Estimating basin brine fluxes to Lake Winnipegosis

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ABSTRACT
Lake Winnipegosis is situated at a regional discharge area for groundwater flow in the Williston Basin. In this study, the flux of solutes to the lake from the Williston Basin is estimated using a mass balance method. The amount of seepage to the lake is estimated using surface water hydrographs and an estimate of evaporation. The solute flux is then estimated using water chemistry samples from the rivers that contribute to and drain the lake. Results indicate that a significant amount of the Prairie Evaporite has been dissolved by subglacial recharge from the last glaciation.

RÉSUMÉ
Le lac Winnipegosis se situe dans une zone de décharge régionale de l'écoulement souterrain du bassin de Williston. Dans cette étude, le flux de produits dissouts du bassin de Williston vers le lac est estimé par une méthode de balance hydrologique. La quantité d'infiltration vers le lac est évaluée grâce aux hydrogrammes d'eau de surface et à l'estimation de l'évaporation. Le flux dissout est alors obtenu à l'aide de la chimie d'échantillons d'eau provenant des affluents et effluents du lac. Les résultats indiquent qu'une importante quantité de la formation Prairie Evaporite a été dissoute lors de la recharge en eau de fonte sous-glaciaire de la dernière glaciation.

1 INTRODUCTION

Lake Winnipegosis is a major lake located in western Manitoba. The lake is the second largest in Manitoba, with an area of 5370 km^2. The watershed that encompasses the lake includes several inputting rivers and a complex output system that eventually leads to Lake Manitoba. Along with the freshwater from the rivers, Lake Winnipegosis receives freshwater from precipitation and groundwater input from seeping basin brines from the Carbonate Rock aquifer (Figure 1; Grasby 2000, Grasby and Betcher 2002).

The objective of this study is to calculate the amount of basin brine flux into Lake Winnipegosis. This flux is an important indicator of formation water contribution to the surficial system in the area. Also, it would allow for calculations of the loss of bedded evaporites from the sub-surface due to groundwater flow.

2 REGIONAL GEOLOGY AND HYDROGEOLOGY

The study area consists of the carbonate rock aquifer within the Paleozoic outcrop in southern Manitoba and is found on the eastern margin of the Williston Basin. A portion of this aquifer acts as an important freshwater resource for Manitoba. The aquifer consists of carbonates with minor shales and evaporites that date from the Middle Ordovician to the Middle Devonian (Grasby and Betcher 2002). Even though here it is referred to as a single aquifer, technically it should be termed as an aquifer system since argillaceous sediments, along with slivers of shale and clay, act as cap rocks and aquitards throughout the carbonate sequence (Grasby and Betcher 2002).

2.1 Geological Setting

The Carbonate Rock aquifer consists of seven separate Formations including, but not restricted to: the Red River, Stoney Mountain, Interlake Group, and Prairie Evaporite Formations (Figure 2).

The Red River Formation is the oldest within the carbonate rock aquifer. It is separated into four members: Dog Head, Cat Head, Selkirk, and Fort Garry (McCabe and Bannatyne 1970). The geology consists of a basal sequence of shelf-type bioclastic dolomitic limestones with an upper layer of dolomitic limestones and lithographic to sublithographic dolomites (McCabe et al. 1993). The depositional environment was the subsidence of the Williston Basin. The entire Formation thins out rapidly towards the north.

The Stony Mountain Formation is dominated by dolostone with argillaceous dolostone, fossiliferous calcite, and red-, green-, and grey shales (Betcher et al. 1995). It has a lower sequence consisting of shale that is indicative of a marine depositional environment, along with upper sequences of dolomite, which are consistent with an intertidal environment. Like the Red River Formation, the Stony Mountain Formation thickens southward, and loses thickness rapidly northward, as dolomitization increases (McCabe 1971).

The Interlake Group Formation has a similar upper and lower sequence as the Stony Mountain Formation.

