the Saginaw Lowlands area. The graben interpretation is based on geophysical and stratigraphic relations involving horizons below the Coldwater shale, which constitutes the base of our groundwater flow model. However, the possible propagation of growth faulting into younger strata might imply that the edges of the bay are fault-bounded, with the Marshall aquifer dropped down in the bay relative to the mainland and ‘‘thumb’’ regions of Michigan. The continuity of groundwater flow from the mainland to the bay would be disrupted by any existing faults. The faults themselves could provide hydraulic conduits to the deeper aquifers and could enhance either recharge or discharge.

Either reconstruction must take into consideration the northeastward pinch-out of the Michigan formation, which results in the Marshall aquifer subcrop present below the outer portion of Saginaw Bay. This pinch-out would lead to a direct hydraulic connection between the Marshall aquifer and the overlying glacial deposits that floor Saginaw Bay. Where such a connection exists, the Marshall aquifer subcrop in Saginaw Bay would likely bear freshwater. Once confined by the Michigan formation, the salinity of groundwater in the Marshall aquifer likely increases down the regional dip southwest toward the center of the basin. As the transition from freshwater to brine is controlled by the Michigan confining unit, the salinity would be further affected by any anticlinal and/or fault structures across the bay.

Fractures resulting from the anticlinal and/or fault structures could play a significant role in regulating Saginaw Bay porewater chemistry. For example, Kolak et al. (1999) noted that the Saginaw Bay sediment cores containing the strongest chloride concentration gradients in porewaters, stations 4, 7, and 24, occurred along a linear trend through the bay (Fig. 1). In addition, the core with the strongest chloride concentration gradient (station 7) mapped near a core with a very weak chloride concentration gradient (station 17), suggesting that fractures facilitated the enhanced salinity encountered in cores 4, 7, and 24. Fractures might be responsible for increasing the concentration of the chloride source at depth in the sediment column, even though the chloride concentration gradients in these benthic sediments are apparently dominated by diffusive transport. For example, fractures associated with regional joint trends and/or joints associated with the presumed anticline may have formed in the underlying Michigan confining unit, providing a conduit between a high-chloride source and the sediments flooring Saginaw Bay. The Saginaw Bay sediment cores containing high porewater chloride concentrations at depth are aligned in a southwest to northeast direction, orthogonal to the anticlinal axis. This orientation is consistent with principal stress fractures that would have developed during the formation of the anticlinal structure.

Fractures associated with the Michigan confining unit not only appear to presently regulate the degree of communication between Saginaw Bay sediments and the high-chloride source at depth in the Marshall aquifer, they also appear to have previously influenced the extent of recharge into the Marshall aquifer from the Port Huron ice lobe. Clark et al. (2000) show that subglacial recharge is capable of displacing brine through a fracture plane in a bedrock aquifer, assuming a direct hydraulic connection between the bedrock aquifer and the overlying glacial ice. In our study area, the Michigan confining unit may have buffered the influence of subglacial recharge, and brine displacement within the Marshall aquifer would likely have been subdued except in areas where the Michigan confining unit is fractured. For example, Ging et al. (1996) document the presence of isotopically light ground water (less than −11‰) in the Marshall aquifer on both the northwest and southeast shores of Saginaw Bay (Fig. 9). These areas are generally overlain by the Michigan confining unit and appear highly correlated to the distribution of downward vertical gradients generated by the ice-induced, hydraulic-loading model (Fig. 7). Nevertheless, the lightest δ^{18}O values documented in groundwater from the Marshall aquifer are still heavier than values recorded for groundwater from the Glaciofluvial (Wahrer et al., 1996) and Saginaw aquifers (Meissner et al., 1996), implying that the Marshall aquifer received a smaller component of subglacial recharge than the other two aquifers. The Michigan confining unit may have limited the extent of glacial meltwater recharge into the Marshall aquifer during the Pleistocene. Presently, the Michigan confining unit limits the amount of groundwater discharging into Saginaw Bay from the Marshall aquifer. In doing so, the Michigan confining unit has preserved beneath the bay a source of relatively high chloride groundwater that was ultimately derived from Michigan Basin brine.

