Applied Ecology and Environmental Sciences, 2015, Vol. 3, No. 4, 108-116
Available online at http://pubs.sciepub.com/aees/3/4/3

DOI:10.12691/aees-3-4-3

Geographically Isolated Depressional Wetlands – Hydrodynamics, Ecosystem Functions and Conditions

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Received August 13, 2015; Revised August 21, 2015; Accepted August 27, 2015

Abstract Wetlands that form in topographically low-lying basins have attracted several studies for their environmental values, functions and unique vulnerability to the impacts of climate and land use changes. Several studies have examined the wetlands' formation, spatiotemporal hydrodynamics, hydrologic controls, and mitigations efforts. This paper briefly summarizes current advances in theoretical understanding of hydrodynamics, ecosystem functions and conditions of these geographically isolated depressional wetlands. It further examines opportunity cost of the wetlands' mitigation, environmental stressors and values of restored wetlands. The paper has identified knowledge gaps, suggesting important considerations for future research planning and developed schematic diagrams that would aid the understanding and education of the depressional wetland's ecosystem.

Keywords: *depressional wetlands, wetland ecosystem, hydrodynamic, hydrologic functions, wetland vulnerability and protection*

Cite This Article: T. S. Gala, and D. Young, "Geographically Isolated Depressional Wetlands – Hydrodynamics, Ecosystem Functions and Conditions." *Applied Ecology and Environmental Sciences*, vol. 3, no. 4 (2015): 108-116. doi: 10.12691/aees-3-4-3.

1. Introduction

Geographically isolated depressional wetlands are well-studied natural resources, perhaps due to their unique hydro-ecological and sociocultural functions and vulnerabilities to the impacts of environmental changes. As early as 1970s, the wetlands classification, seasonal water-level fluctuations and relative importance of atmospheric water balance were established (e.g., [1,2,3]). By the 1980s, conditions necessary for wetlands formation; groundwater-wetland interaction; impacts of agricultural land uses; and wetlands' habitat and water quality functions were recognized (e.g., [4]. The 1990s studies documented water supply mechanisms of snow precipitation processes, magnitudes of snow-free period's evapotranspiration (ET) [5,6]; spatiotemporal wetland distribution and their controls [7,8]. Additionally, biodiversity and wetlands' nutrients; rate of groundwater recharge; dynamic recharge function; detoxifying anaerobic microbes; and floodwater and carbon storage were reported [9,10,11].

More recently, studies have identified dynamic water-level fluctuation rates and responses of hydrologic permanencies to extreme weather conditions (drought and deluge). Additionally, they have identified regionally organized hydro-patterns; and contingent habitat functions based on size, depth, hydro-period, chemistry and upland land use types [12,13,14]). Moreover, carbon budget of the wetland ecosystems and spatiotemporally varying subsurface Greenhouse gas (GHG) fluxes (e.g., [15,16,17]) were studied. Incentives of wetlands restorations [18], impacts of increasing population [19] and changing climate [20] were also documented.

These studies, in part, have been reviewed in the past (e.g., [21,22,23]). The study [23] reviewed the quality and quantity of wetlands, including depressional wetlands, in conterminous United States. According to [23], while extensive studies have been conducted for estimating wetland resources, the intensity of water quality studies are fragmented. Similarly, [21] reviewed the hydrologic studies of prairie wetlands and noted inconclusiveness characterization wetland functions such as flood storage, dynamic wetland-groundwater interactions, and the long-term ET impacts. More recently, [22] reviewed studies, models and local knowledge that described hydrology-ecology relations of depressional wetlands under the natural conditions of Montana. This article will be unique in reviewing: a) an overview of geographically isolated depressional wetlands hydrology, relations with the surrounding uplands, hydrological functions, vulnerability and the opportunity costs of their mitigation; and b) knowledge gaps and areas of study that would enhance knowledge of hydrological functions, environmental stressors and values of wetland restorations. It will also develop schematic diagrams of the wetlands hydrology and functions for aiding the understanding and education of wetland ecosystem processes.