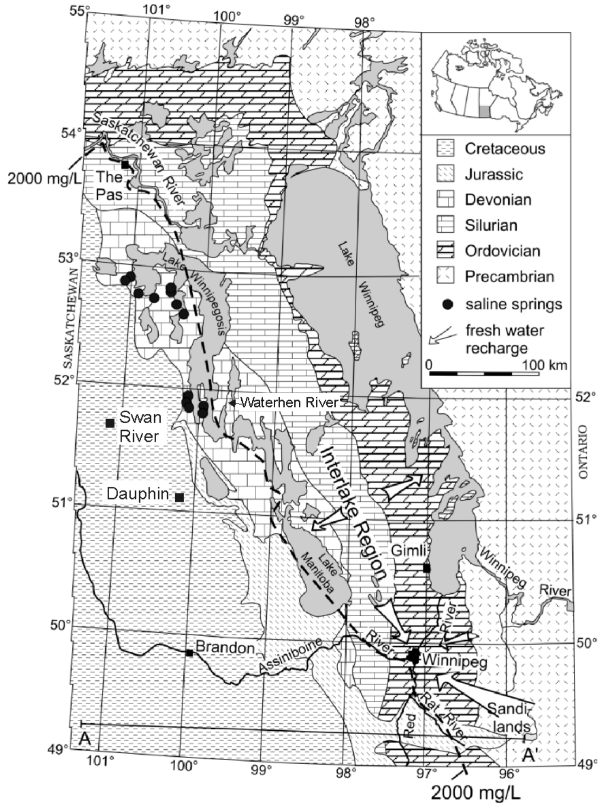

Figure 1: Locations of known salt springs shown on a regional map of southern Manitoba (after Grasby 2000).

The top of the Formation consists of a major pre-Middle Devonian unconformity surface (McCabe 1971). Since the Interlake Group Formation consists of dolostone and minor evaporites (Betcher et al. 1995), karst topography development is possible and has occurred in some areas. The depositional environment of the Formation extends from shallow marine to supratidal that is indicative of attaining equilibrium between subsidence and deposition (McCabe 1971).

The Prairie Evaporite Formation is the youngest of the four Formations mentioned here being Mid-Devonian in age. The bulk of the Formation is restricted to the subsurface, in the area west of the Winnipegosis fringing bank (McCabe 1971). In this area it consists of a 130 m thick sequence of halite beds with minor anhydrite. The Formation is restricted to the subsurface, and is bound in the north and west by a dissolution edge McCabe 1971).

2.2 Hydrogeological Setting

The carbonate rock aquifer is the fresh water-bearing portion of the Paleozoic outcrop belt in southern Manitoba. The fresh water-bearing portion of the aquifer is bound on the western edge by the hydrological divide defined by the Assiniboine, Rat, and Red Rivers respectively along with two major lakes: Lake Winnipegosis and Lake Manitoba. In the study area, the Carbonate Rock aquifer receives recharge through the tills in the Interlake area. To the west of Lake Winnipegosis hydrological divide the salinity of the aquifer increases rapidly to the point of typical formation brines of the Williston Basin (Grasby 2000).

