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THE GROUNDWATER RECHARGE FUNCTION OF SMALL WETLANDS IN THE SEMI-ARID NORTHERN PRAIRIES

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Abstract. *Small wetlands in the semi-arid northern prairie region are focal points for groundwater recharge. Hence the groundwater recharge function of the wetlands is an important consideration in development of wetland conservation policies. Most of the groundwater recharge from the wetlands flows to the moist margins of the wetlands and serves to maintain high evapotranspiration by the vegetation surrounding the wetlands. Only a small portion of the recharged water flows to regional aquifers, but this portion is important for sustaining groundwater resources. Wetland drainage eliminates the local flow systems, but may have little effects on regional aquifers other than a slight lowering of the groundwater levels. Further research should focus on the effects of wetland drainage on regional groundwater levels, the role of small ephemeral ponds in groundwater recharge, and the contribution of groundwater inflow to the water balance of large permanent wetlands.*

Numerous studies of the hydrology of the small wetlands (also known as "potholes" or "sloughs") in the semi-arid northern prairies have shown that they are a focal point of groundwater recharge (e.g., LaBaugh et al. 1998; Meyboom 1966; Sloan 1972; Winter 1989). This "depression-focused" recharge (Lissey 1971) is a consequence of the cold semi-arid climate and the clay-rich glacial deposits that cover most of the region. Water in the form of snow accumulates in the winter. In spring snowmelt water runs off into depressions because the frozen soils have limited infiltration capacity (Gray et al. 1985). The resulting ponds then recharge groundwater during part or all of the rest of the year.

The groundwater recharge function of prairie wetlands is recognized as a valuable aspect of their overall role in the landscape (Fuller 1988; Leitch and Hovde 1996). However, the nature of this function is not well understood, and its importance may be over-emphasized. Rehm et al. (1982) suggest that groundwater recharge may also originate outside wetlands: from shallow ephemeral puddles on the uplands or from areas where the soils are sandy and have low moisture retention capacity. Published estimates of recharge rates from wetlands vary from 1 to 45 mm per year (Hayashi et al. 1998b), as do estimates of recharge to regional aquifers, which vary from a few millimeters per year (e.g., Fortin et al. 1991) up to 40 millimeters per year (e.g., Rehm et al. 1982).

This paper provides an overview of the hydrogeology and permeability of the glacial deposits in the prairie region, reviews published estimates of the rates of groundwater recharge from wetlands, and compares these with measured recharge rates to regional aquifers. Building upon this background information, the effects of artificial drainage of wetlands on groundwater recharge are discussed.

The paper is primarily concerned with wetlands in the semi-arid portion of the northern prairies. Along the northern and eastern edges of the prairies precipitation is higher and evaporation is a less dominant process. Consequently depression-focused groundwater recharge from wetlands is less pronounced in this region.

The Hydrogeology of Glacial Deposits in the Northern Prairie Region

The Pleistocene continental glaciers repeatedly covered the northern prairie region and left extensive glacial deposits (Lennox et al. 1988). These deposits are tens of meters to hundreds of meters thick and consist largely of glacial tills, with interspersed deposits of clays, silts, sands and gravels. The tills generally have a high proportion of silt and clay-sized particles. Virtually all the groundwater flow relevant to the hydrology of prairie wetlands occurs within the glacial deposits. These same deposits also form the hummocky prairie landscape with its numerous closed depressions in which the wetlands have formed. Thus the prairie wetlands are very much a phenomenon of the glaciated terrain which, together with the cold semi-arid climate, creates their unique hydrology (see also LaBaugh et al. 1998).

The glacial deposits are also the source of most of the salts that occur in the northern prairie region (LaBaugh et al. this 1998). Essentially the glaciers pulverized huge masses of fresh bedrock, much of it rich in pyrite and carbonates, and exposed this material to weathering and subsequent dissolution and leaching by groundwater flow. These processes have produced the sulfate salts that are common throughout the region in soils, wetlands and lakes (Hendry et al. 1986; Keller et al. 1991).