2. Formation and Hydrology of Depressional Wetlands

The unique physiographic characteristics, geologic settings and atmospheric waters are responsible for the hydrology that forms depressional wetlands [4]. The physiographic characteristics include topographic depressions, slope breaks and flat landscapes. Topographic depressions are the most common physiographic characteristics, and they serve as focal points where snowmelt runoff water is collected and retained to form wetlands. Geographically isolated depressional wetlands are formed on topographically confined basins that are too small or shallow to be regard as lakes or reservoir. In some areas these basins are geomorphological features created when blocks of ice buried beneath superglacial till melted when the glacier retreated [2]. As the ice melted, areas with saturated glacial deposits and superglacial till containing buried ice collapsed to form hummocky (heterogeneous topography) landscapes, including the depression. In other areas the formations of some depressions have been attributed to gouged, scraped or scoured ground by the glacier [24]. For example, there are an estimated 4 to 10 million prairie potholes in the Canadian prairie potholes region alone. In this region, the average density of potholes is estimated to be 18 potholes per km^2 while their sizes range between a few m^2 to 10 ha [25].

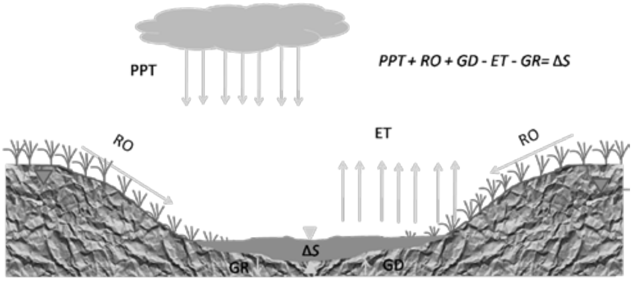

Figure 1. Schematic of the depressional wetland water balance. P = Precipitation (rainfall and snowfall); RO = Snowmelt run-off; GD = Groundwater discharge; ET = Evapotranspiration; GR = Groundwater Recharge and ΔS = Change in wetland water level

Depressional wetlands are also formed from topographic (slope) breaks that cause the slope of groundwater tables and land surfaces to intersect. At the intersection, groundwater discharges onto the surface, creating the hydrologic conditions that lead to the formation of depressional wetlands [26]. Moreover, some wetlands are also formed from slowly moving water on landscapes with flat topography [4,27].

Depressional wetlands are also formed when underlain geological settings exhibit low hydraulic conductivity [4], [27]. These geological settings (i.e., fine textured organic materials, subsurface clayey glacial tills and lacustrine deposits) restrict the downward movement of water and retain it on the landscape to form the wetland [5,10,28].

Atmospheric water (i.e., precipitation) is the most important water source for depressional wetland formation [4,5,28] (Figure 1). For example for depressional wetlands of Prairie Potholes Region (PPR), both snowfall and rainfall precipitation supply water to the wetlands, although the supply from the snow precipitation is the major constituent (75 %). This is despite the fact that snow precipitation from November to April comprises only 25 to 30 % of the region's precipitation [2,29]. There are two mechanisms that allow snow precipitation to supply more water to prairie wetlands. First, during winter, prevailing winds redistribute snowfalls such that more snow accumulates in the depressions vis-à-vis the uplands. The snow accumulated in the depressions melts in situ and forms wetlands in the spring [6,30]. Second, the spring snowmelt water quickly runs down from the uplands into depressions, to form wetlands. The reasons are, in spring, soils are still frozen and the infiltration rate of frozen soils (3 to 30 mm/day) is lower than the same unfrozen soil (100 mm/day) [5,31]. The combined effect of frozen soils and snowmelt viscosity partitions the majority of melt-water into surface run-offs that run down-slope towards the wetland than infiltration.

Summer rainfall comprises 70 to 75% of the region's precipitation but contributes only 25 % of the wetlands hydrology [5]. The rainfall water supply is often limited to rains directly falling onto the wetlands. In the summer, prairie soils are quite permeable, rainfall water is fluid and the vegetated uplands slows the speed by which run-off water runs down-slope towards wetlands [2,5,32]. Lastly, groundwater exchange is also another form of hydrologic input for some (e.g., semi-permanent and permanent) wetlands [17], though it is trivial (about 1 %).

