Wetland drainage effects on groundwater in southern Saskatchewan

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Executive Summary

Available data on the impacts on groundwater levels of wetland drainage in southern Saskatchewan are limited and insufficient for identification of discernible effects on groundwater levels of regionally important aquifers and available groundwater supplies. The net aquifer-wide impact on groundwater of wetland drainage coupled with the removal of perennial wetland vegetation is uncertain, has not been quantified through field studies, and may be small. Impacts of wetland drainage on groundwater resource availability should be evaluated for individual projects on the basis of landforms and hydrogeological settings.

In the prairie region of Saskatchewan most groundwater recharge occurs by infiltration beneath ponds in small depressions and wetlands where water collects during snowmelt and heavy rains. There is a concern that if wetlands are drained so that surface water is not ponded in them, then recharge of groundwater beneath the wetlands may be reduced and groundwater resource availability may be diminished. This concern can be addressed from the point of view of whether wetland drainage causes changes of the groundwater levels, which in turn are a direct measure of changes in groundwater availability: if the background groundwater level around a well declines then the sustainable pumping rate of the well is reduced.

Potential impacts of wetland drainage on groundwater resources were assessed through a review of published literature on groundwater recharge and discharge processes in the prairie region, together with a review of long-term records of groundwater levels for Saskatchewan. There have been numerous field studies of groundwater recharge and discharge in and around intact wetlands. These have shown that within wetlands and their margins there are complex interactions between surface and groundwater, summed up by the concept of “depression-focused groundwater recharge and discharge”. However, no published field studies of the impact of wetland drainage on groundwater resources have been carried out in the prairie region.

Groundwater observation wells have been operated in southern Saskatchewan since the 1960’s and thus provide valuable information on the variability and long-trends of groundwater levels. Water-level records for the observation wells were reviewed, together with an inventory of the status of the wetlands in the surrounding areas, excluding the wells that have been affected by groundwater pumping. The groundwater levels in all these wells fluctuate over the seasons and annually and in response to multi-year wet and dry periods. The long-term trend of the groundwater levels has been steady

or rising over the last five decades. The effects, if any, of wetland drainage are obscured by the fluctuations due to the variations in snowfall and rainfall.

A critical review of groundwater recharge and discharge processes for different types of prairie landforms was undertaken to obtain a more thorough understanding of the possible impacts of wetland drainage and wetland restoration on groundwater levels. Stable isotope data for groundwater indicate that most groundwater recharge occurs during the snowmelt period in small depressions with ephemeral ponding which may not be classified as wetlands and are usually cultivated. Perennial deep-rooted vegetation in and around intact wetlands is a major focus of shallow groundwater discharge by root uptake, as evidenced by the common occurrence of “willow rings” which depend on shallow groundwater that infiltrates beneath the central pond. The NET recharge to the groundwater beneath a wetland is the small difference between the recharge and the discharge that occur in and near the wetland. Changes of the net recharge result in corresponding changes of the groundwater level in underlying aquifers. The effects of wetland drainage on groundwater availability thus depend on how drainage affects the net recharge.

The common removal of perennial vegetation when a wetland is drained reduces groundwater discharge by root uptake, thus counteracting the decrease of groundwater infiltration due to drainage of the ponded water. During snowmelt drained wetland depressions usually hold ephemeral ponds that recharge the groundwater. Drainage ditches also hold water while there is flow through them and thus act as additional sources of groundwater recharge. The change of net recharge due to drainage is uncertain and may be small.

Mitigations of wetland drainage effects on net groundwater recharge would likely involve temporarily retaining water on the landscape after snowmelt. Wetland drainage may reduce groundwater levels in underlying aquifers if pre-drainage infiltration beneath the ponded water is high and discharge by wetland vegetation root uptake is low, as is most likely to be the case for shallow aquifers with groundwater levels that are deep below the ground surface of the overlying wetlands. In all cases of mitigation measures the landforms and hydrogeological setting of a drainage project should be considered, with reference to recharge and discharge processes.

Wetland hydrologic systems are closely connected to groundwater resources. The overall impact of wetland drainage on regional groundwater resources is uncertain but probably small. Increased monitoring and further study of wetland drainage or restoration for high-priority aquifers is recommended, aimed at identifying possible impacts and developing effective mitigation measures if and where these are deemed to be advisable.

1. Introduction - “Depression-focused recharge” and groundwater resources

One aspect of the Saskatchewan Water Security Agency's policy analysis for the development of wetland mitigation policy deals with the possible effects of wetland drainage on groundwater resources. This concern stems mainly from the concept of "**depression-focused" groundwater recharge**. The implication is that if depressions are drained so that no surface water collects in them, then recharge of groundwater beneath the depression may be greatly reduced. For example, a recent synthesis of the science on Canadian prairie wetland drainage (Baulch et al., 2021) states: "There is high certainty that drainage of seasonally and ephemerally flooded depressions will reduce shallow groundwater recharge."

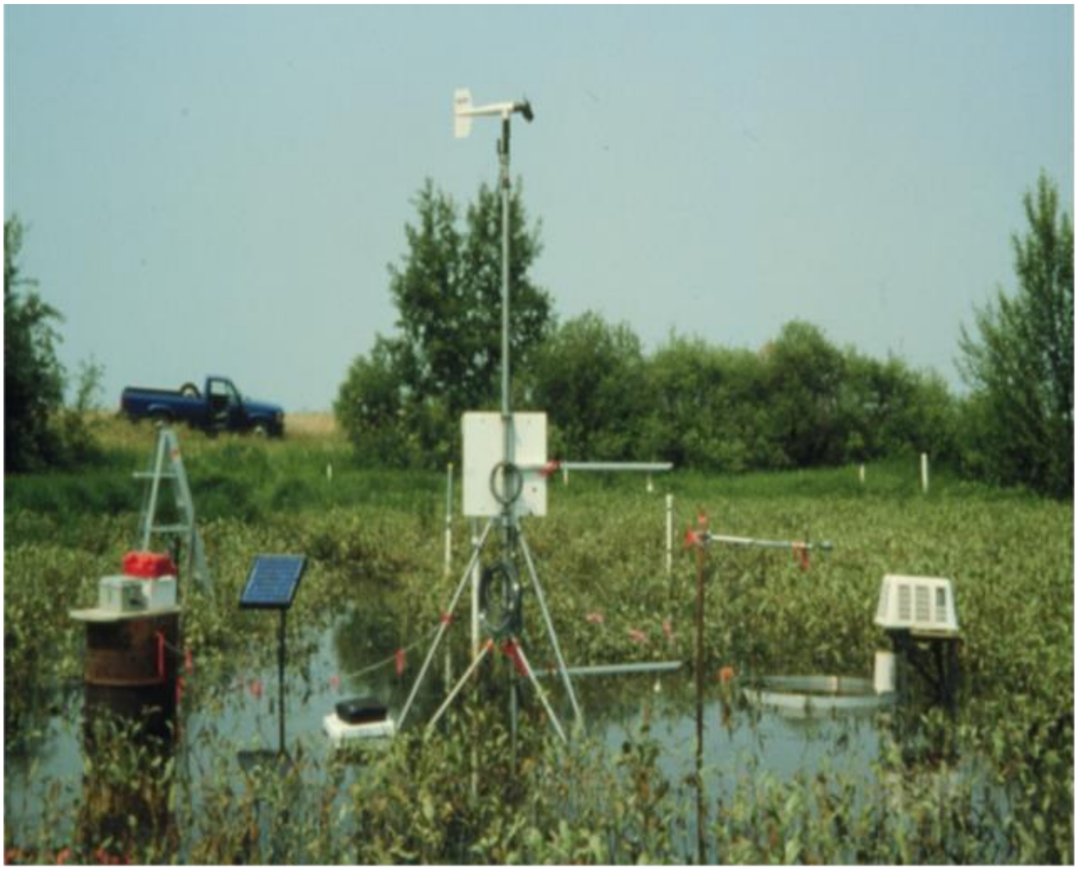

Fig 1. Intensive surface water and groundwater studies of wetland 109, in the St Denis SK National Wildlife Area [photo M. Hayashi]

The phenomenon of depression-focused groundwater recharge has certainly been documented and described in a large number of publications that report the results of detailed field studies, starting with Meyboom's classic study of a small undrained "willow-ring" wetland in the Allan Hills (Meyboom, 1966). The concept was extended to large complexes of intact wetlands in western Manitoba (Lissey, 1971) who formulated the phrase "depression-focused recharge and discharge." Subsequent reviews include van der Kamp and Hayashi (1998), Hayashi et al. (2016), Bam et al. (2020) and Baulch et al. (2021).