The tills and lacustrine deposits within the glacial deposits occur mostly as continuous layers that extend over tens to hundreds of kilometers. These constitute regional aquitards (formations with very slow groundwater flow) because their high clay content imparts a very low permeability to the material. The sands and gravels occur as extensive sheets, long narrow channel deposits, and numerous small deposits of local extent. These have a high permeability and constitute the local and regional aquifers (highly permeable water-bearing formations) from which nearly all the region's wells draw their water. Most of these aquifers are isolated from each other and from the ground surface by the intervening aquitards.

The flow of groundwater through a geological formation is governed by Darcy's law, which relates the flow rate to the difference of water levels between the two ends of a groundwater flow path (e.g., Fetter 1994; Freeze and Cherry 1979). In Darcy's law, the water level is referred to as the hydraulic head. Darcy's law states that the groundwater flow rate q is given by:

$$q = K \times (\text{hydraulic gradient}) \qquad (1)$$

The constant K, called the hydraulic conductivity, represents the permeability of the geological material. The hydraulic gradient is equal to the difference of hydraulic head along the flow path, divided by the length of the flow path. Suppose for example that an aquitard is 20 m thick, has a hydraulic conductivity of 0.04 m/year, and that the hydraulic head above it is 5 m higher than below it. Then the hydraulic gradient across the aquitard is 5/20 = 0.25 and the flow is downward at a rate of 0.04 x .25 = 0.01 m/year or 10 mm/year.

The hydraulic conductivity of unfractured clay-rich tills and clay is generally in the range of 0.001 to 0.01 m/year (van der Kamp and Maathuis 1985; Keller et al. 1989). However, numerous studies in the northern prairie region and elsewhere have shown that clays and tills are commonly fractured and that they have higher hydraulic conductivity when they are fractured

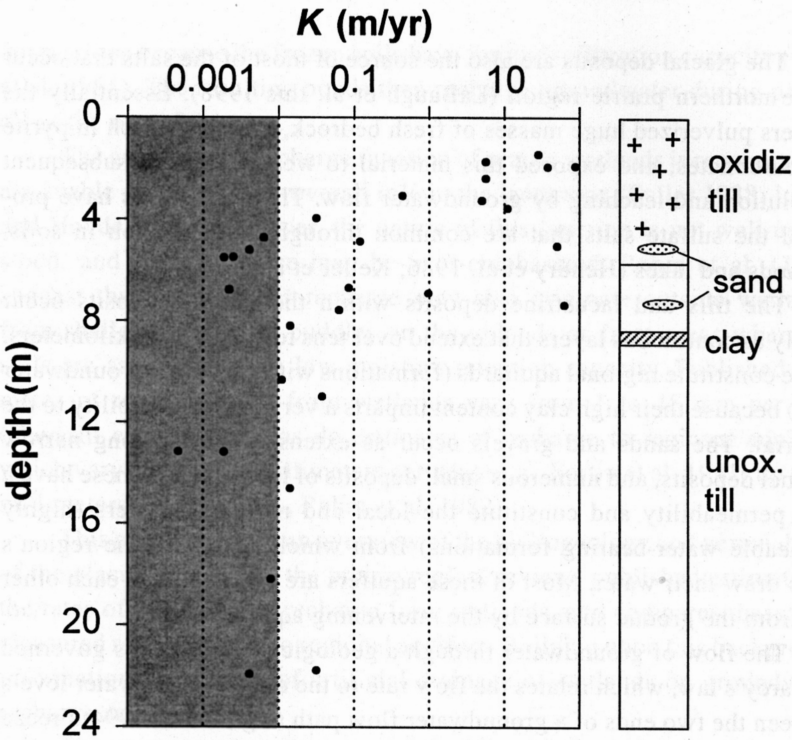

Figure 1. Variation of hydraulic conductivity with depth in glacial till near pothole S109 in the St Denis National Wildlife Area, Saskatchewan (after Hayashi et al. 1998a). The results were obtained by means of in-situ permeability tests (i.e., slug tests) on individual piezometers.