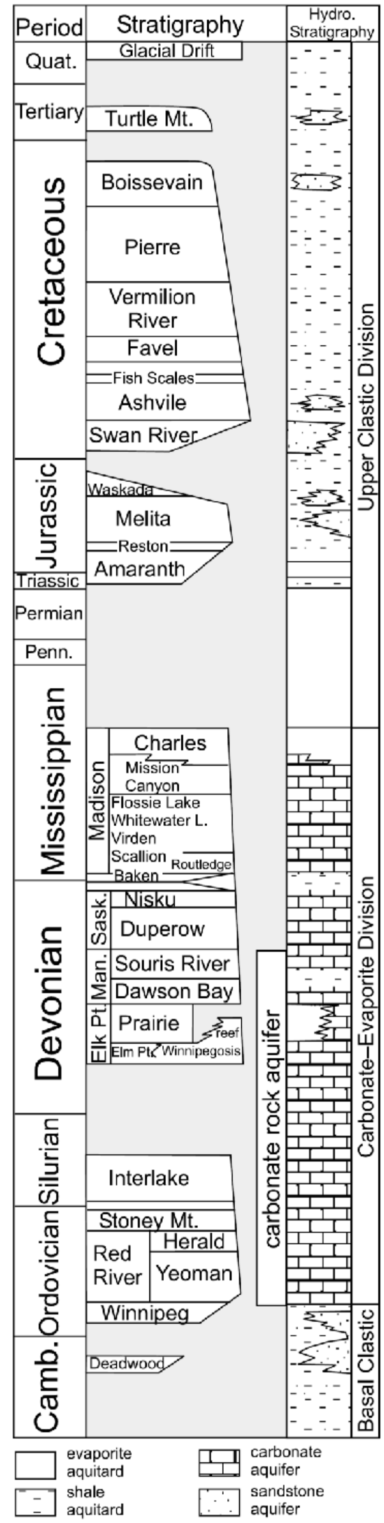

Figure 2: Hydrostratigraphy of the Williston Basin in Manitoba (From Grasby and Betcher, 2002)

The Carbonate Rock aquifer was significantly affected by glaciations in the Pleistocene Epoch. Grasby et al. (2000) proposed a reversal in the regional flow system of the Williston Basin during the Pleistocene glaciation due to the pressure created by the overlying ice sheet. The cryostatic head overlying eastern parts of the Williston Basin would have exceeded the elevation of the Black Hills, which is the modern recharge area of the regional flow system. Once the ice sheet had retreated, the flow system would enter into a phase of readjustment, where the flow system of the Basin would slowly change to accommodate the present day boundary conditions (Grasby et al. 2000).

2.3 Saline Springs

Saline springs in the Lake Winnipegosis area were first reported by Tyrell (1892) and were not studied until the early 1970s (van Everdingen 1971; Stephenson 1973), and early 1980s (Wadien 1984). In 1997, Bezys et al. performed geochemical sampling of the precipitates from several of the springs.

A comprehensive study of the chemistry of these springs was undertaken in 2000 by the Geological Survey of Canada (Grasby 2000). Samples were taken from several different springs along the western coast of Lake Winnipegosis. Stable-isotope data from the saline springs plots along the global meteoric water line as expected when working with springs (Grasby 2000). This distinguishes the springs from formation brines found deeper within the Basin, west of Manitoba (Rostron et al.

1998) and indicates that the springs originate from meteoric water. TDS content is variable with a range from 2000 mg/L to 114 000 mg/L (Grasby and Londry 2007). These values are due to thought to be the result of dissolution of the Prairie Evaporite by an influx of low TDS water during the Pleistocene.

3 ANALYSIS

3.1 Water and Solute Balance

A schematic was devised to represent the general overall hydrology and hydrogeology of the study area (Figure 3). According to this schematic there is one water reservoir, Lake Winnipegosis. Fluxes about this reservoir include: river input from the Swan, Woody, Red Deer, and Overflowing rivers, river output via the Waterhen system, evapotranspiration, precipitation, and inflow from groundwater seepage. These fluxes can be represented by the mass balance Equations 1, 2, and 3:

$$F_{ro} = F_{ri} + F_{gw} + F_p - F_e \quad [1]$$

$$Q_{ro} = Q_{ri} + Q_{gw} + Q_p - Q_e \quad [2]$$

Where instantaneous mass flux:

$$F_i = C_i * Q_i \quad [3]$$

Where F is solute flux, *ro* is river output, ri is river input, *gw* is groundwater input, *p* is precipitation, *e* is evaporation, Q is fluid flux, and C is chloride concentration. Values used in the instantaneous mass flux equation for C_i and Q_i are measured on the same day. Based on equipotentials in the region (Grasby and Betcher 2002), it was assumed that there was no groundwater outflow from Lake Winnipegosis.

