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Synthesis of science: findings on Canadian Prairie wetland drainage

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Background, and goals of this synthesis

Extensive wetland drainage has occurred across the Canadian Prairies, and drainage activities are ongoing in many areas (Dahl 1990; Watmough and Schmoll 2007; Bartzen et al. 2010; Dahl 2014; Prairie Habitat Joint Venture 2014; Dumanski, Pomeroy, and Westbrook 2015; Waz and Creed 2017). In 2017 the Global Water Futures program funded the Prairie Water project, with the broad goal of helping to foster improved water security in the region (Spence et al. 2019). Throughout the duration of this project, it has been clear that a diverse group of stakeholders (including river basin organizations, government agencies, and landowners) is seeking the same information – a synthesis of what is known and not known about the effects of wetland drainage.

This synthesis of the state of the science on wetland drainage in the Canadian Prairies is aimed at assembling current knowledge based on western scientific methods to articulate what is known about the variability of drainage effects across the region. Traditional knowledge, which represents a different but complementary way of knowing the functioning of prairie watersheds (sometimes also termed catchments, or basins), and the processes driving change within them, is not discussed here. Instead, this synthesis is presented in the spirit of building such collaborations. It summarizes current western scientific knowledge on surface hydrology, groundwater interactions, nutrient export, biodiversity, carbon storage and greenhouse gas dynamics, and wetland conservation socioeconomics. The implications for water security now and in the future are also discussed.

Context and key definitions

1. A wetland is an area of land where inundation with water creates a distinct ecosystem based on hydrology, development of hydric soils (distinct in their development due to the presence of water and low-oxygen conditions) and growth of vegetation adapted for life in water-saturated soils (Stewart and Kantrud 1971; Warner and Rubec 1997; van der Kamp et al. 2016). A wetland may be classified by the patterns of inundation or ‘pond permanence’. A wetland may have areas that are permanently, semi-permanently or seasonally saturated with water and in some cases, water may be present at the surface for only a period of weeks (Stewart and Kantrud 1971; van der

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Kamp et al. 2016). Wetlands often occur at the edges of other water bodies, like streams and lakes. In the Canadian Prairies, wetlands also commonly occur in geographically isolated, internally drained topographic depressions; this review is focussed on these depressional wetlands, which are an important feature of the Canadian Prairie landscape and are subject to management and change (eg via drainage and restoration). The terms 'sloughs', 'marshes' and 'prairie potholes' are commonly used to refer to these depressional wetlands.

a. Prairie potholes exhibit a diversity of functions, including hydrological (fill, spill, merge: Leibowitz, Mushet, and Newton 2016; Chu 2017), biogeochemical (reception, processing, storage, release) and biodiversity-related functions including crucial habitat for native flora and fauna. These functions vary with time and across space and among pond permanence classes (Stewart and Kantrud 1971). Wetlands with temporary and seasonal ponds are numerically dominant, although those with semi-permanent and permanent ponds account for the majority of wetland area (Ducks Unlimited Canada, unpublished data in Doherty et al. 2018).
b. A wetland complex refers to the cluster of wetlands within an area, landscape or watershed. A wetland complex contains wetlands spanning a diversity of sizes and with varying pond permanence and depth of inundation. Wetland complexes are ecological functional units of the Prairie Pothole Region (Johnson et al. 2010), and provide ecosystem services at a landscape scale, including flood and drought mitigation, groundwater recharge, benefits to water quality, maintenance of biodiversity, and carbon processing (Gleason, Laubhan, and Euliss 2008; Johnson et al. 2010). The functions and services of wetland complexes differ from those of individual wetlands and depend in part on the size distribution and spatial arrangement of wetlands within the complex. The response of the wetland complex to inputs from snowmelt and/or rainfall will depend on this arrangement and on the antecedent storage within each of the individual wetlands.
c. Wetland complexes are highly influenced by inter-annual and inter-decadal variability in precipitation, and thus the presence of water within wetland complexes is temporally dynamic (Niemuth, Wangler, and Reynolds 2010). These temporal and spatial factors are important to contextualize 3when considering impacts of management and policies, such as those relating to wetland drainage.