The hydrological basis of depression-focused recharge is that in the semi-arid prairie region potential evapotranspiration exceeds the annual precipitation. Thus the water that infiltrates during snowmelt and rainfall could all be returned to the atmosphere by evaporation and by transpiration via root uptake of soil moisture. That would indeed be so if all snowmelt water and rainfall is evenly distributed as it infiltrates into the soil and if the soil can retain all the infiltrated water, even in extremely wet years. In that case the infiltrated water would be lost to evapotranspiration, very little water would move down beyond the reach of the roots, and there would be very little deeper percolation of water to the water table and the groundwater zone.

However, the ground surface of the prairie landscape has numerous smaller and larger depressions. Snowmelt water does not easily infiltrate into frozen cultivated soil and instead runs off over the ground surface. Much of the prairie landscape is "non-contributing" in the sense that the runoff water does not go to connected streams which carry the water out of the region. Instead, the runoff water collects in depressions where the water accumulation is sufficient to exceed evaporation and transpiration so that a portion of the water infiltrates deeply beyond the reach of the vegetation and recharges the groundwater: hence "depression-focused recharge". However, the net recharge is the difference between infiltration and root uptake and may be very small or even negative (i.e. net discharge) if the water table is near the ground surface. As we shall see, the difference in timing between spring snowmelt and summer transpiration is important because water that infiltrates beneath depressions in the spring may move beyond the reach of water uptake by roots during the summer growing season, especially if the vegetation consists of annual crops which do not use much water until two or three months after snowmelt.

This understanding of wetland hydrology is based on numerous published studies of the water balance of individual undrained wetlands (e.g. Hayashi et al, 2016). However, it should be noted that in the prairie region there have been no experimental field studies of the effects of typical wetland drainage practices on groundwater resources. In addition, snow accumulation and rainfall vary widely from year to year and can exceed the moisture holding capacity of the soil, especially in areas of sandy soils. The infiltration capacity of soils is also dependent on land-use and vegetation. Cultivation tends to break up macropores that allow infiltration even when the soil is frozen. In general therefore recharge may also occur beneath the uplands outside of depressions. In sum, the effects of wetland drainage on groundwater recharge and discharge involve the interactions of complex and difficult to measure processes which can vary a great deal from place to place and over the seasons and the years.

The availability of groundwater resources can be viewed as the sum of the yields from individual water-supply wells. The sustainable yield of any well depends on the available drawdown of the water level in the well and on the surrounding hydrogeology. The hydrogeologic factors do not change and are measured by means of pumping tests. The available drawdown is the amount to which the water level in a well can be lowered by pumping without causing problems. This is normally estimated as the difference between the "static" (or non-pumping) water level and the top of the well screen, usually including a safety factor. Drawdown of the aquifer groundwater levels due to pumping induces an increase of inflow to the aquifer and a decrease of natural outflow, more or less in proportion to the drawdown. For the groundwater withdrawals to be sustainable the induced changes of inflow and outflow will after some time match the increased outflow by pumping. The maximum yield of water-supply wells can increase or decrease depending on the available drawdown which in turn depends on the pre-pumping "static"groundwater level near the well. (Changes of groundwater levels may also have ecological impacts which, especially with regard to groundwater discharge to streams.) Thus the possible impacts of wetland drainage on groundwater resource availability can be examined on the basis of that portion of observed changes of the groundwater levels which can be attributed to drainage. Fortunately groundwater levels can be easily measured and many years of water-level records are available from the observation well network.

The purpose of this report is to review available data and insights relevant to wetland drainage and groundwater, to evaluate the possible impacts of drainage and to suggest mitigation measures and further investigations.

2. Review of available groundwater data

2.1 Available groundwater data and information for southern Saskatchewan

Regional groundwater data for southern Saskatchewan relevant to wetland drainage effects include hydrogeology and aquifer maps, estimates of recharge rates for a few aquifers, many years of groundwater-level data from some 50 observation wells, and stable isotope data which provide an indication of the sources of groundwater. These are summarized and reviewed next.

2.2 Aquifers of southern Saskatchewan

Information on the aquifers of southern Saskatchewan in the form of maps and reports is available from the SK Water security Agency [http://www.wsask.ca/Water-Info/Ground-Water/].

All of southern Saskatchewan lies within the Glaciated Interior Plains of North America. The near-surface geology and landforms are dominated by glacial processes and glacial deposits. With regard to groundwater dynamics the aquifers of southern Saskatchewan can be roughly classified into three types: unconfined, semiconfined and confined, according to the degree to which they are isolated from the water table by intervening layers of low permeability such as clay and clay-rich glacial till.

The unconfined aquifers occur in surficial sands and gravels that extend to the ground surface. The saturated aquifer zone is bounded above by the water table and below by underlying low-permeability materials. The depth of the water table below the ground surface varies from a few meters to tens of meters. The extent of these aquifers is shown on the Surficial Geology map of Saskatchewan, (Saskatchewan Ministry of the Economy and Saskatchewan Research Council, 1997), mapped as eolian and glaciofluvial deposits.

The greater part of southern Saskatchewan is covered by clay-rich glaciolacustrine (silt and clay) and moraine (glacial till) deposits. The semiconfined aquifers lie beneath deposit of clays and clay-rich glacial tills that are thick enough to slow the inflow of groundwater to the aquifers from the ground surface and from overlying unconfined aquifers where these are present. The extent of most of these deeper aquifers is at best only approximately known because they have no ground surface manifestation and have been identified and mapped almost entirely by means of drilling. Where the overlying low-permeability layers have thicknesses of about 40 m or more the aquifers are considered highly confined. Most of the major groundwater supplies in southern Saskatchewan draw on extensive semiconfined or highly confined aquifers which have large available drawdowns.

2.3 Estimates of aquifer inflow/outflow rates

The semiconfined and highly confined aquifers in southern Saskatchewan are isolated from the water table by low-permeability layers (aquitards) of glacial till, clay and silt. The inflow to such aquifers is largely controlled by the permeability of the confining aquitards, with limited sensitivity to the rate of groundwater recharge and discharge at the water table above the aquitards. In the context of groundwater resources it is therefore preferable to use the term “inflow” and “outflow” rather than “recharge” and “discharge” to describe the water balance of an aquifer. In this report, the terms “recharge”and “discharge” are used to denote the rate of water flow to and from the water table, including the common case where there is no surficial sand and the water table occurs within clay or glacial till. Outflow from aquifers may occur by flow to other aquifers, and by discharge via root uptake, springs, and seepage to wetlands and streams. Outflow includes pumping of groundwater from the aquifer. It is important to bear mind that the “natural” rates of inflow, prior to any pumping, should not be considered to be the limit on availability of groundwater because the drawdown of the groundwater levels due to pumping may induce an increase of inflow to an aquifer.

The rates of inflow for aquifers are most reliably estimated through measurement of the aquifer outflow at springs, or by measurement of the declines in storage and of outflow by springs in response to known rates of pumping. Aquifer inflow (aka recharge) rates in southern Saskatchewan have been estimated for a few cases and lie in the range of 5 to 40 mm per year for semiconfined aquifers (Keller et al., 1988; van der Kamp and Hayashi, 1998). Inflow to highly confined aquifers may be less than 1 mm per year. For unconfined (water-table) aquifers, typically surficial sands, the annual inflow equals the recharge to the water table and is in the range of a few 10’s of mm. The special but common case of “semiconfined water-table aquifers” i.e. aquifers which are overlain by aquitards and for which the water table lies within the aquifer is further discussed below. The rates and processes of inflow to such aquifers are not well understood.

The rates of inflow and outflow for particular aquifers are very difficult to measure directly and accurately. Detection of small changes of these rates would be uncertain even with major and long-term instrumentation. Thus, with respect to the possible effects of wetland drainage on groundwater resources the detection of such effects must rely primarily on recording and interpretation of changes of groundwater levels.

2.4 Observation well records

To look at regional changes of groundwater levels the long-term groundwater observation well records for southern Saskatchewan provide essential data. These observation wells were installed by the Saskatchewan Research Council in the 1960's and continue to be operated by the Saskatchewan Water Security Agency (https://www.wsask.ca/water-info/ground-water/observation-well-network/). All these wells are installed in aquifers. For unconfined aquifers, the groundwater level records record the changes of the water table in the aquifer. The groundwater levels in semiconfined aquifers follow the changes of the water table within the overlying aquitard above the aquifer, but in a damped and delayed manner.

The more confined the aquifer, the larger is the area which an observation well monitors. Thus wells in unconfined water table aquifers are sensitive to changes in hydrologic conditions, including wetland drainage, over a distance of usually less than a few hundred meters from the well, corresponding to areas of at most a ¼ section (about 0.6 km^2. Observation wells in semiconfined aquifers sense changes in hydrologic conditions over scales of a few km; areas of at most about one township (approximately 100 km^2).