3. Hydrodynamics of the Wetlands

The spatiotemporal hydrodynamics and hydrologic controls of depressional wetlands have been studied [1], [3,5,28,33,34]. According to the studies [1,5], during the growing season, the wetland water level peaks in the beginning of spring and then recedes throughout the summer because of ET. As a result of this recession, small wetlands dry-out for the most of the year and large wetlands (greater than a hectare) often shrink. Five wetland types (Class I, II, III, IV & V) are recognized based on this hydrodynamics [3] (Figure 2). Class I (ephemeral) wetlands are inundated from the beginning of spring to mid-June and then dry for the reminder of the season. Class II (temporary) wetlands are inundated until the last week of July and dry for the reminding periods of the season; while Class III (seasonal) wetlands are inundated until the end of summer. Class IV (semi-permanent) wetlands never dry unless there are drought periods, and Class V (permanent) wetlands are always inundated and often referred to as lakes. These classifications control various wetland services and functions, which depend on the hydrologic permanencies. However, there isn't a study conducted to specify the relative occurrence, distribution and abundance of one form of wetland class over the other. Additionally, the classification did not account the chemistry of wetlands water, even if salinity plays an important role in determining wetlands' ecosystem functions.

The seasonal hydrodynamics are contingent on the wetland hydrology, types of the surrounding land cover and climate [1,33,34]. Higher rates of water-level fluctuations were observed on vegetated compared to clear wetlands. Wetlands surrounded by agricultural land dry earlier than those surrounded by natural grassland. In addition, water levels recede faster in seasonal and temporary than semi-permanent wetlands [33]. Furthermore, the water-level fluctuations also responds to extreme weather conditions (i.e., dry and wet), with a possible effect of spilling into the following year [34].

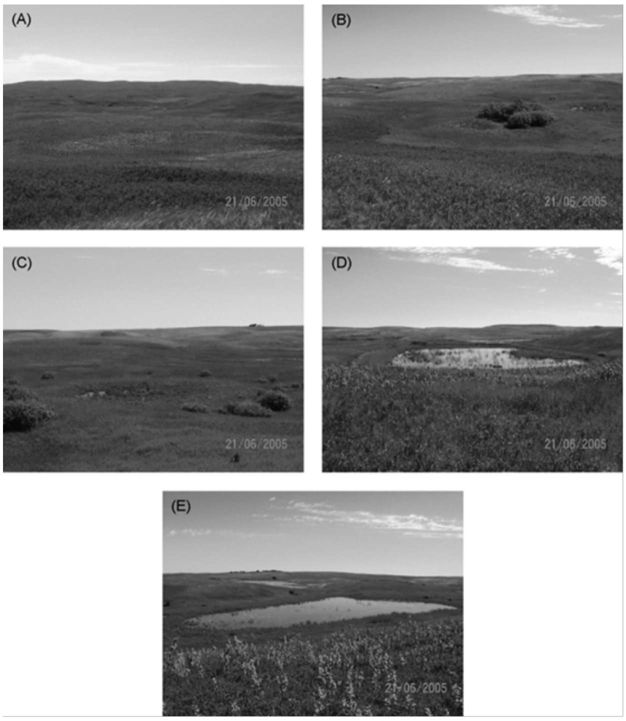

Figure 2. Examples of hydrodynamics of depressional wetland types (Stewart and Kanturd, 1971): (A) Class I (Ephemeral wetland), (B) Class II (Temporary wetland), (C) Class III (Seasonal wetland), (D) Class IV (semi-permanent wetland), (E) Class V (permanent wetland)

Long-term hydrodynamics of the wetlands are dependent on weather conditions [32,35,36,37]. Over 17 years water-level monitoring data (1980 to 1997) of the Cottonwood Lake area of North Dakota indicate wetlands responded to the pacts of drought and deluge conditions [32]. During deluge, the small wetland basins were filled with water to the extent that geographically "isolated" wetlands coalesce. Thirty seven percent more temporary wetlands cover landscape during wet vis-à-vis dry seasons [37]. Besides, the semi-permanent, seasonal and temporary wetlands, which are inundated for 100 %, 46 to 100 % and 0 to 69 % of the growing season during the wet years, respectively, were inundated only for 71 %, 0 to 29% and 0 %, respectively, when it is dry [16]. During draught, the semi-permanent wetlands dry in the summer, except those on the bottomland, because additional water from the groundwater inflow is received [8]. Even then they eventually dry, in subsequent years, if drought prolonged [33,38].