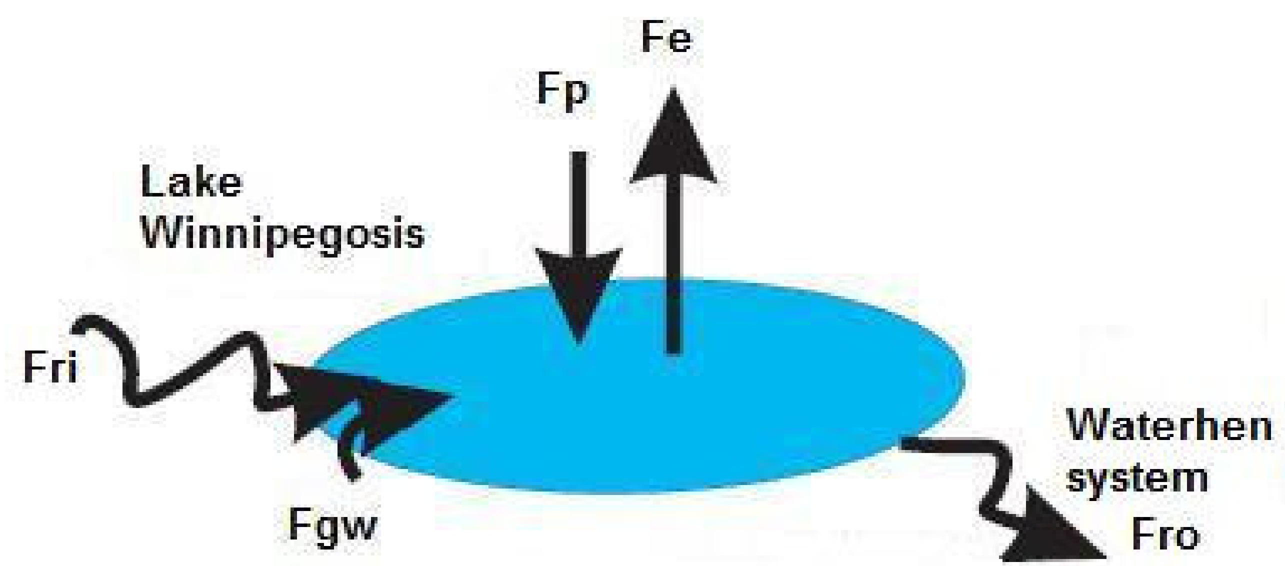

Figure 3: Schematic of the hydrology of the study area

Hydrographs for Lake Winnipegosis (Figure 4) and the various rivers used in this study (Figure 5), as well as historic water chemistry (Figure 5) is derived from Water Survey of Canada's Hydrometric Archive. While hydrograph records are extensive, water chemistry records are sparse and sporadic and the period where all records overlap is brief, in the 1970s. No water chemistry was available for this time period for the Red Deer River and these missing concentrations were estimated from Overflowing River samples based on limited data in other years.

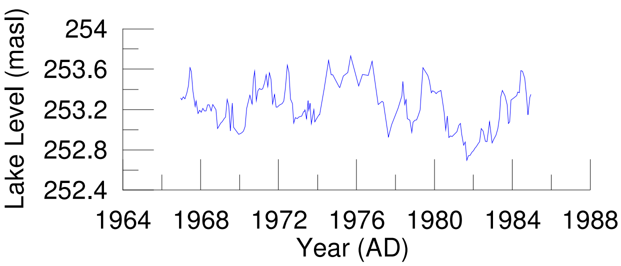

Figure 4: Hydrograph for Lake Winnipegosis.