(Note: Groundwater flow theory shows that the sensing distance of an observation well can be estimated by the "leakage factor" $B=(Tc_e)^{1/2}$ *[m], where T is the transmissivity of the aquifer [*m^2*/day] and* c_e *[days] is the total vertical hydraulic resistance of the confining layers and the aquifers (e.g. Freeze and Cherry, 1979, p. 320). The vertical hydraulic resistance is calculated as the vertical thickness of each confining layer or aquifer layer, divided by the hydraulic conductivity [m/day] and is commonly reported in days. This hydraulic resistance is the basis of the Aquifer Vulnerability Index (AVI) used in southern Saskatchewan to map the aquifer vulnerability to contamination emanating at the ground surface [MDH Engineered Solutions, 2011]. Values of the leakage factor vary from about 100 m for water table aquifers to several km for semiconfined aquifers, and tens of km for deep highly confined aquifers.)*

The deep highly confined aquifers sense changes in hydrologic conditions over distance scales of tens of km, particularly for the deep buried-valley aquifers, such as the Tyner Aquifer which is monitored by several observation wells (WSA Tyner, Conquest 504, Vanscoy, Warman-2). Observation well records for these aquifers do not provide useful indications of changes of the overlying water table. The groundwater levels in these wells respond to changes in the total weight of groundwater, soil water and surface water above the aquifers (van der Kamp and Schmidt, 2017). The levels in these aquifers are also likely to be affected by numerous small and undocumented rates of pumping spread over areas that extend to 10's of km distance from the observation wells.

Observation well records for water table aquifers and for semiconfined aquifers not affected by pumping or other specific causes such as lake level changes, are shown in Figures 1 and 2. The data are in the form of median monthly water levels and have all been supplied by the Groundwater Management Division of the SK-Water Security Agency (WSA). Records that are affected by specific causes such as pumping are not included. For example, WSA observation well Regina 530 is not included because it was influenced by groundwater withdrawals and the rising groundwater levels that resulted when the City of Regina largely stopped groundwater withdrawals in the late 1990's. Similarly, Baildon 059 and 060 are affected by effluent irrigation starting in the early 1980's. (The list of all the observation wells that were considered for this report is given in the appendix, including a brief mention of the nature of the effects that result in the exclusion of affected wells.)

The water level records are shown as changes above and below the average water level for each individual well, so as to emphasize long-term changes. The typical seasonal responses of the observation wells have been described by Maathuis and van der Kamp (1986). Multi-year changes predominantly reflect dry and wet periods: for example, the very wet conditions from about 2010 to 2015 show up as high groundwater levels.

The groundwater records for unconfined water-table aquifers (Fig. 2) show both annual variations of 0.1 to 0.5 m and multi-year variations in response to prolonged dry and wet periods. Overall, the water table for these aquifers appears to show no up or down trend from the late 1960's through to about 2009, followed by a general rise from 2010 onwards for several years. In other words, there is no clear indication that the balance between recharge and discharge for these unconfined aquifers over the long-term has changed.

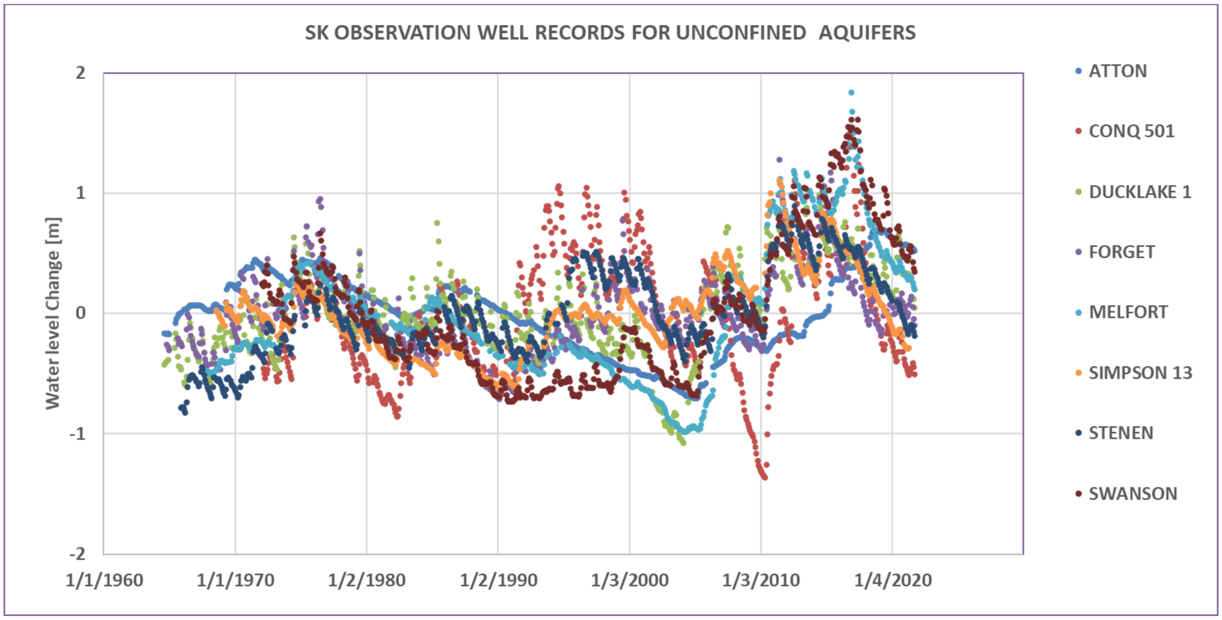

Figure 2. Observation well records for wells completed in unconfined aquifers that are not affected by pumping.

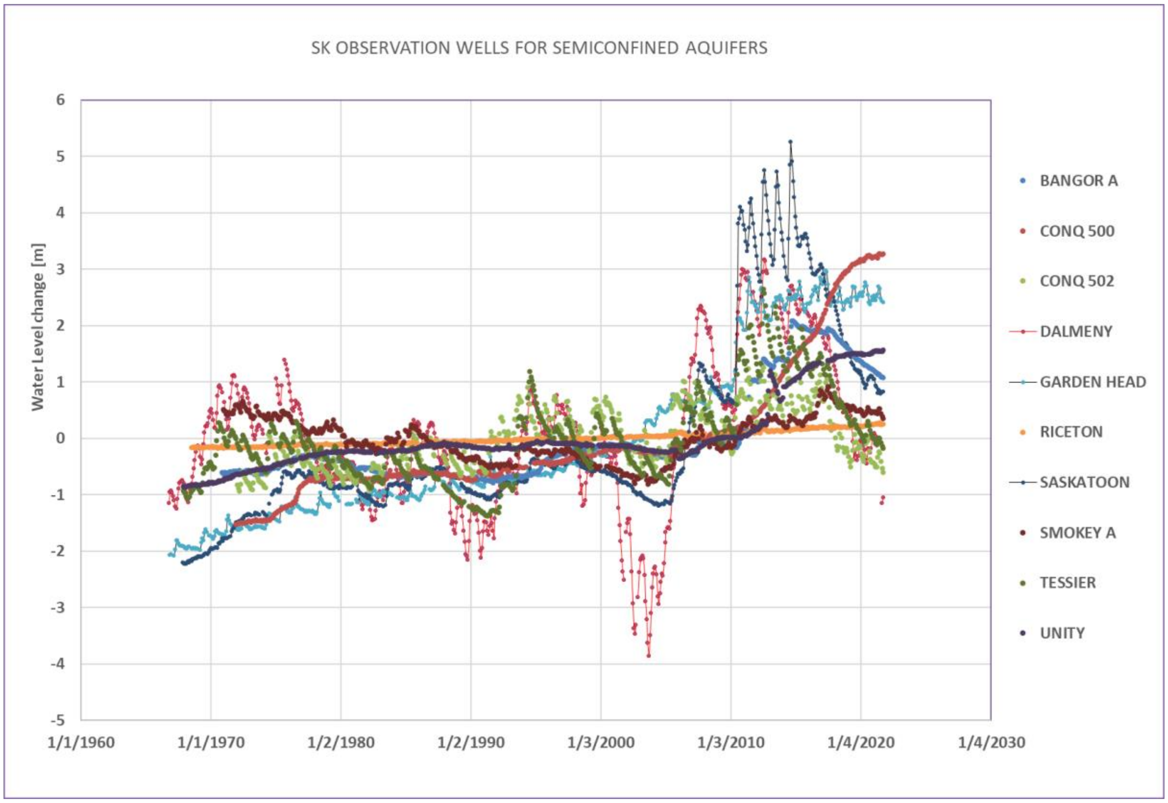

Figure 3. Observation well records for semiconfined aquifers that are not affected by pumping.