The spatially organized hydro-patterns of the wetlands also respond to regional climatic variations [7,12,39]. The study [7] examined the pattern of wetland distributions in three regions, namely: Canadian parklands, Canadian grasslands and US grasslands. It identified the effect of the north-south regional climatic gradient on the number and density of wet basins in the landscape such that the wetland density was higher (10.35 wet basins per km^2) in Canadian parklands compared to Canadian (4.13 wet basins per km^2) and US (3.46 wet basins per km^2) grasslands. Additionally, [12] have observed spatial pattern in the organization of wetlands' density and areal coverage among prairie eco-regions. The density at boreal transition was 32ponds per km2, while it was 19ponds per km2 at moist mixed grassland and 17ponds per km2 at mixed grassland prairie. Wetlands cover 32 % of the landscape in boreal transition, 17 % in moist mixed grassland and 14 % in the grassland. Regionally, [39] identified two primary factors controlling hydrologic connectivity of intermittent wetlands, namely precipitation and relief. According to [39], precipitation enhances connectivity by filling the ponds, while relief controls the amount of precipitation needed to produce hydrologically connected wetlands. There is clear east-to-west gradient of hydrologic connectivity due to the corresponding relief increases and precipitation decreases westward across the US PPR.

4. Hydro-ecological and Socio-cultural Functions

Geographically isolated depressional wetland have many ecosystem functions such as, but not limited to, habitat, groundwater recharge, surface water purification, flood control, and carbon sequestration functions. Additionally, there are some ecosystem services beneficial to mankind are attributed to the wetland. For instances, the wetlands support domestic animal farming by providing additional foraging sources, particularly during drought periods [40]. They also have aesthetic value, making them attractive for recreational purposes. Considerable revenues are generated from recreational hunting, fishing, boating and wildlife photography [41,42]. Additionally, the wetlands also serve as cultural heritage sites for indigenous people; educational sites to study plant and animal community structures; and scientific research sites for limnological, paleolimnological and other ecological and environmental studies [41,42].

4.1. Habitat Functions

Depressional wetlands exhibit diverse, rich and dynamic species of plant and animal communities (Figure 3), especially when compared with the surrounding uplands [33,43,44]. The plant communities are consisted of meadows and marshes characterized as sedges, wet prairies, emergent and submergent aquatic plants and floating leaves (e.g., water-lilies, water milfoils and duckweeds). The diversity, evenness and richness of these communities are dynamic depending on size, depth, hydro-period, land use and water chemistry [12,22]. For example, permanent wetlands have aquatic communities with reduced below ground biomass, contrary to ephemerals and temporary wetlands, which have both below and aboveground biomass [45]. Similarly, aquatic plant communities and associated rare and uncommon species upsurge with increasing wetlands' nutrient content [46], although their richness and diversity declines as nutrient content increase beyond certain thresholds [47].

The habitat functions of the prairie wetlands are enormous. The wetlands' diverse and thriving biotas are critical in maintaining the region's genetic pools. First, biodiversity is an essential function to enhance plant and animal adaption to changing environment. Second, dead plants and animal remains accumulated sustain communities at the basis of food chain i.e., saprophytes and anaerobic and facultative microbes (Figure 3). Additionally, wetlands provide supplemental forage for domestic animals and habitat for various endangered, threatened and vulnerable wildlife species. Third, endangered bird such as Pallid Sturgean, Bald Eagle, Interior Least Tern and Piping plover depends on these wetlands for survival. Whooping cranes and Eskimo Curlew get protein-rich invertebrates from the wetlands. The wetlands are also nesting, feeding, breeding and brood-rearing sites and migratory corridors of 138 species of water-birds, including North American Waterfowl. Approximately, 10% of all North American waterfowl and 50 to 80 % of ducks hatch on prairie wetlands [14,48], and thus important for providing recreational and commercial hunting industries.

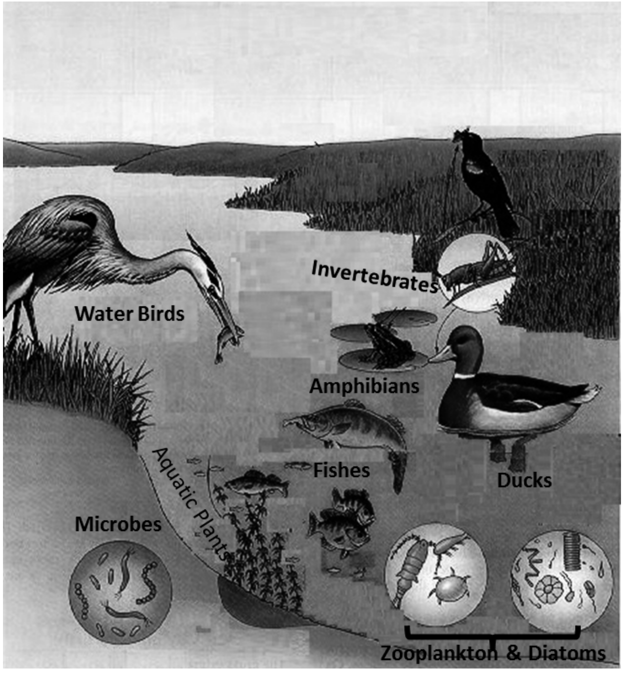

Figure 3. Diagram showing the diverse and thriving flora and fauna of wetland ecosystem