2. Drainage, one in a suite of practices termed 'agricultural water management', is used to manage surface water in agricultural landscapes. Drainage practices vary widely and can include ditching, infilling and consolidating. The latter, consolidation, involves draining multiple small wetlands into a single larger wetland. Drainage channels can also be gated to help control peak flows, or other flow-control options may be used. In most of the Canadian Prairies, surface drainage is more common than tile drainage, although tile drainage is expanding, most rapidly in Manitoba. The focus here is on surface drainage.
3. The effects of drainage are varied and can be complex. The structure of the natural landscape (eg slope; land cover; number, position, size and permanence of ponds within the wetland complex) and the locations of grid and paved road networks and culverts dictate the effects of drainage. The response to drainage can be specific to the changes that are made to the landscape, including the adoption of practices for managing flows such as gated or throttled culverts or constructing small reservoirs to restore storage capacity.
4. Estimates of wetland loss due to drainage remain uncertain due to challenges in identifying historical drainage; limited monitoring; challenges associated with methods, definitions of loss and measurement scale; and variable hydrologic conditions creating high natural variability in pond extent. Nonetheless, it is clear that there has been a very large effect on both the number and area of wetlands throughout the region, and that the rate of loss due to drainage varies spatially (Watmough and Schmoll 2007). Historical estimates, while uncertain, suggest there has been a 40–70% wetland loss by area since agricultural expansion began (Watmough and Schmoll 2007; Davidson 2014). As noted, drainage is ongoing in many regions; hence, wetland loss continues.

While place-based context and nuances are important, there is a significant body of knowledge about the effects of drainage across the Canadian Prairies. The following sections synthesize scientific and economic knowledge regarding surface drainage in this region, complemented by generalizable process-oriented insights from other regions. A description of confidence in effects is provided, based on the relative amount of direct evidence and relative agreement in the evidence (sensu Mastrandrea et al. 2010).

Impacts of wetland drainage

PART A: IMPACTS OF WETLAND DRAINAGE ON WATER STORAGE AND MOVEMENT

1. Wetlands add to a watershed's storage capacity, the volume of water that can be held within the watershed (Fang et al. 2010; Ehsanzadeh et al. 2012; Shaw, Pietroniro, et al. 2013). Wetland drainage reduces surface water storage capacity (Ehsanzadeh et al. 2012; Shaw, van der Kamp, et al. 2012; Evenson et al. 2018).
2. Reducing the capacity of the landscape to hold water increases runoff connectivity and hence the contributing area that can generate runoff to streams (Godwin and Martin 1975; Shook et al. 2013). It also reduces the threshold rainfall or snowmelt volume needed for local runoff to generate streamflow (Hubbard and Linder 1986; Shook, Pomeroy, and Van der Kamp 2015). As a result, less precipitation or snowmelt is needed to generate an equal amount of runoff in a drained watershed than was required prior to drainage. Watershed discharge volumes increase with wetland drainage and decrease with wetland restoration (Wang et al. 2010).
3. Large wetlands in diverse regions can act as notable 'gatekeepers', holding back uphill runoff until their storage capacity is filled (Tiner 2003; Phillips, Spence, and Pomeroy 2011). Hence, drainage of one small wetland has less impact on discharge than drainage of one large wetland because there is less storage capacity in a small wetland (Shaw, van der Kamp, et al. 2012). The spatial arrangement of depressions can influence runoff response by dictating hydrological connectivity (Fossey, Rousseau, and Savary 2016) and contributing to area dynamics (Grimm and Chu 2018; Wang, Chu, and Zhang 2021). In the typical dry climate of the Canadian Prairie, where wetlands often provide storage capacity, drainage of wetlands closer to the stream outlet results in a more rapid expansion of area contributing to the outlet than does drainage of wetlands in upper reaches.
4. Wetland drainage can increase the efficiency with which water runs off fields. Ditches often have less surface roughness and greater slopes than agricultural fields (Acreman and Holden 2013). This reduces detention storage (ponding) between depressions and allows faster discharge of water.
5. A major effect of reducing storage capacity and surface roughness is that it can make some high-flow events more frequent or greater in magnitude (Evenson et al. 2018; Spence and Mengistu 2019). Conversely, having more wetlands in the landscape can reduce peak flow events (Shook and Pomeroy 2011; Shook, Pomeroy, and Van der Kamp 2015; Evenson et al. 2015, 2018; Fossey, Rousseau, and Savary 2016). Importantly, how drainage influences flood frequency and severity will depend on the precipitation and climate, structure of the watershed (eg slope, and number, size and position of wetlands: Shook et al. 2013; Fossey, Rousseau, and Savary 2016; Evenson et al. 2018), watershed size (Ehsanzadeh, van der Kamp, and Spence 2016), and extent and nature of drainage (Ehsanzadeh, van der Kamp, and Spence 2016). There remain important gaps in our knowledge of how individual watershed structures respond to drainage (e.g. Wolfe et al. 2019). Deficiencies in regional precipitation data and records of the historical extents of drainage make it difficult to disentangle the effects of weather, climate, antecedent wetland storage and drainage on floods in Prairie watersheds (eg Smith Creek, Assiniboine River) (Dumanski, Pomeroy, and Westbrook 2015; Ehsanzadeh, van der Kamp, and Spence 2016).
6. The impact of drainage on the outflow from any individual wetland is hard to predict, because:
    a. There is high natural variability in water storage and flows. One crucial control is the impact of the redistribution of blowing snow from adjacent fields to the depression, and from local snowmelt from snowdrifts on slopes above the wetland (Fang and Pomeroy 2009). Snow redistribution is dependent upon surrounding vegetation heights, seasonal snowfall and winter storm conditions and is relatively insensitive to wetland drainage.
    b. While drainage reduces surface storage, it does not immediately affect subsurface storage. Depressions without ponded water will lose subsurface water from evapotranspiration during the growing season (Hayashi, van der Kamp, and Rosenberry 2016). This can contribute to moisture deficits in the soil