Precipitation figures used in these calculations were obtained from Environment Canada. Values of precipitation used were 508 mm/yr (1.6×10^{-8} m/s) for Dauphin, 394 mm/yr (1.2×10^{-8} m/s) for Swan River and 443 mm/yr (1.4×10^{-8} m/s) for The Pas (Figure 1). Evaporation was estimated from average data for the 1971-2000 period compiled by Agriculture and Agri-Food Canada, which ranged from approximately 650 mm/yr at the south end of Lake Winnipegosis to less than 500 mm/yr at the north end of the lake. This implies that on an annual basis, evaporation exceeds precipitation by approximately 250mm/yr (7.9×10^{-9} m/s) in the south and 50 mm/yr (1.6×10^{-9} m/s) in the north. These values were used to constrain the estimates of groundwater seepage rates in the water budget calculations.

3.2 Bulk Groundwater Seepage and Solute Fluxes

Depending on the difference between evapotranspiration and precipitation, a range of groundwater seepages and groundwater chemistries could be possible (Figures 6 and 7). The calculated groundwater seepage rates, which were only possible for selected dates in the 1970s due to lack of overlapping data for the various parameters, ranged from 3.6×10^{-9} to 3.1×10^{-8} m/s. Assuming that groundwater seepage is fairly constant throughout the year, the true value is likely in the middle of this range. Seepage will be under predicted when lower evaporation rates are used during summer months and vice versa for winter months. Estimated chloride concentrations ranged from 200 to 1700 mg/L, although most estimates were at the lower end of this range. These estimates will also suffer from inaccuracies due to seasonal changes in precipitation and evaporation. The mean chloride concentrations for evaporation minus precipitation values of 0, 100, 200 and 300 mm/yr (0, 3.2×10^{-8}, 6.3×10^{-8} and 9.5×10^{-8} m/s). were 600, 420, 330 and 280 mg/L respectively.