4.2. Groundwater Recharge Functions

Groundwater (GW) is a major source of domestic water use for sizeable population in some regions [49] (Figure 4). For instances, it is a source for 39% of the population in North Dakota, 83% in Iowa, 34% in Montana and 55% in Minnesota. Therefore, in this region where small wetlands are reported as focal points for groundwater [10], the groundwater recharge function of wetlands must assume important considerations. Generally, wetlands recharge groundwater at rates ranging from 0.03 cm/day to 1.1 cm/day in areas that were originally considered regional discharge area [50].

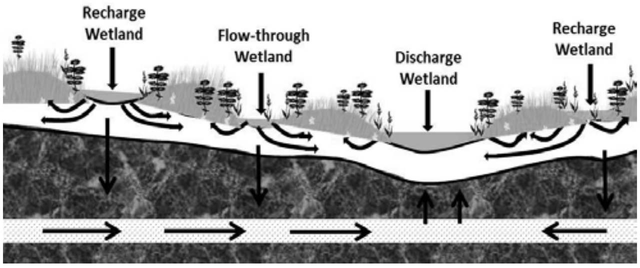

Figure 4. Diagram showing groundwater flow systems associated with prairie wetlands. Arrows indicate direction of groundwater flow. The average position of the water table is indicated by solid line and the shaded region indicates saturated substrate

However, the groundwater recharge rates are spatiotemporally dynamic [17,51]. Spatially, depressional wetlands have high hydraulic conductivity (i.e., 300 cm day^{-1}) along margins with macrpores and in the top several meters of the soil profile beneath the wetlands [10,17]. The conductivity to deep groundwater was low (i.e., 0.0003 – 0.03 cm day^{-1}) and had minor effect on water balance, though it has significant ecological implication due to the influence on salinity [10,17,51]. Temporally, the recharge function varies depending on differences of dynamic hydrologic head between the wetlands and groundwater, which are controlled by seasonal as well as regional climates [10,12,16]. Where and when wetland's hydrologic head is higher than the groundwater, the wetland recharges the groundwater, whereas when or where the water-table is higher than the wetland; water moves from groundwater to wetlands [10,16]. The wetlands may attain static or dynamic category of recharge, discharge or flow-through wetlands [51]. Whilst the recharge wetlands release water to underlying aquifer, the discharge gains water from the underlying aquifer. The flow-through wetlands gains water from groundwater in one location and lose in another location.

Generally, the groundwater recharge function of depressional wetlands are not conclusive. Most the groundwater recharge processes are studied for the depressional wetlands formed on glacial tills. It would be interesting to see the processes on other geological settings such as outwash or lacustrine deposits. Future research should also focus on the effects of wetland drainage, and the relative contribution of varying wetland types. Moreover, it needs to investigate the role of organic soils, irrespective of the bedding mineral soils, on recharge/discharge functions of wetlands.

4.3. Water Quality Functions

Even though most depressional wetlands are geographically isolated, at least superficially [39], those that interface between terrestrial and aquatic ecosystems may contribute toward water quality improvement [52]. Wetlands often experience nutrient loading from the surrounding agricultural lands, industrial plants and urban areas, via run-off because of their position on the landscape. However, wetlands also mediate several physical, biological and chemical processes that can transform and retain the nutrient load from being transported into adjacent surface water (Figure 5). Wetlands' vegetation poses physical roughness that slows run-off velocities thereby enhancing gravitational settlement of suspended sediments and nutrients. Aerobic and anaerobic microbes of the wetlands attack the settled nutrients and chemically transform, which include either breakdown or combining nutrients, into harmless substances [39,49,53,54]. Floras and faunas' uptake and hydric soils' sorption also remove some nutrients from the surface water [49]. Wetlands reduce downstream pulses of N by 64%, P by 28% and enhanced sediment retention of 500MT year^{-1} [55]. A 2,500 acre restored wetland would save $1 million in water pollution control costs annually; a finding which incentivizes wetland creation or restoration operation for the treatment of municipal and industrial wastewater [56].