which will help accommodate snowmelt. If soils of drained wetlands become unsaturated because of dry conditions and freeze in this state, then infiltration of snowmelt water into frozen soils the following spring may be enhanced. This can help to reduce runoff as compared to what would be observed from saturated frozen soils; however, the overarching effects on runoff are also governed by the loss of surface storage associated with drainage.

Clearly, site-specific knowledge related to wetland and watershed conditions is important for understanding the effects of drainage.

PART A – SYNTHESIS. The most important impact of wetland drainage on surface water storage and movement is an increase in discharge volume with declining storage capacity and more efficient runoff generation. This increase in discharge volume can be large. A second impact is an increase in flood frequency for some watersheds. Greater flooding is expected from drained watersheds, under fixed climate conditions. Variability in hydrometric geometry and structure within watersheds and in climate between watersheds creates regional differences in hydrological responses to drainage and thus the magnitude of drainage impacts. Determining the exact influence of drainage on floods in large watersheds is more difficult because of the complicating influences of climate change and river regulation by dams and diversions.

Confidence of effects: There is *moderate to high certainty* that wetland drainage can increase annual discharge volumes and *moderate to high certainty* that wetland drainage can increase flood magnitudes and frequency (*high agreement*, *medium evidence*). Local variations in the magnitude of hydrological impacts from drainage are due to watershed drainage system structure, wetland sizes and climate.