The observation well records for “unaffected” semiconfined aquifers (Fig. 3) give no discernible evidence of long-term declines and also show marked increases of the groundwater levels from 2010 onwards. The annual changes of levels for these wells vary from several meters to only very small slow changes, with some records transitioning from small to much larger annual variations from 2010 onwards. These contrasting regimes are mainly a consequence of whether the groundwater level occurs above the top of the aquifer or as a water table within the aquifer below the confining layer (Maathuis and van der Kamp, 1986). The latter condition is referred to as “confined water- table aquifers”. The hydrograph for the Garden Head and Conquest observation wells, show a steady increase of the groundwater levels through the years from the 1960’s onward, rising by about 5 m The reasons for these rises are not clear.

The groundwater level changes over the last five decades are dominated by the effects of seasonal and multi-year moisture conditions. With respect to the possible effects of wetland drainage on groundwater resource availability these long-term records show no discernible sign of overall reductions of groundwater levels. This finding is most meaningful for the semiconfined aquifers since these wells respond to changes of surface hydrological conditions over areas of the township scale (~ 100 km^2). The wells in the unconfined water table aquifers would only respond to wetland drainage if drainage has been carried out within at most a few 100 m. This lack of clear evidence in the observation well records for decreased rates of net groundwater recharge is discussed in detail in a following section.

The total areas of wetlands with various drainage impacts, within 5 km of each of the “unaffected” observation wells in semiconfined aquifers, as determined by the Saskatchewan Wetland Inventory (SWI), are summarized in Table 1. With the exception of the Riceton well most of the wetlands near the other wells are intact, and the total areas of partly filled and completely drained wetlands ranges from 0.4 to 8.1 % of the total wetland areas. The average of the total area of all wetlands is 7.3 % relative to the total land area. The comparative average amounts for southern Saskatchewan established by the Saskatchewan Wetland Inventory are 8 % of wetland area that has been drained (Associated Engineering, 2023) and 10% of the total land area is occupied by wetlands (pers. com. E.Shupena-Soulodre). The relatively large area of completely drained wetlands for the Riceton well reflects drainage of a large wetland several km from the well. Some visible impact of this drainage might be expected, but that depends on the local hydrogeology, especially whether the aquifer extends to beneath this wetland, and is not apparent in the hydrograph. It should be noted that the SWI probably underestimates the total area and numbers of small wetlands (Associated Engineering, 2023).

Apparently none of these observation wells, except Riceton, happen to be located in areas where intense drainage has taken place. Therefore a large impact of wetland drainage might not be expected to be identifiable in these records. The case of the Dalmeny observation well is interesting. This well is completed in the Dalmeny Aquifer, an extensive semiconfined aquifer north-west of Saskatoon, which has been studied and mapped in detail (e.g Fortin et al, 1991). The percentage of drained wetlands, by area, near this well is 8.1%, near the average for the entire SWI area. The water-level record for the well (Fig 3), as for the other well records, shows no discernible decline that might be attributed to wetland drainage.

Impact code:	**0 (Intact)**	**1 (Partly Drained)**	**2 (Farmed)**	**3 (Constructed)**	**4 (Partly filled)**	**5 (Completely Drained)**	**% Drained & Filled or Constructed**	**Total wetland Area**	**Wetland area % of total area**
Well Name									
Bangor A	6.72	0.15	1.57	0.02	0.09	0.04	2.5	8.58	11
Conquest No.500	1.87	0.01	1.13	0.07	0.00	0.03	3.3	3.11	4
Conquest No.502	2.66	0.00	0.42	0.05	0.00	0.02	2.5	3.16	4
Dalmeny	4.59	0.01	0.16	0.41	0.00	0.00	8.1	5.17	7
Riceton	0.18	0.09	1.19	0.05	0.00	**4.98**	78.2	6.49	8
Saskatoon	3.86	0.06	0.17	0.05	0.00	0.01	2.1	4.14	5
Tessier	7.36	0.01	2.28	0.01	0.00	0.02	0.4	9.68	12
Average	3.89	0.05	0.99	0.09	0.01	0.73	13.8	5.76	7.3

Table 1. Total areas in km^2 of wetlands subject to various drainage impacts within 5 km radius of observation wells in semiconfined aquifers. Farmed wetlands are included with the % of intact wetlands. Half of partly drained wetlands are assumed to be intact.

Strong evidence for the impact (or lack thereof) of wetland drainage on regional groundwater levels is not available, at least in Saskatchewan. Studies of the extensive drainage in the Smith Creek watershed do not include data on groundwater levels (Holly Anand, personal communication).

2.4 Stable isotope data for groundwater, surface water, and precipitation

Stable isotope data (δ^2 H and δ^{18} O) for precipitation, surface water and groundwater, from across southern Saskatchewan, show that most groundwater carries little or no signature of evaporation and that the isotopic signature of groundwater indicates recharge is biased towards cold-season precipitation (Jasechko et al, 2017)). These data indicate that more permanent wetland ponds which last into the summer evaporation season are at most a minor source of aquifer recharge because the water in such ponds carry a distinct isotopic signature due to evaporation (e.g. Keller et al., 1988; Fortin et al., 1991; Bam et al., 2020). In other words, type, 4 and 5 wetlands (Stewart and Kantrud (1971) classification) with seasonal or more permanent ponds do not play a dominant role in aquifer recharge. Instead the isotope data indicate that most aquifer replenishment occurs via smaller depressions with ephemeral ponds (non-wetland depressions and type 1,2 and 3 wetlands) which fill with cold-season runoff water).

Bam and Ireson (2018 and Bam et al. (2020) describe a detailed study of stable isotope data for precipitation, ponded water and groundwater in a small area of the St. Denis National Wildlife Area (also designated as National Research Area) east of Saskatoon. Their results show that the groundwater beneath the small depressions matches the groundwater in the deeper underlying aquifer). Ponded water in the larger (types 3 to 5) wetland depressions with seasonal and permanent ponds, and the shallow groundwater beneath them, tends to show enrichment of the heavier isotopes due to evaporation. The isotope concentrations of the groundwater in the underlying semiconfined aquifer at their site are close to the average of isotope values for numerous groundwater samples from southern Saskatchewan, including the observation wells (unpublished data, U of Saskatchewan, Global Institute for Groundwater Security). Bam et al. (2020) conclude that ephemeral ponds are the main source of aquifer replenishment at the St Denis site and throughout southern Saskatchewan.

3. Groundwater recharge and groundwater levels

3.1 Depression-focused recharge, discharge and groundwater levels

The five decades of observation-well records show no discernible evidence for any long-term decline of the groundwater levels in aquifers that are not affected by pumping, despite the extensive amount of wetland drainage which has occurred since the start of the well records in the 1960’s. The effects, if any, of wetland drainage are obscured by the larger long-term variations due to the effects of changes in moisture conditions and possibly of land-use changes. This finding suggests that wetland drainage to date in southern Saskatchewan has at most had little effect on groundwater resources. To further understand this finding it is necessary to take a closer look at the interplay of recharge and discharge processes that control changes of the water table, paying especial attention to the probable hydrologic effects of typical wetland drainage methods.

Depression-focused shallow groundwater recharge is certainly a major and likely dominant recharge process in the prairie region, as attested by numerous detailed field studies (Hayashi et al. 1998; 2016). In relation to groundwater resources for water supply it is important to note the distinction between shallow recharge of water to the water table and inflow of groundwater to semiconfined aquifers. Within and near wetlands with permanent vegetation nearly all the water that infiltrates below the ponds (groundwater recharge by definition) is lost (i.e. groundwater discharge) to evapotranspiration by the wetland vegetation, while a small but important portion of the infiltrated water is the net recharge which provides inflow to the underlying semiconfined aquifers. For example, Hayashi et al., (1998) describe the water balance of a small type 3 wetland (Fig. 1) and showed that about 50 mm of water infiltrates below the ponded water, but averaged over the total area of the wetland and its watershed, there is only 2 mm of inflow to the underlying semiconfined aquifer. With respect to the processes that control the height of the water table in and near a wetland it is clear therefore that water uptake by vegetation plays a major role and needs to be taken fully into account.