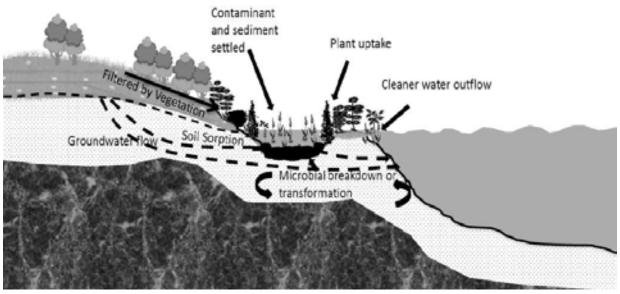

Figure 5. Diagram showing wetlands mediated surface water purification processes of soil sorption, microbial breakdown, transformation, plant uptake, and gravitation settlement of suspended particles

Depressional wetlands are variable with regard to the water quality functions [57,58,59]. Wetlands formed in riparian and riverine areas are better at nutrient transformation and sediment retention, while lacustrine wetlands and lakes are least important. This is because of lakes inherent small vegetated area to open water ratio [58]. In addition, the population and activities microbes that take part in wetlands' chemical transformation of nutrient also vary depending on wetland types [59]. Meadows wetlands have higher microbial biomass and activities than other wetland types (i.e., fens, swamps, and forested wetlands), followed by swamps and forested wetlands, which have similar amount of microbes [59]. However, despites these documented water quality functions, further studies are necessary to investigate wetlands' resilience to nutrient and sewage loading. Additionally, side effects of wetlands' water quality functions on the other functions are not fully understood.

4.4. Flood Control Functions

Depressional wetlands protect life and properties from flooding (Figure 6). This is attributed to the characteristics of storing run-off water during rainstorm and spring snowmelt events [22,49]. For instances, Devil's Lake region of North Dakota store up to 72% of annual snowmelt thereby containing what would have been downstream floodwater [22]. By storing floodwater, wetlands facilitate percolation and evapotranspiration. In addition, the unique vegetation of the wetlands' ecosystem, dissipates the downward momentum of the floodwater. The roots of the vegetation also hold the soils in place and thus reduce erosion by stabilizing stream banks and floodplains. For example, a wetland increase by 2% in Rat river watershed of Manitoba reduced a floodwater volume by 3.7% [60]. On contrary, a land use change, which involved wetlands drainage, increased the downstream floodwater by 15 – 20% [61].

The flood control function of depressional wetland has increased awareness of wetlands' ecological solution to the flood problems. According to [62], restoring Flood zone along upper Mississippi could store about 39 million acre feet of floodwater and save a damage estimated to cost over $16 billion. Although, restoring flood plains is, perhaps, costly (e.g., in Minnesota restoring 5000 acre wetlands can cost about $1.5 million), it pales in comparison with millions of dollars lost due to flooding. It is also cheaper than adapting other flood mitigation structures such as dikes, levees, and floodways. For instance, the net benefit of converting a cropland into 100 year flood zone, in upper Mississippi river basin, amounts to $120.9 million or $68 per acre [62].

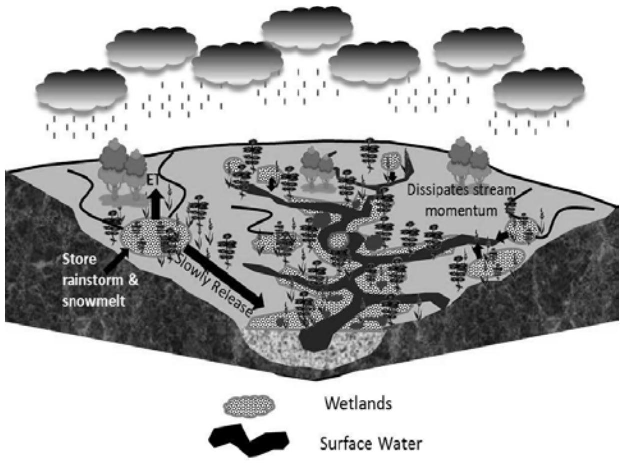

Figure 6. Diagram showing wetlands' flood control function through the processes of floodwater storage, dissipating the momentum of runoff and maintaining the stability of floodplain

4.5. GHG Sequestration Functions

Recently, depressional wetlands have also been recognized as valuable reserves and potential sinks for atmospheric carbon (C) [15,63,64,66]. Restored depressional wetlands can sequester a net GHG that amount to 3.2 Mg of CO_2 ha^{-1} $year^{-1}$, while draining the wetlands release 326 Mg of CO_2 ha-1 year-1 into atmosphere [15]. Further CO_2 are released when the drained wetlands were converted into agricultural land [15].