PART B: IMPACTS OF WETLAND DRAINAGE ON NUTRIENT EXPORT

1. Wetland drainage can increase nutrient export through a variety of mechanisms (Cohen et al. 2016; Badiou, Page, and Akinremi 2018; Wilson et al. 2019). The most direct driver of this effect is greater discharge volumes with drainage of wetlands (see Part A). In the Canadian Prairies, nutrient concentrations typically remain constant, or increase with increasing flows (Ali et al. 2017; Wilson et al. 2019); hence, an increase in flow volume is expected to lead to an increase in nutrient loads. More frequent high flows (see Part A) can lead to higher nutrient concentrations and loads in some areas due to increased soil erosion and nutrient transport (Ali et al. 2017; Zhang et al. 2017; Wilson et al. 2019). Nutrient loads are positively related to the contributing area of a watershed (Badiou, Page, and Akinremi 2018; Wilson et al. 2019); hence, an increase in contributing area associated with drainage (see Part A) is an important mechanism affecting nutrient export. It is important to note there is high inter-annual variation in nutrient loading. The effects of drainage on nutrient loading are expected to be most pronounced in wet periods, with little or no effect in dry periods.
2. Wetlands globally and regionally are known to be ecosystems with high rates of biogeochemical processing, which can contribute to nutrient and sediment retention (Cheesman et al. 2010; Evenson et al. 2015; Marton et al. 2015; Cohen et al. 2016; Cheng and Basu 2017; Haque, Ali, and Badiou 2018).
    a. Drainage of wetlands results in the loss of wetland biogeochemical functionality and a decrease in the nutrient retention capacity of the landscape (Brunet and Westbrook 2012; Marton et al. 2015; Van Meter and Basu 2015).
    b. Some functionality may be partially compensated by nutrient processing occurring in soils and sediment within drainage ditches and crop nutrient uptake; however, these processes will vary by chemical. In addition, pools and process rates also vary in space and time (Brunet and Westbrook 2012; Brown et al. 2017a, 2017b; Zhang et al. 2017).
    c. Other land-use practices that are employed in conjunction with drainage, such as fertilizer additions and tillage, could exacerbate potential nutrient loss from drained wetland soils, although high rates of plant removal may partially mitigate this effect (Streeter and Schilling 2015; Brown et al. 2017a). Conversion of wetlands to cropland can change an area that previously functioned as a nutrient sink to a nutrient source (Badiou, Page, and Akinremi 2018; Evenson et al. 2018; Haque, Ali, and Badiou 2018). Drained and cultivated wetlands can be areas of high nutrient concentration or export (Skopec and

Evelsizer 2018; Martin, Soupir, and Kaleita 2019).

d. Finally, while nutrient retention along drainage channels may be low or insignificant in cold periods (Brunet and Westbrook 2012), active nutrient cycling in other periods can also influence the effects of drainage on nutrient export (Zhang et al. 2017).

PART B – SYNTHESIS. Wetland drainage is expected to increase nutrient export. There are documented effects on chemistry, contributing area and flow, all of which can impact nutrient transport and erosion risk. Similarly, drainage can result in loss of nutrient retention capacity. Factors altering the impact of drainage on nutrient export across watersheds include the physical structure of a watershed, extent of drainage-induced change to wetland complex function, nutrient management practices, erodibility of soils, weather and climate.

Confidence of effects: There is *moderate to high certainty* that drainage can increase nutrient export (*high agreement*, *medium evidence*). The magnitude of impacts is less certain due to limited direct study and geographical variation amongst Canadian Prairie watersheds, as well as high inter-annual variation in precipitation and runoff.

PART C: IMPACTS OF WETLAND DRAINAGE ON SURFACE WATER–GROUNDWATER INTERACTIONS AND SALINITY

1. Individual wetlands are diverse in the ways that they interact with groundwater. Wetlands that have a dominant role in recharging groundwater are often the ephemerally or seasonally flooded wetlands in elevated parts of the landscape (van der Kamp and Hayashi 1998; Pavlovskii, Hayashi, and Cey 2019; Bam et al. 2020). Drainage of these seasonally flooded wetlands may result in reduced groundwater recharge. In contrast, large, permanently ponded depressions in lower elevation parts of the landscape can often receive discharge from groundwater (Hayashi, van der Kamp, and Rosenberry 2016). Discharge wetlands are unlikely to be candidates for drainage due to their location and salinity. Where drainage of these wetlands does occur, this could also lead to decreased groundwater storage due to enhanced groundwater discharge.
2. Salts of geological origin accumulate in prairie soils. In an undrained wetland, the salts are flushed into the wetland with rainfall and snowmelt events and migrate back into the soils and groundwater, particularly in the riparian zone, through infiltration and percolation, driven in part by riparian and upland transpiration (Nachshon et al. 2013). In a drained wetland this cycle may be interrupted, whereby the salts are flushed from the soils into the wetland and exported downstream over a long period of time, perhaps over decades (Heagle, Hayashi, and van der Kamp 2013; Levy et al. 2018). The potential negative consequence of this would be the long-term salinization of downstream soils and receiving water bodies.

PART C – SYNTHESIS. Drainage of seasonally and ephemerally flooded depressions will lead to reduced groundwater recharge. This may affect groundwater availability for domestic use, particularly to rural residents and municipalities dependent upon shallow groundwater resources. Drainage can also result in the export of salts from upland soils, with the risk of long-term salinization of downstream soils and water bodies.

Confidence of effects: There is *high certainty* that drainage of seasonally and ephemerally flooded depressions will reduce shallow groundwater recharge (*high agreement*, *medium evidence*). The certainty regarding drainage impacts on salt transport is *moderate* due to high spatial variability.