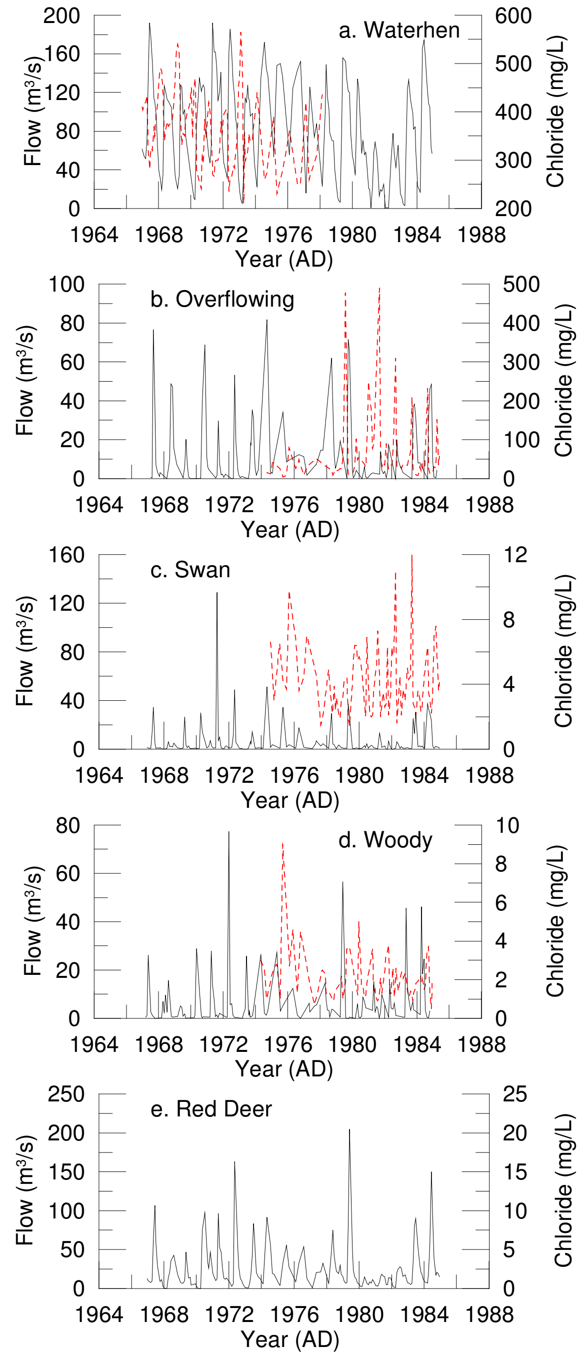

Figure 5: Hydrograph and chloride concentrations for: a) Waterhen River; b) Overflowing River; c) Swan River; d) Woody River; and e) Red Deer River. Note variable scales on axes.

3.3 Estimate of Basin Brine Discharge Rate

To determine the amount seepage rates coming from the east and west a further calculation was required. In this calculation a Cl concentration of 30000 mg/L (Grasby and Londry, 2007) was used as an end member for basin

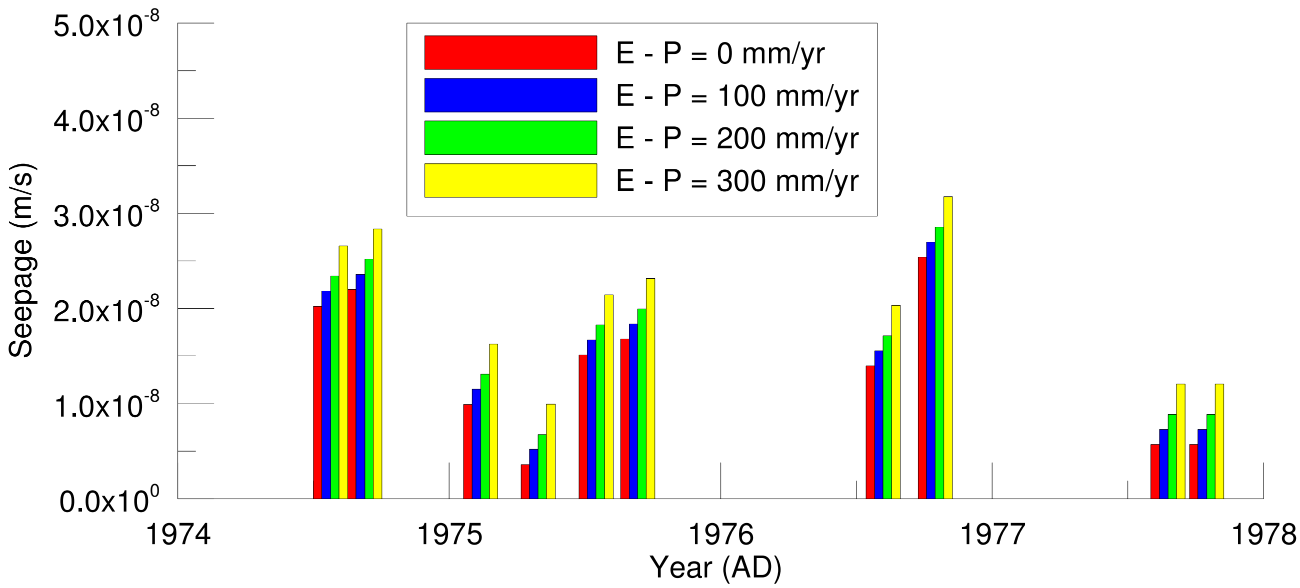

Figure 6: Estimated groundwater seepage rates for various evaporation minus precipitation figures. Position of right side of red bar along the horizontal axis indicates time of measurements used in calculation.