(e.g., Williams and Farvolden 1967; Hendry 1982; Keller et al. 1986; Cravens and Ruedisli 1987; Simpkins and Parkin 1993).

Fractures in tills are due to desiccation of the material during dry climate phases, or disturbance of the material by over-riding glaciers (Haldorson and Kruger 1990). Some fractures have visible red and brown coatings but some, especially in unoxidized material, are invisible and can only be identified on the basis of in-situ permeability tests (e.g., Keller et al. 1986; 1988). The fracture-augmented hydraulic conductivity of the tills generally decreases with depth, ranging from values exceeding 100 m/year just below the ground surface to less than 0.01 m/year at depths below 30 m. A typical example of the variation of hydraulic conductivity with depth (Fig. 1) was reported by Hayashi et al. (1998a) for a site in south-central Saskatchewan, Canada.

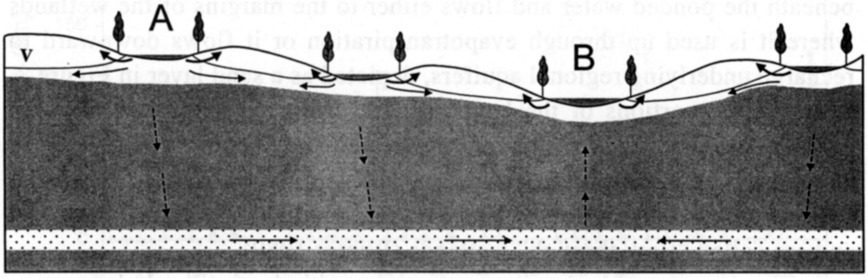

Figure 2. Diagram of groundwater flow systems associated with prairie wetlands. Arrows indicate direction of groundwater flow. The average position of the water table is indicated by the symbol V. The shaded region indicates unoxidized glacial till that is lightly fractured or unfractured. A sand layer, indicated by dots, is an aquifer. The non-shaded region indicates oxidized and fractured till or clay.

The low permeability of the till and clay aquitards in the prairies is a major limiting factor on the rate of recharge to underlying aquifers. In fact, the hydraulic conductivity of an aquitard provides a good measure of the maximum possible rate of recharge to underlying aquifers.

Groundwater Recharge From Prairie Wetlands

The ponded water in wetlands is generally connected to and continuous with the water table in the surrounding area (Fig. 2) and therefore all seepage of water from the ponds into the subsurface can be regarded as groundwater recharge. This definition of recharge is consistent with standard text book definitions of groundwater recharge which include all the water that enters the groundwater zone, i.e., the zone of water below the water table (e.g., Fetter 1994; Freeze and Cherry 1979).

The typical groundwater flow systems that are associated with the wetlands (Fig. 2) extend over horizontal distances of hundreds of meters to a few kilometers and depths of a few meters to tens of meters. Larger-scale systems may also exist beneath these, but the flow through such systems are significant only where there are extensive regional aquifers to conduct the flow to far-off discharge areas.

In the higher parts of the landscape (A in Fig. 2) water infiltrates beneath the ponded water and flows either to the margins of the wetlands where it is used up through evapotranspiration or it flows downward to recharge underlying regional aquifers, depicted as a sand layer in Figure 2. In the lower portions of the landscape (B in Fig. 2) groundwater flows upward from the regional aquifers to wetlands or river valleys, and water also flows from the ponded water to the margins. Some wetlands have shallow groundwater inflow from the one side and outflow to the other side, and are called "flow-through" wetlands (Winter 1989).

The decrease of hydraulic conductivity with depth (Fig. 1) has a controlling influence on the patterns of groundwater flow near prairie wetlands. Water infiltrating from the ponds in the wetlands can move readily through the relatively permeable fractured material within a few meters of the ground surface (Fig. 2). Thus evapotranspiration losses from the moist margins of the wetlands are replenished by recharge, via shallow flow, from the ponded water. Millar (1971), analyzing waterlevel records for a large number of wetlands of various sizes, estimated mid-summer seepage rates to be as high 50 liters per day per meter of shoreline. Shallow seepage was also observed by Rosenberry and Winter (1997). Such seepage losses, which can account for more than half of the water lost from small wetlands, could not occur if the underlying tills did not have high hydraulic conductivity near the ground surface, imparted by fractures.