Figure 4 is a schematic cross-section illustrating the groundwater flow patterns beneath and near undrained wetlands with intact vegetation. Fig. 4 also indicates the average position of the water table and of the groundwater level in an underlying semiconfined aquifer. The water table around the wetlands is continuous with the water level in the wetland ponds if ponds are present, (except during snowmelt if the ground below the pond is frozen (Hayashi et al, 2003). Beneath the higher-lying wetlands the water table elevation is above the groundwater level in the aquifer and the flow is downwards to the aquifer, meaning that this is a net groundwater recharge area. Beneath the lower-lying wetland the flow is upward, and this is a net groundwater discharge area. The portion of the water table shown in Fig 3 represents conditions when the ponds are full, as is usually the case after spring snowmelt. However, the water table position is highly variable. At the end of dry summers, when the ponds have dried out, the water table below the wetlands is much lower due to water uptake by the wetland vegetation including the "willow ring" and the lateral flow may reverse from outward from the pond to inward from the surroundings (Meyboom, 1966). Flow to or from the underlying aquifer is comparatively small in most cases and has little discernible impact on the position of the water table and the water balance of the wetland.

The important point is that the groundwater level in the aquifer responds to the changes of the spatially average of the water table elevation above it. If the average water table declines or rises then the aquifer level will decline or rise accordingly. For example, suppose that drainage of wetlands in the recharge area lowers the water table then the aquifer level will decline. Or, suppose that the wetland pond level in the discharge area is raised due to wetland consolidation, then the level in the aquifer will rise.

The question with regard to the impacts of wetland drainage can be phrased in terms of the effect of drainage on the over-all water table in the vicinity of the wetland, averaged over time and area, and the resultant changes of the groundwater level in the aquifer. The discussion does not directly involve knowledge of recharge rates, which in any case are very difficult to estimate. However, understanding and predicting the effects of wetland drainage on the groundwater levels requires understanding of the hydrologic processes which control the position of the water table.

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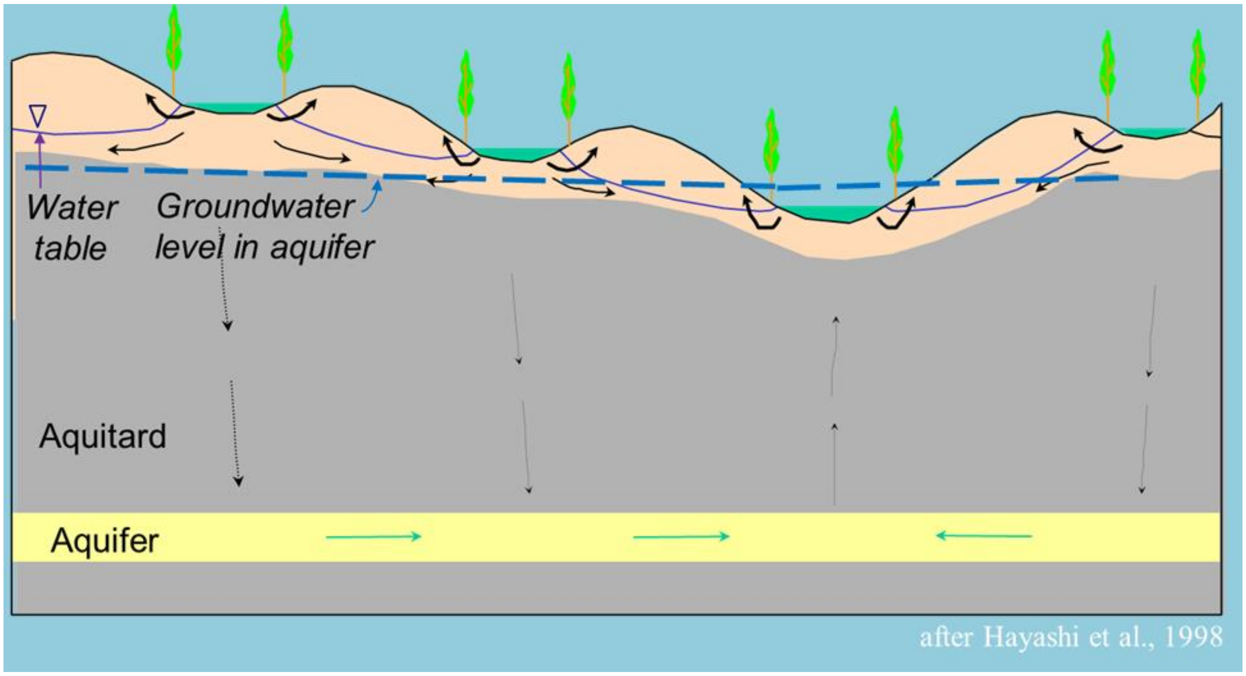

Figure 4. Schematic cross-section of a wetland complex showing groundwater flow directions and the position of the water table and of the groundwater level in an underlying aquifer. The shallow fractured and more permeable part of the aquitard is indicated by lighter colour.

3.2 Dominant role of small depressions with ephemeral ponding

Recent studies have shown that most of the depression-focused recharge takes place through the smallest depressions that are classified as type 1 and 2 wetlands (ephemeral ponding) or through small and shallow depressions. The latter may not be classified as wetlands or may not be recognized at all, other than as temporary shallow “puddles” in the landscape. Water collects in these small depressions during snowmelt, by surface runoff over frozen soils and, rarely, after intense rainfall events. These small depressions store much of the surface runoff water that is generated in the uplands and feed water to lower-lying depressions by fill and spill of surface water, or by shallow subsurface flow of groundwater, especially during wet periods when the water table is near the ground surface (Brannen et al., 2015; Nachshon et al, 2014).

Fig 5. Field study of springtime infiltration under a small cultivated depression in the ST Denis National Wildlife Area, described in Hayashi et al. (2003), [photo G.van der Kamp, 2002].

The small depressions play a dominant role because they are by far the most numerous by number and typically they can each store 10's to 100's of cubic metres of surface water (Fig 5). The soil beneath the ponded water thaws out preferentially during snowmelt and these small depressions usually dry out within a few weeks by infiltration (Hayashi et al. 2003). They are typically cultivated except in very wet years and are not drained or at most partially drained or infilled. The lack of permanent vegetation enhances the recharge beneath these small depressions because there is no significant root uptake of water until root uptake by crops becomes active, 2 to 3 months after the water has infiltrated. By that time the water table "mounds" beneath the depressions have spread out beneath the surrounding dry land, at least in part beyond the reach of root uptake by crops.

In relation to wetland drainage it should be noted that the ditches leading from the drained depressions can be considered as depressions with ephemeral water storage and are likely to be sources of infiltration and recharge to the groundwater (Fig 5). Haque et al. (2018) report on a study carried out in the Broughton Creek watershed of Manitoba during which they observed water table rises beneath drainage ditches resulting from flow in the ditches. Similarly other artificial depressions such as roadside ditches and dugouts are also potential sources of recharge. The net rates of recharge beneath such ditches have not been evaluated in field studies and remain to be assessed.

Fig 5 A newly drained small wetland. Note the removal of the wetland vegetation and the ponded water remaining in the drained depression and in the drainage ditch (Photo; G. van der Kamp, 1999)

3.2 Recharge and discharge focused on wetlands in large depressions

Lissey (1971) formulated the role of depressions as "depression-focused groundwater recharge and discharge". The mention of discharge is important though often not considered. In hummocky landscapes a large fraction of groundwater discharge by its very nature is focused within depressions because discharge by root uptake and evaporation can occur only where the water table is near or at the ground surface (Fig. 4). Larger wetlands with permanent ponds tend to occur at the lowest elevations in the landscape and therefore typically receive groundwater discharge. Discharge of this type is not limited to isolated wetland depressions but also occurs in connected channel depressions that contain more or less ephemeral streams (e.g. Brannen et al., 2015).

Net groundwater discharge occurs at the edges of fresh-water "recharge" wetlands, especially if permanent vegetation is present (Hayashi et al., 2016). Meyboom (1966) already noted that removal of "willow-ring" vegetation from "sloughs' would increase the net groundwater recharge beneath them. The soils at the outer margin of most wetlands are enriched in carbonate and phosphate due to the discharge by root uptake of groundwater which was recharged beneath the wetland ponds and carried with it the carbonates that were leached from the soils of the wetland centre (Pennock et al., 2014; Lokken et al., 2017).

In the context of wetland drainage it is likely that larger drained wetland depressions (especially fresh-water type 2 and 3 wetlands with seasonal ponds) may continue to act as sources of groundwater recharge after drainage because there is likely to be ephemeral ponding of water within the drained wetland depressions during snowmelt. In other words, after drainage such drained wetland depressions should be considered as depressions with ephemeral ponds (Fig 6).

Fig. 7. Flooded wetland that receives overflow from the drained wetland in Fig 6 [G. van der Kamp photo]

Where wetland drainage occurs as consolidation by drainage of small higher-elevation wetlands into lower-lying wetlands the pond water levels in the receiving wetlands are increased (Fig 7). The effect will be that the groundwater levels in the underlying aquifer will also rise to match the increased water level in the pond. Higher aquifer water levels mean increased well yields. Thus wetland drainage coupled with wetland consolidation may increase groundwater resource availability.