PART D: IMPACTS OF WETLAND LOSS ON BIODIVERSITY

1. Wetlands are a defining natural feature of the Prairie region and are biodiversity 'hotspots' – supporting hundreds of animal and plant species (Semlitsch and Bodie 1998; Jenkins, Grissom, and Miller 2003; Calhoun et al. 2017; Mantyka-Pringle et al. 2019; Vickruck et al. 2019).
2. Maximum biodiversity is achieved when there are a variety of wetland sizes and permanence classes present in wetland complexes, such that a diversity of habitats are available (Euliss et al. 2004; Johnson et al. 2010; Mushet, Euliss, and Stockwell 2012; Mushet et al. 2013; Uden et al. 2014; Evenson et al. 2018; Schofield et al. 2018; Elliott, Igl, and Johnson 2020). At a landscape scale, shifting from a natural wetland structure with a variety of sizes and permanence classes to consolidated wetlands will lead to loss of biodiversity, especially if natural pathways among wetlands are lengthened or restricted (Mushet, Euliss, and

Stockwell 2012; Uden et al. 2014; McLean et al. 2020).

3. Drainage to date has led to significant habitat loss (see 'context and key definitions') although it can be difficult to accurately quantify wetland loss, both because of the variable nature of inundation and because drainage activities preceded the collection of observational data for use as a baseline in many areas (Davidson 2014).
4. Wetland drainage and wetland consolidation have a negative impact on biodiversity.
   a. All aquatic biota (microbial, plant, animal) are lost when a wetland is permanently converted to agricultural land (Dahl 1990; Jenkins, Grissom, and Miller 2003); local terrestrial biota also lose a water source, aquatic food subsidies and remnant upland habitat within the wetland (Mushet, Euliss, and Stockwell 2012; Steen and Powell 2012; Mantyka-Pringle et al. 2019; Vickruck et al. 2019).
   b. Small ephemerally and temporarily flooded wetlands are among those most impacted by agricultural practices (Bartzen et al. 2010; Van Meter and Basu 2015; Serran and Creed 2016). These wetlands provide habitat to plants, macroinvertebrates and amphibians as well as important food sources for migrating birds in the early spring, and the loss of these wetlands has negative impacts on biota that rely on their services (Semlitsch and Bodie 1998; Balas, Euliss, and Mushet 2012; Mushet, Euliss, and Stockwell 2012; Uden et al. 2014; Schofield et al. 2018; Vickruck et al. 2019). Despite their small size, these wetlands may be particularly important or 'keystone' natural features of prairie landscapes (Hunter 2017) due to their disproportionate impacts on biodiversity (Bartzen et al. 2017; Calhoun et al. 2017).
   c. Eliminating wetlands and surrounding riparian habitat reduces the capacity of Prairie landscapes to support native fauna and flora (Aronson and Galatowitsch 2008; Balas, Euliss, and Mushet 2012; Steen and Powell 2012; Mushet et al. 2018; Mantyka-Pringle et al. 2019).
   d. The habitats provided by wetlands (including ponds, riparian areas and adjacent upland areas), and thus the species assemblages these habitats can support, are not interchangeable, as each will support different communities. Maximizing species richness in a landscape is a balance of available habitat, diversity of available habitat and habitat heterogeneity (Uden et al. 2014; Elliott, Igl, and Johnson 2020). This is especially true in the case of wetland-obligate species, which rely on habitat and services provided by wetlands at some point in their life cycle (Mushet, Euliss, and Stockwell 2012; Bartzen et al. 2017).
5. Some drainage practices and patterns can result in changes to the distribution of types of wetland, contributing to loss of function even where drainage is limited to a subset of wetlands in a complex (Van Meter and Basu 2015; Evenson et al. 2018; Johnston and McIntyre 2019). Drainage tends to alter the size structure of wetlands. In particular, consolidation drainage can cause homogenization of available habitat towards larger, deeper, more permanently flooded wetlands (Euliss and Mushet 2004; Van Meter and Basu 2015; McLean et al. 2020). While consolidation drainage can partly compensate for drainage by retaining water, helping to maintain habitat for some species (especially during drought periods), the benefits of wetland consolidation may be biased towards certain species tolerant of reduced habitat heterogeneity (Euliss and Mushet 2004; McLean et al. 2020; Elliott, Igl, and Johnson 2020).