The flow of groundwater from the ponded water to the margins is a highly transient phenomenon that changes over the hours, days, seasons and years (Meyboom 1966; Winter and Rosenberry 1995; Hayashi et al. 1998a). The average flow is outward at most locations, but it frequently reverses in response to changes in the supply and depletion of water in the pond and beneath the surrounding upland.

Detailed field studies and long-term water level records for wetlands in St. Denis National Wildlife Area (SDNWA) near Saskatoon, Saskatchewan, Canada provide a good illustration of the groundwater recharge functions of typical wetlands. The site is in an area of hummocky moraine and contains a range of wetlands from small seasonal wetlands at higher elevations to larger permanent wetlands at lower elevations (Woo et al. 1993). Average annual precipitation in the area is 360 mm per year of which about 80 mm water equivalent falls as snow.

Hayashi et al. (1998a) studied the water balance and groundwater flow regime of a small (0.24 ha) seasonal wetland in the SDNWA, denoted as S109. Its position in the landscape corresponds to A in Figure 2. The long-

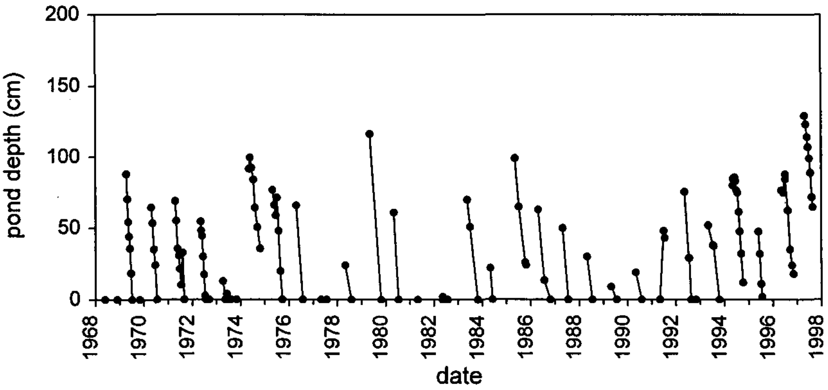

Figure 3. Water level records for a seasonal small wetland (S109) in the St. Denis National Wildlife Area. The gaps in the record represent the winter periods when the ponds were frozen and snow-covered.

term water level regime of wetland S109 (Fig. 3) shows that the water level in the wetland is usually highest at the end of the snowmelt period and declines after that. From field observations Hayashi et al. (1998a) found that in 1994 seepage losses from the open water in wetland S109 amounted to almost 500 mm, of which only 20 mm flowed towards an underlying aquifer at about 30 m depth. All the rest of the seepage was lost by evapotranspiration from the surrounding moist margin (the "willow ring") and from the lower portions of the surrounding cultivated slopes. By contrast evapotranspiration from the open water was about 300 mm. Summer precipitation was also about 300 mm and roughly matched the evaporation from the open water. Thus the summer-time decline of water levels (Fig. 3) essentially represents recharge of groundwater, mostly to the local system to replenish losses from moist margins.

The drainage basin of wetland S109 has an area of a 2.4 hectares, so that the wetland occupies about 10 per cent of the drainage basin. The wetland supplies 20 mm per year of water to the underlying aquifer, which translates to 2 mm per year averaged over the entire drainage basin. This is the regional groundwater recharge rate.