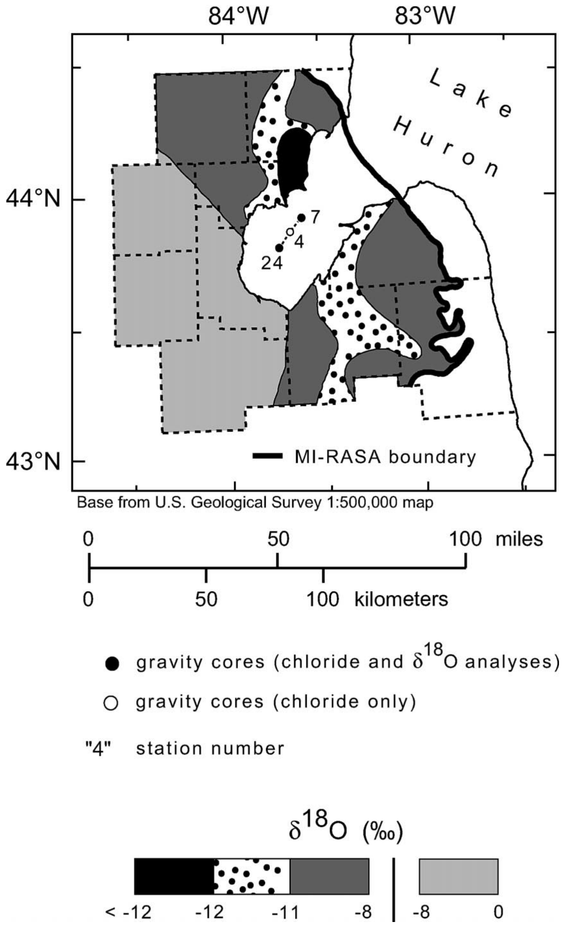


Figure 9. Distribution of δ^{18}O values measured in groundwater from the Marshall aquifer unit (modified from Ging et al., 1996). Locations of Saginaw Bay sediment cores 24, 4, and 7 (cores with highest porewater-chloride concentrations) are plotted for comparison.

CONCLUSIONS

A modern groundwater-flow model and a Pleistocene ice-induced hydraulic loading model were coupled to investigate the extent of modern and Pleistocene interactions between groundwater and large lakes in the Saginaw Bay (Lake Huron) area. Modern groundwater discharge from the Glaciofluvial aquifer to the lake shoreline is relatively low because of low gradients across the Saginaw Lowlands area and low hydraulic conductivities of the clay-rich lodgement tills and glaciolacustrine clays. Bedrock geology immediately below glaciofluvial deposits in the Saginaw Lowlands and Saginaw Bay areas strongly influenced groundwater mixing during the Pleistocene and presently regulates groundwater discharge and geochemistry. The highest vertical gradients between the Marshall and Glaciofluvial aquifers occur along an anticlinal crest coincident with the contact between the Saginaw and Parma-Bayport aquifers with the Michigan confining unit. The groundwater flux to the region of Saginaw Bay underlain by the Michigan confining unit is an order of magnitude lower than the flux to the region underlain by the Saginaw aquifer. This disparity is due in part to the contrast in vertical hydraulic conductivity of the Saginaw aquifer versus that of the Michigan confining unit subcrop areas.

Modeling of ice-induced hydraulic loading from the Port Huron ice advance shows that hydraulic loading produced a groundwater-flow reversal localized to the region of the ice sheet and its proglacial margin. In response to hydraulic loading, vertical gradients between the heads simulated in the Glaciofluvial aquifer and both the Saginaw and Marshall bedrock aquifers show a general pattern of groundwater flow downward under the ice sheet and upward into proglacial Lake Saginaw. There is a strong relation between these areas of simulated downward vertical gradients and the isotopically light groundwater presently observed in the Marshall aquifer. Chloride concentrations and $\delta^{18}O$ values serve to constrain possible mixing scenarios between the water masses; a multi-event mixing scenario provides a plausible explanation of the geochemical signature observed in porewater samples from the Saginaw Lowlands area. The geochemical evolution of Saginaw Bay porewater samples is less well constrained, but it appears to have evolved along a different mixing trajectory. The Michigan confining unit plays a prominent role in both the geochemical evolution and present spatial variations of Saginaw Bay porewater chemistry. The Michigan confining unit appears to have limited the extent of subglacial recharge during the Pleistocene, particularly in the Saginaw Bay area, thus preserving a high-chloride source, derived from brine in the Marshall aquifer, below the bay. Fractures in the Michigan confining unit associated with an anticlinal structure presently regulate the degree of communication between Saginaw Bay sediments and the high-chloride source at depth.

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