PART D – SYNTHESIS. Wetland loss has numerous negative impacts on biodiversity and habitat. Drainage to date has had adverse implications for biota, including macroinvertebrates, waterfowl, marsh birds and especially wetland-obligate species. Retaining more wetlands and a distribution of wetland sizes and permanence classes without notable lengthening of distances between them is important for supporting biodiversity.

Confidence of effects: There is *very high certainty* that habitat loss has directly impacted and will continue to directly impact the overall abundance and diversity of wetland species (*very high agreement, robust evidence*).

PART E: CARBON AND GREENHOUSE GAS BUDGETS

1. Wetlands are important sites of carbon storage (Bedard-Haughn, Matson, and Pennock 2006; Euliss et al. 2006). Drainage can result in reduced carbon storage in near-surface soils due to increased mineralization of organic matter (Brown et al. 2017b). At a larger scale, changes in practices following drainage are likely to influence soil redistribution and soil characteristics that can also influence carbon storage.

2. Wetlands are also important sites of carbon and nitrogen processing, which can lead to exchange of greenhouse gases with the atmosphere (Tangen, Finocchiaro, and Gleason 2015; Badiou, Page, and Akinremi 2018; Bansal, Tangen, and Finocchiaro 2018). There is the potential for some of the benefits of carbon storage to be offset by the release of greenhouse gases from undrained wetland ecosystems (Pennock et al. 2010; Badiou et al. 2011; Bansal, Tangen, and Finocchiaro 2018).
3. Greenhouse gas generation in wetlands depends on water chemistry, moisture conditions (Pennock et al. 2010; Bansal, Tangen, and Finocchiaro 2016; Badiou, Page, and Akinremi 2018), and input of organic materials and nutrients (Tangen, Finocchiaro, and Gleason 2015; Bansal, Tangen, and Finocchiaro 2016; Badiou, Page, and Akinremi 2018). Drainage is likely to alter greenhouse gas generation by affecting vegetation, soils, hydrology, and carbon and nutrient loads, although the net effects are not known. This remains an important knowledge gap, in part because the majority of work on greenhouse gas exchange in prairie wetlands has focussed on diffusive fluxes and not other release pathways (vegetative transport, ebullition). As a consequence, it remains uncertain how wetland greenhouse gas budgets, even for individual greenhouse gases, will be affected by drainage.

PART E – SYNTHESIS. Wetland drainage has an impact on carbon and greenhouse gas budgets. The effects will depend on specific characteristics of a given wetland (such as salinity and permanence), and land-use characteristics (eg agricultural practices). The net effects of large scale drainage on carbon and greenhouse gas balances are not known.

Confidence of effects: There is *moderate certainty* that carbon cycling will be impacted (*moderate agreement*, *medium evidence*). There is *low certainty* regarding the magnitude of these effects and impacts on associated greenhouse gas budgets, due to minimal comprehensive study of all greenhouse gases and emissions pathways.

PART F: WETLAND CONSERVATION SOCIOECONOMICS

1. Wetlands can impose private net costs on landowners, including the opportunity cost of nonproductive land and field obstruction costs (Cortus et al. 2011; Lawley 2014). These private net costs alongside broader social factors inform the decision to conserve a wetland on the field (Yu and Belcher 2011).
2. Ecosystem services provided by wetlands can have substantial economic value to society and producers (eg by flood protection, nutrient retention, providing pollinator habitat; Dias and Belcher 2015; Pattison-Williams et al. 2018; Vickruck et al. 2019) see preceding sections for information on ecosystem services).
3. The costs and benefits of wetland conservation are heterogeneous across the landscape (eg Hansen and Loesch 2017; Clare et al. 2021), and will vary significantly based on wetland biophysical characteristics, farm production practices, proximity to adequate receiving water bodies, land productivity and the societal demand for ecosystem services (Cortus et al. 2011; De Laporte 2014). For example, on-farm benefits of wetlands to producers may be more common for pasture land relative to croplands (Kirby et al. 2002; Johnson 2019).
4. The societal benefits of wetland conservation can outweigh the costs, and yet the financial incentive for individual landowners to conserve wetlands is often insufficient due to a mismatch between who bears the costs of wetland conservation (eg the farmer) and who benefits (eg the public) (Dias and Belcher 2015).
5. The costs and benefits of wetland conservation can accrue to different groups of stake- and rights-holders, causing potential conflict (Breen, Loring, and Baulch 2018). Conflict over drainage can involve disagreements regarding wetland definition, the status or accuracy of knowledge in place-based contexts, and values for deciding among trade-offs (Minnes et al. 2020). These conflicts have social impacts on local communities and can undermine effective governance (Minnes et al. 2020).