Woo and Rowsell (1993) described the hydrology of a larger (3.1 hectare) wetland within the SDNWA, denoted as S50. This wetland lies at a lower elevation in the landscape than S109, corresponding to position B in Figure 2. It receives some groundwater discharge as evidenced by hydraulic gradients directed towards the wetland from the underlying aquifer and from

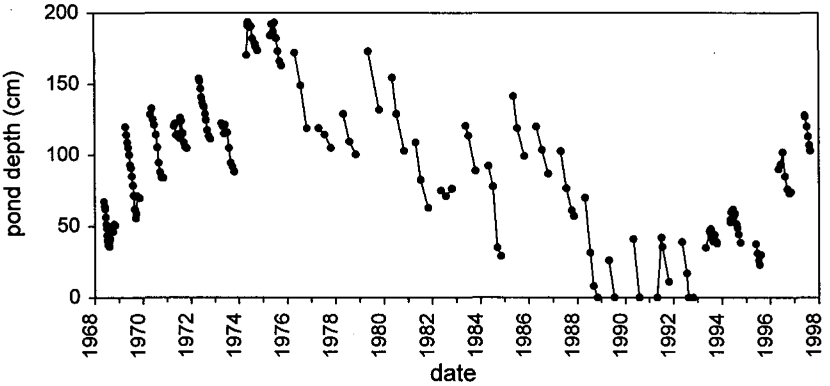

Figure 4. Water level records for a permanent large wetland (S50) in the St. Denis National Wildlife Area. The gaps in the record represent the winter periods when the ponds were frozen andsnow-covered.

the surrounding higher land, and by moderately high salinity of the water in the wetland. Much of the groundwater flowing towards the wetland is intercepted by evapotranspiration from the wet margins, which draws the water table down to an elevation below that of the ponded water. Woo and Rowsell concluded that during their study period (1989-1991) seepage losses from the open water averaged about 90 mm per year, and their results indicate that evaporation from the open water was about 400 to 500 mm per year. The 30-year water level record for S50 (Fig. 4) shows the same pattern of summertime declines as for S109, (Fig. 3) but the rate of decline for S50 is considerably smaller than for S109. In the case of S50 the regional recharge rate is negative (i.e., the wetland is receiving groundwater discharge from the regional aquifer), but the pond still acts as a source of recharge to the surrounding margins. The lower rate of summer decline is a consequence of the larger size of the pond as compared to S109, which means that shoreline seepage losses are a proportionately smaller component of the water balance (Millar 1971). Groundwater discharge into the pond may also contribute to the slower decline of the water level.

The water level regimes for wetlands in the SDNWA (Figs. 3 and 4) are similar to regimes for wetlands in other parts of Saskatchewan (Price 1993) and in North Dakota (Winter and Rosenberry 1995; LaBaugh et al. 1996). In general groundwater recharge is a major component in the water balance of small wetlands at higher elevations and is important even for larger wetlands at lower elevations that receive net discharge from underlying aquifers and from surrounding higher lands. In the latter case the recharge emanating from the ponded water goes entirely to local flow supplying evapotranspiration from the moist margins.

Detailed field investigations have indicated that there is not much groundwater recharge under dry uplands outside of depressions (Keller et al. 1988; Mills and Zwarich 1986; Hayashi et al. 1998a; Zebarth and de Jong 1989). The clay-rich soils have high moisture retention capacity and therefore the limited amount of water that infiltrates into the soils under dry land usually does not reach the water table, but is stored in the soil and used up by evapotranspiration. However, groundwater recharge may also occur through small depressions that do not contain ponded water long enough to support wetland vegetation (Rehm et al. 1982; Keller et al. 1988). It may be that such recharge constitutes a large proportion of the total recharge in many areas and plays an important role in maintaining water tables and contributing groundwater input to lower-lying wetlands and regional aquifers.

Recharge to regional aquifers

Most of the water wells in the prairie region draw water from regional aquifers overlain by aquitards of till and clay. Recharge to the aquifers depends on the availability of water in wetlands and other depressions in the overlying landscape, as well as on the hydraulic conductivity of overlying aquitards. The question is whether drying out of wetlands by drainage or other processes could have a significant impact on recharge to regional aquifers. It is therefore instructive to review measured rates of recharge to regional aquifers and compare these with the measured rates of recharge from wetlands. The most reliable values for recharge to regional aquifers are based on direct measurements of groundwater discharge by spring flow or by long-term pumping.