3.3 Recharge in non-depressional areas

Recharge can also occur in non-depressional areas if the infiltrated water (precipitation minus surface runoff and evaporation) exceeds the moisture-holding capacity of the soil or the water uptake capacity of vegetation such as grasses or annual crops. In areas of clay-rich soils such recharge can occur during particularly wet periods when infiltration exceeds the demands of evaporation and root uptake by vegetation. At such times the water table rises beneath the uplands and the groundwater flow direction may be reversed from its normal outward flow direction. Shallow groundwater then carries dissolved salts towards the wetland ponds, sometimes resulting in marked increases of the total solute concentration of the ponded water (Nachshon et al., 2014). The rise of the water table during such wet periods will be reflected also as a rise in the groundwater levels of underlying semi-confined aquifers if any are present.

In areas of sandy soils, which have low moisture retention capacity, groundwater recharge beneath uplands occurs in most years, especially during snowmelt. The resulting spring-time rises of the water table in the surficial aquifers show up clearly in the hydrographs of observation wells completed in such aquifers (Fig. 7). Average annual recharge rates for such aquifers amount to several 10's of mm and the groundwater in such aquifers also tends to have low dissolved solids because the sands contain few soluble minerals. In areas of surficial sands wetlands occur only where the water table in depressions remains near or above the soil surface for most of the year. Usually wetlands are less numerous in such areas if the underlying water-table aquifer drains to nearby streams or lakes. Wetland drainage is probably also less common, if only because the soils may be suitable only for pasture.

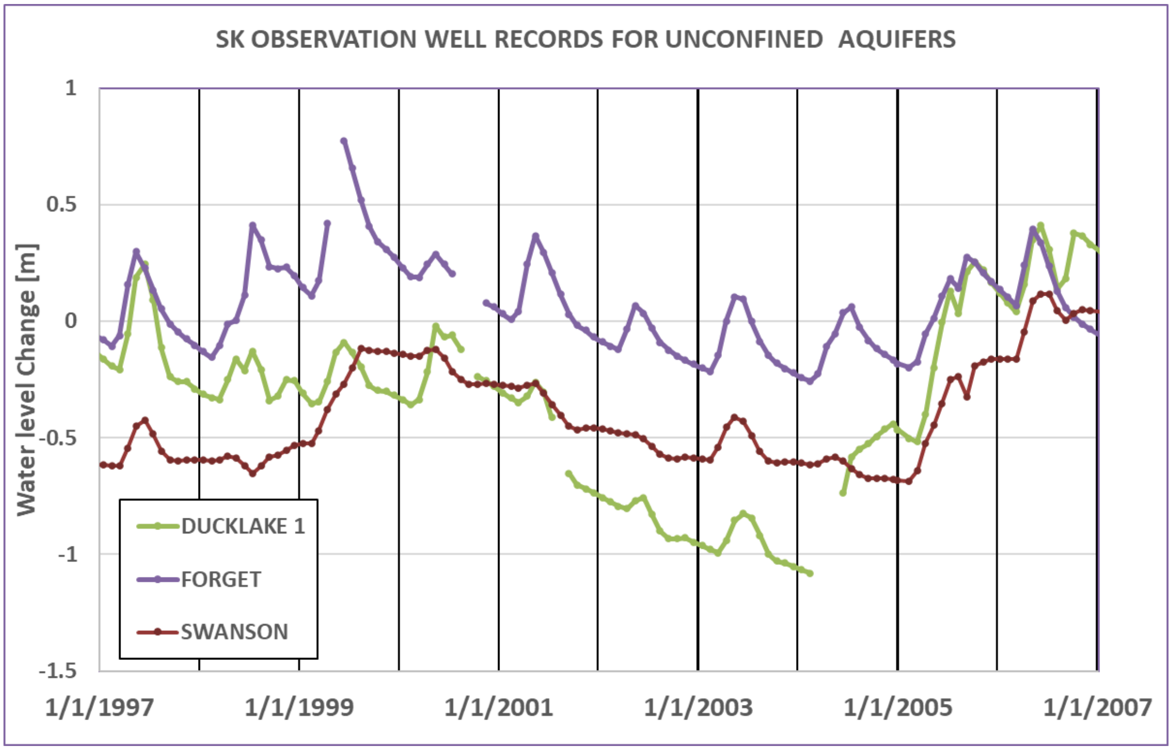

Figure 7. Details of hydrographs for three observation wells in shallow unconfined water table aquifers: Duck Lake 1 (average water table depth 3.6 m), Forget (average water table depth 2.4 m). Swanson (average water table depth 5.7 m).

3.4 Effects of upland and wetland vegetation

Vegetation plays a critical and complex role in the uptake of water from the soil and from shallow groundwater. That much is obvious already from a consideration of the water balance of the southern Saskatchewan landscape: while annual precipitation lies in the range of 350 to 500 mm, the outflow from non-wetland areas and flow from hydrologically connected areas out of the region is estimated to be a few tens of mm (Toth et al., 2009; Hayashi et al., 2016). Virtually all the rest of the water loss is via root uptake by plants to support transpiration. The vegetation may be native prairie grass and tame grasses, shrubs and trees or annual crops. Figure 7 shows how in water table aquifers there is a marked decline of the groundwater level during the summer growing months, June to August, due to root uptake even where the water table is several metres below the ground surface. Details of this rapid decline show daily declines due to root uptake during the hours of most transpiration. The rapid summer decline may be followed by a slower decline during the following winter due to seepage to discharge areas. Each of these wells is surrounded by permanent grass and some trees and shrubs.

There have been major changes of vegetation in the prairie region over the past 100 to 150 years and the impacts of these ongoing changes on groundwater recharge and groundwater levels are only poorly understood. However, various studies have shown that soils beneath permanent undisturbed native grass are drier than beneath adjacent cropped land (van der Kamp et al., 2003), at least in part because deep-rooted permanent grasses transpire water during the shoulder seasons when annual crops are not yet growing or have matured and are harvested (Morgan et al 2021, Fig. .).

Any consideration of long-term changes of groundwater levels and of net groundwater recharge rates, whether beneath dry uplands or at wetlands, clearly must take into account the major changes of vegetation that have occurred and continue to occur. Even small changes of the timing and rate of transpiration due to changes of vegetation likely have had major impacts on soil water regimes, on wetland water regimes and on groundwater recharge and discharge. Added to that are effects of vegetation on snow accumulation and on the proportion of infiltration versus local runoff to ponds and streams.

The removal of perennial deep-rooted wetland vegetation which nearly always accompanies wetland drainage (Fig 5) is particularly important with regard to the hydrological effects of wetland drainage. Intact wetland vegetation is likely to begin active transpiration soon after snowmelt is complete and then begins to draw down any remaining ponded water and after that will draw on shallow soil moisture and groundwater, thus lowering the water table within the depression. In contrast, transpiration from annual crops seeded in a drained depression is not likely to become important until some time in June, by which time the infiltrated water has had time to spread laterally away from the depression, raising the water table over a larger area. The net effect of vegetation removal means that drainage coupled with vegetation removal may not lower the average height of the water table, and may even raise it.

3.5 Water table fluctuations and aquifer groundwater levels

The recharge and discharge processes summarized above together control the fluctuations of the water table with time, on time scales of days and seasons to annual and multi-year variations. Figures 2 and 7 show the water table variations recorded by observation wells completed in surficial sand and gravel aquifers. These records represent the response of the aquifer groundwater levels to recharge and discharge processes within the 100 metre scale of the sensing areas of the observation wells. As such these observation well records reflect local conditions, such as the influence of recharge and discharge at one or two of the nearest depressions and drainage of such depressions, snow-drift accumulations at a nearby windbreak tree line, and discharge of groundwater by root uptake during the summer. The annual fluctuations rarely exceed 0.5 metres (Fig. 1, 4) due to the high water storage capacity (or specific yield) of the sands which is typically equal to about 0.3.

Very few records are available for water table variations within clay and clay-rich till deposits. None of the Saskatchewan observation wells are completed in such materials. However observations of water table changes within the aquitards have been obtained and reported at individual research sites, typically within and around wetlands and small depressions and beneath nearby uplands (Keller et al., 1988, Fig. 11; van der Kamp et al., 2003, Fig. 7))). The fluctuations of the water table within the aquitards may be very small beneath well-drained and vegetated upland area and may amount to several metres of annual fluctuation in locations where infiltration is favored. The highest level of the water table in such settings usually occurs after spring snowmelt, much as for the water table in surficial sands.