PART F – SYNTHESIS. Individual crop producers can lose net income by conserving wetlands on their land. Conversely, drainage can impact downstream landowners in adverse ways due to higher risk of flood events (see Part A). Wetland landscape position and topography affect private drainage costs and the costs of retaining wetlands. The impacts of wetland losses and associated ecosystem services can impose costs on society including increased flooding, nutrient pollution, and loss of wildlife and other components of biodiversity.

Table 1. Summary of drainage effect categories, impacts of drainage and scientific confidence regarding effects from drainage. The magnitude of a given effect depends on watershed characteristics and conditions such as weather, climate and drainage intensity (see main text for details).

Category of effect	Impact of increased drainage	Confidence of effects	Synthesis
Discharge volume	*Increase*	*Moderate to high*	Drainage can increase annual discharge volumes.
Flooding	*Increase*	*Moderate to high*	Drainage can increase flood magnitude and frequency.
Nutrient export	*Increase*	*Moderate to high*	Drainage can increase nutrient export. Note: the magnitude may vary depending on in-field management practices and extreme climate events.
Groundwater recharge	*Decrease*	*High*	Drainage of seasonally and ephemerally flooded depressions will reduce shallow groundwater recharge.
Salt transport	*Increase*	*Moderate*	Drainage could potentially result in export of salts, risking salinization of soils and receiving water bodies.
Biodiversity	*Decrease*	*Very high*	Habitat loss directly impacts overall abundance and diversity of wetland species.
Carbon and greenhouse gases	*Poorly known*	*Moderate*	Carbon cycling and greenhouse gas budgets will be impacted. Note: the direction and magnitude of impacts are poorly known.
Economics	*See synthesis*	*Very high*	Economic drivers favour wetland drainage activities by producers. While drainage increases the amount of arable land, society loses economically valuable ecosystem services when wetlands are not conserved.

Confidence of effects: There is *very high certainty* that economic drivers favour the practice of wetland drainage for individual agricultural producers, and that society loses economically valuable ecosystem services when wetlands are not conserved (*very high agreement*, *robust evidence*).

Summary: Prairie wetland drainage impacts are numerous and widespread

The current western scientific knowledge about the effects of wetland drainage in the Canadian Prairies presents a compelling case that past and future wetland drainage will have profound impacts (Table 1). A major cause of drainage is economic pressures that encourage agricultural producers to drain wetlands. This drainage results in increased discharge volumes from streams. Drainage may increase flood risk while transporting greater nutrient loads to downstream aquatic ecosystems where deterioration of water quality can occur. Wetland drainage reduces surface water storage and hence can mean less groundwater recharge, potentially limiting the availability of this resource. In addition to hydrological effects, wetland drainage contributes to lower biodiversity and poorer water quality, with additional effects on groundwater resources, soil and water salinity, and carbon storage. These impacts may have other indirect effects that have not yet been quantified.

The effect of changing climatic conditions on hydrological patterns across the Canadian Prairies, including drying in the west and wetting in the east (Whitfield, Shook, and Pomeroy 2020), as well as increased frequency of extreme precipitation events (Bush and Lemmen 2019), has the potential to magnify the impacts of wetland drainage. With climatic variability expected to increase, the loss of wetlands may worsen risks associated with extreme wet and dry periods in Prairie watersheds and communities. Arresting or mitigating the impacts of wetland drainage will require renewed attention to the development of alternative strategies and management practices. The onus for wetland conservation should not fall only on individual producers; rather, collaboration among multiple stakeholders and areas of government is needed. Development of adaptive strategies and policies must emphasize approaches that can manage conflict, sustain agricultural livelihoods, reduce flood and nutrient pollution risk to promote water security, preserve other ecosystem goods and services, and maintain healthy communities and industry.

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