The Dalmeny aquifer in central Saskatchewan extends under an area of 700 km^2 and is overlain by 20 to 40 meters of till (Fortin et al. 1991). The rate of recharge averaged over the area of the aquifer is 5 mm per year, as determined by the measured flow rates of the springs through which most of the aquifer's ground water discharge occurs. This is the recharge rate under the natural conditions. If this aquifer was pumped heavily, the hydraulic head in the aquifer would be significantly lowered. In turn the downward hydraulic gradient through the overlying till would be increased and thus the rate of recharge would be increased. The maximum possible rate of recharge (i.e., with downward gradients through the till equal to 1.0) is about 10 to 15 mm per year. This is the maximum sustainable yield of the Dalmeny aquifer.

Using long-term pumping and water-level records, Maathuis and van der Kamp (1988) determined that the 150 km^2 Zehner aquifer near Regina, Saskatchewan has a recharge rate of about 25 to 40 mm per year, averaged over the area of the aquifer. This aquifer is overlain by 10 to 30 meters of till and has water levels in the range of 20 to 40 meters below ground surface (generally the water level lies within the sands of the aquifer) so that a strong downward hydraulic gradient exists beneath the many wetlands that lie above the aquifer. This aquifer is therefore receiving recharge at the maximum possible rate, limited by the hydraulic conductivity of the overlying aquitard and by the supply of water in the depressions above it..

The Estevan Valley Aquifer in south-eastern Saskatchewan has an area of about 300 to 400 km^2 and is covered by 30 to 60 m of till. Maathuis and van der Kamp (1989) determined its maximum sustainable yield to be about $4.5 \infty 10^6$ m^3 per year, equivalent to 10 mm of water per year over the area of the aquifer. Six years of subsequent heavy pumping from 1988 to 1994 showed this yield estimate to be accurate (Van Stempvoort and Simpson 1995).

Other studies of recharge rates in the prairies, based mainly on point measurements of permeability and gradients, arrived at rates of recharge in the range of 10 to 40 mm per year (Rehm et al. 1982). Simpkins and Parkin (1993) estimated recharge rates in the range of 3 to 76 mm per year through till of the Des Moines Lobe in Iowa. Barari et al. (1990) described an aquifer in South Dakota, overlain by till, which appeared to be receiving very little recharge even with heavy pumping, but gave no quantitative estimates for recharge rates.

In general these results suggest that the present-day rates of recharge for prairie aquifers confined by aquitards of till and clay are in the range of 5 to 40 mm per year, while the maximum sustainable yields are in the range of 10 to 75 mm per year. By comparison estimates of recharge from small upland prairie wetlands to regional aquifers obtained by various researchers, as summarized by Hayashi et al. (1998b), lie in the range of 2 to 45 mm/year, averaged over the areas of their drainage basins. The similarity of these two ranges of values suggests that wetlands may indeed be the main source of recharge to regional aquifers. However, the possibility that other sources of recharge are also important cannot be excluded on the basis of these results.

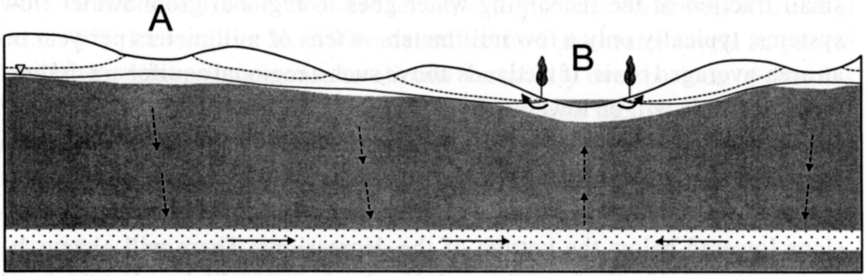

Figure 5. Effects of wetland drainage on the groundwater flow systems (cf. Fig. 2). Dotted lines indicate the water table before drainage, and solid lines indicate the water table after drainage.