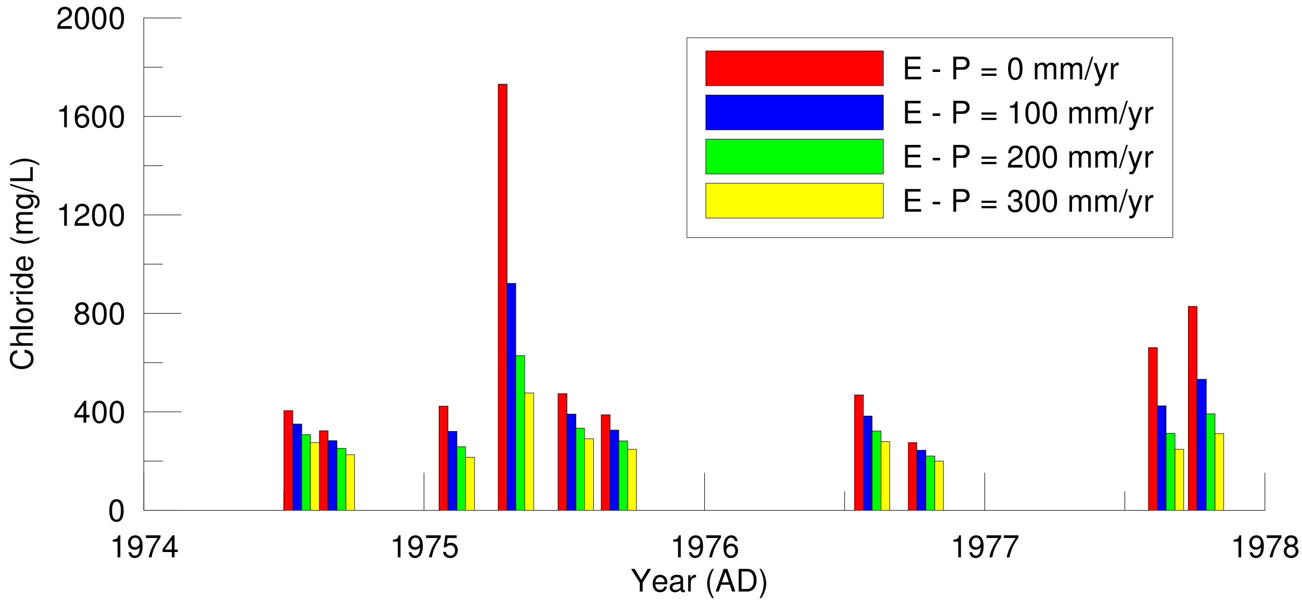

Figure 7: Estimated groundwater Cl concentrations for various evaporation minus precipitation figures. Position of right side of red bar along the horizontal axis indicates time of measurements used in calculation.

brines and 200 mg/L was selected as an approximate value for groundwater to the east (Grasby and Betcher 2002). Using those concentrations with an estimated groundwater seepage of 2.0 x 10^{-8} m/s and an estimated average groundwater Cl of concentration of 400 mg/L, seepage of deeper basin brines occurs at a rate of approximately 10^{-11} to10^{-10} m/s. This corresponds to a total discharge of approximately 10^{9} kg of Cl from groundwater to Lake Winnipegosis each year. The total solute flux would be slightly less than double this amount, given that Na is the other major constituent of this water and is present in one-to-one molar ratio with Cl. This implies that approximately 10^{13} kg of the Prairie Evaporite has dissolved and discharged into Lake Winnipegosis as the result of intrusion of freshwater during the Pleistocene Epoch if these discharge conditions are representative of those since deglaciation, which occurred approximately 10000 years ago in this region.

4 DISCUSSION AND CONCLUSIONS

Basin brine accounts for a relatively small amount of the total seepage into Lake Winnipegosis but represents a large portion of the solute flux into the lake. The amount of dissolution required to maintain this solute flux since the last glaciation indicates that a significant amount of rock was dissolved by subglacial recharge to the Williston Basin. This is evident when it is considered that the mass required to maintain the solute flux to Lake Winnipegosis represents only a small fraction of the total dissolution. Additional discharges to Lake Manitoba and other surface water bodies and the increased solute concentrations in formation water suggest that the total dissolution is much larger than the figure of 10^7 kg given here.

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