The groundwater level records for semiconfined aquifers (Fig.3) show the damped and delayed response to water table fluctuations within the overlying clay and glacial till units. The water-table fluctuations are highly variable in space on the scale of the individual depressions and other variations in the landscape. The semiconfined aquifer groundwater records represent the smoothed and averaged response to the spatially and temporally variable water table above the aquifer, averaged over the 10 to 100 km^2 sensing areas of the observation wells if and where the aquifer extends that far. However, local hydrogeology and aquifer boundaries are generally not well known.

In the context of wetland drainage the large sensing areas of observation wells in semiconfined aquifers means that the groundwater levels in such aquifers “see” the effects of recharge and discharge at numerous small undrained depressions with ephemeral ponding, plus the effects of drainage of a smaller number of individual wetlands and the effects of the accompanying drainage ditches. Superimposed on these effects are the impacts of changes of vegetation and the large variations due to annual and multi-year changes of precipitation.

3.6. Impact of climate change on Prairie groundwater resources

Aquifer recharge is the net effect of complex interacting and opposing water fluxes each of which is influenced by precipitation, snow accumulation and snowmelt and evapotranspiration. Therefore, consideration of the long-term impact of wetland drainage on groundwater resources must take climate change into consideration. Not surprisingly, the impact of climate change on groundwater resources in the Prairie pothole region is uncertain, with some research predicting an increase in recharge to the water table due to an earlier start to a longer recharge season with lower recharge rates (Zhang et al. 2020), while other models predict a decrease in groundwater recharge due to lower snow accumulation and reduced spring runoff (Negm et al. 2021).

4. Does wetland drainage reduce groundwater recharge and groundwater resource availability?

As indicated by the foregoing review, the concept that wetland drainage will reduce groundwater recharge needs to be considered critically in the light of several important factors:

a) surface runoff water flowing into a drained depression is not completely and instantaneously removed to a stream, but lingers in the depression and in drainage ditches because the bottom of the ditches is rough and traps some of the water and because significant flow of water in the ditches cannot happen until the water depth is sufficient to allow flow

b) the removal of deep-rooted perennial vegetation from the drained depressions, with its high water demand in spring and early summer, must be taken into account,

c) assessment of net recharge and changes of groundwater levels in regional aquifers must take into account the important role of net recharge in very small cultivated depressions, most of which are not drained because they fall dry within weeks in any case, and which may not be classified as wetlands,

d) depression-focused groundwater **discharge** must be taken into account and the small difference between recharge and discharge which equals net recharge or discharge,

e) Net groundwater recharge also occurs beneath dry uplands during extended very wet periods, and almost every year in areas of sandy soils.

Wetland drainage turns the former vegetated wetlands into cultivated depressions with ephemeral ponds and adds drainage ditches which also act as depressions with ephemeral ponding. Such ephemeral ponds without permanent vegetation are known to be a focus of groundwater recharge. Consideration of all these factors indicates that the net effect of wetland drainage on groundwater levels and groundwater resource availability is uncertain and likely small.

Numerical models of the effects of wetland drainage cannot be adequately tested because there is a shortage of experimental field data on the groundwater effects of wetland drainage and restoration. Thus such models cannot provide reliable assessments and predictions of the effects of wetland drainage on groundwater recharge and discharge. The long-term observation well data show that groundwater level changes in regional aquifers are dominated by the variability of precipitation and by the effects of groundwater withdrawals. The observation well records show no identifiable effects of drainage on groundwater level. However, none of the observation wells are located in areas of intense wetland drainage in Saskatchewan. Further consideration and study of the effects of wetland drainage appears to be necessary and will probably involve a review of presently available data, experimental field studies of wetland drainage, assessment and adaptation of numerical process models and long-term monitoring of drainage projects in different settings.

5. Mitigation and management to maintain or enhance aquifer groundwater replenishment

What mitigation and management practices can be adopted to ensure the sustainability of Prairie groundwater resources? Answering this question is important to developing sound, science-based wetland management policies. Given the uncertainties with regard to the impact of wetland drainage on groundwater resources it would be premature to specify mitigation measures, but some general insights and measures can be described.

5.1 Physiographic indicators of critical wetlands-groundwater interactions

Topographic, geological, and land-use features provide some indication as to the role of a wetland in supporting shallow groundwater resources. Identifying these features can be a first step in developing effective wetland mitigation and management practices.

Pond permanence:

As discussed above, recent site-scale research and analysis of the isotopic data provide evidence that small depressions with ephemeral ponds and slightly larger depressions that are classified as type 1 and 2 wetlands are the primary source of shallow groundwater recharge and groundwater resource replenishment for unconfined water table and semiconfined aquifers (Bam et al. 2020). More permanent wetlands are more likely to act as a groundwater discharge point.

Hydraulic resistance of deposits overlying regionally important aquifers:

Wetland complexes overlying regionally important aquifers are significantly more likely to act as a source of groundwater replenishment if the hydraulic resistance of the deposits overlying the aquifer is low. The hydraulic conductivity, and therefore the ability to transmit water, commonly decreases with depth in clay rich tills (Hayashi and van der Kamp, 2016; Ferris et al., 2020). Therefore groundwater resources in areas with shallow semiconfined aquifers are more likely to be sensitive to the hydrological effects of wetland drainage, particularly if the groundwater level in an aquifer is deep below the ground surface in the wetlands. Deeper aquifers overlain by thick, low-hydraulic conductivity aquitards are unlikely to be significantly impacted by wetland processes. The Aquifer Vulnerability Index (AVI) and aquifer maps of south Saskatchewan prepared on behalf of the Water Security Agency provide a regional assessment of the hydraulic resistance of confining units in southern Saskatchewan.

Classification of landscape features critical for groundwater processes:

The identification of landscape features that control groundwater processes and the development of hydrogeological classification systems can aid in the development of science-based, coherent groundwater management and protection policies. To this end, the province of Alberta has developed a hydrogeological classification system based on the description and delineation of 10 hydrogeological regions. These hydrological regions are defined on the basis of the primary characteristics of land elevation, bedrock physiography, sediment thickness, bedrock geology as well as regional climate, surficial geology, surface morphology, groundwater resources (Alberta Geological Survey, 2021). To date, such a regional hydrogeological classification has not been conducted in Saskatchewan, although excellent groundwater resource maps have been developed at the NTS map sheet scale on behalf of the Water Security Agency. In the absence of regional hydrogeological classification, the classification systems for hydrological basins in the Prairie region - such as Wolfe et al. (2019) may provide a useful basis for developing wetland management strategies based on landscape types. However, such classifications should include hydrogeological factors.

5.2 Mitigation of the impact of wetland drainage on groundwater resources

The preceding discussion suggest considerations that are most important with respect to maintaining groundwater resources in the context of wetland drainage. These considerations can guide the development of mitigation and management practices that could be adopted to ensure the sustainability of Prairie groundwater resources. Such mitigation practices are not likely to be widely applied, but may be advantageous in focused areas where groundwater resources are particularly important and where wetland drainage is most likely to have a negative impact on groundwater resources.

Preservation and management of surface runoff water collection:

Retention of surface runoff water in drained depressions and ditches for a few weeks enhances groundwater recharge. Such temporary retention happens in any case but could be increased if and where enhanced groundwater recharge is judged to be important. Such temporary retention of surface water can be adjusted depending on wet or dry conditions. During dry years temporary water retention for enhanced infiltration would serve to maintain groundwater levels and can also benefit crop growth. Current farming practice deals with variable moisture and could be adjusted to incorporate water retention in dry years. The same retention methods that may be used for mitigation of flooding during wet conditions may also be used during dry conditions to maintain groundwater levels.

Management of vegetation:

Vegetation in small depressions and drained wetlands can be used to manage subsurface water storage, much as summer fallowing conserves soil moisture. Removal of vegetation reduces water losses and maintains the water table. Presence of deep-rooted vegetation increases water losses by transpiration and increases available subsurface storage, thus possibly mitigating downstream flooding while keeping water tables low. Retention or removal of vegetation may need to take groundwater recharge into account during dry periods if and where mitigation of drainage impacts on groundwater resources are found to be important. Probably this already happens because small depression that are cultivated during dry periods may be left uncultivated and vegetated during wet years.

Assessment of regionally important aquifers:

Wetland complexes that are potentially significant to supporting regional groundwater resources may be identified by assessing the depth to regionally important aquifers and estimating the hydraulic resistance of overlying confining units, as in the mapping of the Aquifer Vulnerability Index (AVI). Wetland complexes overlying regional aquifers with low hydraulic resistance (high vulnerability) could be identified for evaluation and possible mitigation of the potential impacts of wetland drainage on the groundwater resources of the aquifers, with priority given for aquifers that support significant groundwater withdrawals, as for example the aquifers supplying groundwater for Yorkton, and the Zehner Aquifer near Regina.