Effects of Wetland Drainage on Groundwater Recharge

A large number of the wetlands in the prairie region have been drained since cultivation began, and drainage is continuing as farm operators strive to obtain greater farming efficiency and yields. The effects of wetland drainage on groundwater recharge and groundwater levels is an important consideration in evaluation of the economics and other impacts of wetland drainage. The recharge function of wetlands described in the preceding sections provides a framework for evaluating the value of wetlands with respect to groundwater recharge.

The key point is that most of the groundwater recharge from wetlands goes to the highly localized and transitory flow systems at the margins of the wetland. Therefore, the main value of groundwater recharge from prairie wetlands lies probably in the maintenance of vegetation in the surrounding "willow ring" and to some extent in nearby cultivated lands. This vegetation depends for much of its water supply on recharge from the open water through the shallow and relatively permeable subsurface. If a wetland has nearby shallow wells, infiltration from the wetlands is also important for maintaining the water level in the wells. Drainage of a wetland will certainly lower the water table in the vicinity of the wetland, drying out nearby vegetation and reducing the yield of nearby shallow wells.

Compared to the strong effects on local groundwater, wetland drainage may have little effect on regional groundwater recharge. On average only a small fraction of the recharging water goes to regional groundwater flow systems; typically only a few millimeters to tens of millimeters per year on an area-averaged basis. If wetlands above such a regional aquifer are drained the water table will be lowered, but the recharge to the regional system may not decrease very much. This situation is sketched in Figure 5, which is a copy of the general profile shown in Figure 2, but now with the wetlands at higher elevations drained; i.e., with the average water table in the depressions lowered below the bottom of the depressions. There will always be some recharge, if only from the water in the drainage ditches, but the local flow system near the wetlands is now largely gone. It requires very little recharge to maintain the water table below the former wetland at a few meters below ground level, because the evapotranspiration losses are much reduced with such a low water table. However, even with this drop in water table there may still be a strong downward gradient to the regional aquifer, maintaining the regional recharge rate at close to its original rate. Thus water levels in deep wells tapping regional aquifers may decline slightly if extensive wetland drainage occurs, but the sustainable yields of the aquifers may not be significantly reduced.

Long-term groundwater level records support the above reasoning. For example, groundwater level observations collected since the 1960s by the Saskatchewan Research Council give no indication of widespread lowering of water levels in Saskatchewan (Maathuis and van der Kamp 1986). Significant decline of groundwater levels in some locations can usually be related to heavy pumping from the aquifer itself. On a regional scale the effects of wetland drainage may be offset by increased recharge from artificial depressions such as dugouts and ditches.

In areas where the regional recharge rate is relatively high, say 10 mm/year or more, extensive wetland drainage could conceivably have a significant impact on the sustainable yields of underlying aquifers. The Zehner Aquifer near Regina, Saskatchewan, mentioned above, may be a case in point. This aquifer has been pumped at about 4,000,000 m^3 per year since early in the century, a rate equivalent to about 25 to 40 mm/year averaged over the area of the aquifer. Replacement of this groundwater supply by surface water would cost the City of Regina at least several millions of dollars per year (Calam 1988). It seems likely that the wetlands above such a heavily used aquifer may have significant value with respect to maintenance of the regional recharge.

Impacts of Climate Change, Land Use and Groundwater Pumping

Water levels in wetlands are sensitive to climatic variability (Covich et al. 1997). LaBaugh et al. (1996) described how the water levels in prairie wetlands change in response to climate variability over periods of decades to centuries. The water level data for wetlands in the St. Denis National Wildlife Area (Figs. 3 and 4) also indicate how the water levels can vary. Extended periods of drought that lead to lower water levels in wetlands also lead to lowering of the local water table around the wetland and to a reduced rate of recharge to regional aquifers.