Methods of wetland management and drainage:

Drainage of wetlands is most likely to decrease groundwater levels if the drainage water is conveyed out of the area rapidly and with minimal water losses to infiltration. That is likely one of the reasons why subsurface tile drainage is commonly practiced in the parts of Iowa and south Dakota that lie within the glaciated interior plains, where precipitation is high and farmers try to keep the water table down even in drained depressions. If and where efficient tile drainage is introduced in Saskatchewan the effect on water table levels and aquifer groundwater levels should be taken into consideration.

Consolidation drainage leads to increased pond water levels in the receiving wetland and may lead to increased groundwater levels in underlying aquifers. The net effect of consolidation drainage may be a local enhancement of groundwater resource availability.

6. Understanding the role of wetlands in regional groundwater resource management - future research directions

Field studies of the groundwater effects of wetland drainage or restoration would presumably involve extensive arrays of shallow water table piezometers, comparable to the piezometer network in the St Denis National Wildlife Area (e.g Hayashi et al., 1998, 2003, 2016) and the network that was installed in the late 1980's to study the effects of irrigation in the Luck lake SK irrigation area. The shallow piezometer network should be complemented by observation wells in an underlying semiconfined aquifer. Multiple years of observations before and after drainage would be called for so as to allow for the observation of groundwater fluctuations due to multi-year wet and dry periods. Where no baseline data are already available a “space-for-time” design could be adopted in which several adjacent small wetlands are instrumented, monitored for a short time; some of the wetlands are drained or restored while others are left unchanged; and monitoring is continued.

The important role of vegetation in the water balance of wetland and water-collecting depressions requires attention. The comparative water losses from a depression by evapotranspiration from bare cultivated soil, annual crops, or perennial vegetation are not well understood or quantified. While evapotranspiration from intact vegetated wetlands has been studied in detail, very little information is available on how evapotranspiration changes if the permanent vegetation is removed and replaced by bare soil, annual crops or stubble. Detailed field studies of wetland drainage and restoration are called for in this regard, acknowledging and meeting the logistical challenges of installing and operating continuously monitoring instrumentation in the presence of disturbance by farm machinery and flooding. Such data would allow development and testing of numerical models that can provide reliable predictions of the effects of drainage and vegetation changes on hydrological processes within and near small depressions, which can then be extrapolated to larger areas and drainage projects.

It will be useful and necessary to conduct a systematic examination of how farmers choose which depressions to drain, and how they drain them, maintain the drainage ditches and how vegetation is managed in the drained wetlands. Such a study could utilize remote sensing (old aerial photographs, recent satellite images, etc.), ground-based validation, and interviews with farm operators in various parts of the province. Tile drainage should also be considered and its possible effects on groundwater assessed.

Several numerical models have recently been developed that provide results relevant to understanding the impact of wetland systems on groundwater (Zhang et al. 2020; Negm et al. 2021). The Versatile Soil Moisture Budget – Depression Upland System (VSMB-DUS) model developed in Alberta (Norduijn et al. 2018) in particular could be used to simulate changes to groundwater recharge at a regional scale and could provide insight into the impact of various drainage scenarios by modifying the depression area to catchment area ratios or volumetric capacities (Klassen et al. 2018). The Prairie Hydrological Model (PHM), based on the Cold Regions Hydrological Model (CRHM), represents dominant hydrological processes through physically-based modules and is capable of simulating the snow water equivalent and reasonably simulating runoff ratios and streamflow (Spence et al., 2021). This work may provide the foundation for the development of a model that can explore the impacts of wetland drainage on groundwater under different climate change, land-use, and wetland distribution and drainage scenarios.

7. Conclusions

Available data on the impacts on groundwater levels of wetland drainage in southern Saskatchewan are limited and insufficient for identification of discernible effects on groundwater levels of regionally important aquifers and available groundwater supplies.

The net aquifer-wide impact of wetland drainage coupled with the removal of permanent vegetation is uncertain and has not been quantified through field studies. It may be that groundwater recharge is not significantly changed by wetland drainage or may even be increased, while discharge of groundwater by evapotranspiration is reduced by removal of perennial deep-rooted vegetation that accompanies nearly all wetland drainage..

The short review of the concepts and groundwater data suggests that any impacts of wetland drainage on regional groundwater resource availability are probably small. The other strong influences on groundwater recharge, discharge, and groundwater levels, especially climatic variability, obscure any wetland drainage effects. However, wetland systems are closely connected to groundwater resources and the overall impact of wetland drainage on regional groundwater resources is uncertain. Increased monitoring and further study of wetland drainage or restoration and groundwater for high-priority aquifers is recommended, aimed at identifying possible impacts and developing effective mitigation measures if and where these are deemed to be advisable.

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Appendix

TABLE Summary of "affected"/"unaffected"long-term WSA observation wells				
Well Name	**Depth**	**Aquifer**	**formation**	**Affected/unaffected by pumping, other effects?**
	Below TOC			
	m			
Agrium 43	18	intertill	Intertill Undefined	Yes - mine tailings area
Armley	155	bedrock	Mannville Group	Yes
Atton's Lake	16	surficial	Surficial Stratified Drift	No
Baildon 059	30	intertill	Intertill Undefined	Yes? Effluent irrigation
Baildon 060	13	surficial	Surficial Stratified Drift	Yes- effluent irrigation
Bangor A	39	buried valley	Empress Group	No
Bangor B	15	intertill	Intertill Undefined	No
Beauval	16	intertill	Intertill Undefined	No
Blucher No.3	79	buried valley	Empress Group	Yes
Blucher No.4	51	intertill	Intertill	Yes
Bruno	180	buried valley	Empress Group	Yes - pumping
Conquest No.500	19	intertill	Intertill Undefined	No
Conquest No.501	8	surficial	Surficial Stratified Drift	No
Conquest No.502	19	intertill	Intertill Undefined	No
Conquest No.503	8	surficial	Surficial Stratified Drift	No
Conquest No.504	83	Tyner Aquifer	Intertill Undefined	Yes - pumping
Coronach 001	37	bedrock	Ravenscrag Formation	Yes - coal mining
Crater Lake	12	surficial	Till	Yes - surface water
Dalmeny	27	Dalmeny Aquifer	Intertill Floral Formation	Yes - minor pumping
Duck Lake No.1	13	surficial	Surficial Stratified Drift	No
Duck Lake No.2	125	buried valley	Empress Group	No

Estevan No.1	143	Estevan Aquifer	Empress Group	No
Estevan No.2	145	Estevan Aquifer	Empress Group	Yes -pumping
Fife Lake 002	10	bedrock	Ravenscrag Formation	Yes - surface water
Forget	6	surficial	Surficial Stratified Drift	No
Garden Head	23	bedrock	Eastend-Frenchman Formation	No
Goodale Farm 009	10	surficial	Surficial Stratified Drift	Yes - surface water (wetland)
Hague	50	intertill	Intertill Undefined	Yes -surface water (S Sask River)
Hearts Hill	77	bedrock	Judith River Formation	Yes ? Minor pumping
Instow	555	bedrock	Judith River Formation	Yes -pumping
Lilac	123	buried valley	Empress Group	No
Meadow Lake	73	buried valley	Empress Group	No
Melfort	11	surficial	Surficial Stratified Drift	No
Nokomis	100	Hatfield Aquifer	Empress Group	Yes? Minor pumping
Outram (SRC 2)	111	Estevan Aquifer	Empress Group	Yes - pumping
Regina 530	39	Regina City Aquifer	Intertill Floral Formation	Yes - pumping
Riceton	22	Emp.	Empress Group	No
Saskatoon	27	Forestry Farm Aq	Intertill Floral Formation	No
Shaunavon	16	bedrock	Eastend-Frenchman Formation	Yes? Pumping
Simpson 13-04	7	surficial	Surficial Stratified Drift	No
Simpson 16-05	6	surficial	Surficial Stratified Drift	No
Smoky Burn A	37	bedrock	Mannville Group	No
Smoky Burn B	6	surficial	Till	No
Stenen	15	surficial	Surficial Stratified Drift	No

Swanson	9	surficial	Surficial Stratified Drift	No
Tessier	26	Tessier Aquifer	Intertill Undefined	No
Tyner	114	Tyner Aquifer	Empress Group	No
Unity	27	intertill	Intertill Undefined	No
Vanscoy	89	Tyner Aquifer	Empress Group	Yes pumping
Verlo	13	surficial	Surficial Stratified Drift	No (vegetation change?)
Warman No.1	108	Tyner Aquifer	Empress Group	No
Warman No.2	109	Tyner Aquifer	Empress Group	Yes? pumping
Yorkton 517	40	Emp.	Empress Group	Yes - surface water connection
Yorkton 519	7	surficial	Till	Yes - surface water connection