Hendry et al. (1986) suggested that the depth of transition from oxidized to unoxidized till (i.e., oxidation front) corresponds to the water table in the driest period since the retreat of the last continental glaciation from the northern prairies, between 18,000 and 10,000 years before the present. Various studies (e.g., Hendry et al. 1986; Keller and van der Kamp 1988; Zebarth et al. 1989: Hayashi et al. 1998a) have shown that the oxidation front generally occurs a few meters below the present water table and below present-day wetlands. This finding suggests that the local flow system delivering water from the wetland to the surrounding vegetation was not functioning during the dry periods, but that groundwater levels never dropped more than a few meters, even during extended periods of drier climate.

Changes of land use in the drainage basins of the wetlands may also reduce or enhance surface runoff into the wetlands and thus affect water levels and groundwater recharge. van der Kamp et al. (1998) report that a change of land use from dryland cultivation to permanent brome grass led to a complete drying out of small wetlands. Large-scale change of land use in the prairie region is an on-going process and may have profound effects on the hydrology and groundwater recharge functions of wetlands.

Lowering of water levels in regional aquifers due to heavy pumping will increase the rate of regional recharge from overlying wetlands. The sustainable groundwater yields of regional aquifers under heavy pumping range from 10 to 75 mm per year on an area-averaged basis. If most of this recharge originates from wetlands the seepage rates from the ponds in wetlands, induced by the pumping, could amount to several hundred mm per year. Such seepage losses would represent a significant component of wetland water balances and would lead to degradation of wetlands. Heavy pumping will also lead to drying out of springs and wetland areas that are maintained by natural groundwater discharge. Thus the potential effects of groundwater withdrawals on wetlands should be taken into account when the impacts of groundwater pumping are evaluated.

Suggestions For Further Research

The potential deleterious effects of wetland drainage on groundwater recharge to regional aquifers may not be as significant as is sometimes implied, but is an important concern. It would be a valuable exercise to review and summarize wetland drainage and groundwater records across the prairie wetland region, with respect to the question of recharge. Reliable groundwater data from before the 1960s are rare, but such data as are available on water levels, pumping rates and flow of springs could be reviewed to see if regional groundwater levels have noticeably declined over the long term.

Recharge from wetlands has been well documented, but groundwater recharge may also occur through small ephemeral ponds. Studies to quantify recharge from small depressions in typical landscapes would make a useful contribution to understanding of prairie hydrology and could have important applications in land management practices.

It is a common assumption that larger, more permanent wetlands owe their permanence to groundwater input. Water chemistry indicates that such wetlands receive groundwater discharge, but there are no reliable methods for estimating the rate of such input. The difficulty arises because most groundwater discharge is intercepted by evapotranspiration from the margins in summer and is obscured by snow accumulation and freezing of pond water in winter. Further research on this question is needed to provide insight into the water balance of permanent wetlands, particularly because such wetlands are an important component of wildlife habitat in the prairies.

It could be useful to compare the hydrogeology and hydrology of wetlands under the different climatic regimes, varying from highly arid to humid, that exist in the northern glaciated plains. Such a study would provide a test of the models for wetland hydrology, groundwater recharge and the effects of drainage.

Conclusions

The groundwater recharge function is an important aspect of prairie wetland hydrology, but most of the recharge originating from the wetlands goes to highly localized groundwater flow systems. Only a small fraction of the recharging water goes to regional aquifers. Consequently, drainage of wetlands will lower the water table in the vicinity of the wetland and will dry out the vegetation in the wetland margins that is dependent on the supply of plentiful shallow groundwater. Most regional aquifers have low rates of recharge and are not greatly impacted by wetland drainage. However, regional aquifers that draw high rates of recharge, say in excess of 10 mm/year, could be impacted by extensive wetland drainage in their recharge areas.

Further research is needed on the inter-relationship between groundwater recharge from wetlands, regional groundwater levels, and groundwater withdrawals. The rates of recharge from small ephemeral ponds should be studied because such ponds may play an important role in the regional hydrology. It is commonly taken for granted that groundwater discharge is a major factor in the permanence of larger wetlands, but this relationship is unproved and should be verified by means of field and theoretical studies.

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