Carbon (C) enters wetland ecosystems through wetland plant and algal photosynthesis and in the form of suspended organic sediment and/or dissolved organic C with run-off water from the surrounding uplands [11] (Figure 7). The C is retained due to anaerobic conditions that slow the rate of decomposition [65]. Higher moisture status creates anaerobic conditions where the activities of microbes to oxidize organic C are arrested by the lack of oxygen.

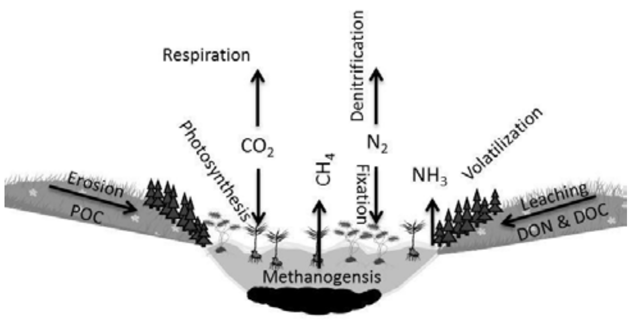

Figure 7. Diagram showing processes involving in dynamic GHGs fluxes: erosion, respiration, photosynthesis, denitrification, nitrogen fixation, methanogensis, volatilization and leaching

While, wetlands are the sinks for atmospheric CO_2 [15], [65], several biogeochemical reactions within the wetlands ecosystem emit other GHGs (e.g., methane (CH_4) and nitrous oxide (N_2O)) which have higher global warming potential than CO_2. Due to this trade-off between CO_2 influx and other GHGs effluxes, defining the source-sink role of the depressional wetlands is difficult [67,68]. Additionally, although, the wetlands is a net C sink [11], they remain dynamic in GHG fluxes due to seasonal hydrologic changes. The direction of GHGs fluxes changes from net sink in the spring to a source later in the summer. A comprehensive assessment of wetlands' GHG sequestration function must also consider these dynamics into account.

5. Vulnerability of Depressional Wetlands

5.1. Land Use Change

Depressional wetlands are threatened by the impacts of land use change, particularly agricultural practices. For example, several attributes of the PPR make depressional wetlands extremely attractive for agricultural land uses. The region has leveled topography, fertile clay soils with abundant organic matter, and the humid moisture conditions in an otherwise relatively semi-arid environment [69]. Agriculture has expanded in part by draining prairie wetlands, risking their ecosystem functions and services as wetlands are often viewed as obstructions to efficient agricultural field operations [53]. In this region, agricultural drainage has caused an estimated 27 to 90 % wetland loss [36,40].

Agricultural industry is still targeting the region to meet a rising food demands and biofuel energy from the growing population risking the wetlands health [19]. For instances, 50% of Saskatchewan depressional wetlands are still threatened from the impacts of agricultural land uses [19,53,70]. According to [19], the recent doubling of commodity prices (i.e., soybean and maize) from rising demands of biofuel, has increased the grassland conversion into arable land at an annual rate of 1 – 5.4% [70]. The conversions are mainly on areas closer to the wetlands causing a water quality deterioration through fertilizers and pesticides transport [71]. Besides, erosion and sedimentation processes are also reducing basin water holding capacity [71].

5.2. Climate Change

Climate change also impacts the physical and hydrological condition of PPR's depressional wetlands. Most climate change models (e.g., General Circulation Model's scenarios) predict a warming global climate by between 3 - 6°C by the end of this century [35]. For the depressional wetlands of the PPR, these models predict drought conditions with longer growing seasons, early springs, milder winters and warmer and drier summers [35]. Similarly, the wetlandscape-model further predicted a warning condition characterized by wetlands with reduced water volume, short hydro-periods, less resilience ecosystem and less dynamic vegetation structure [20]. Moreover, a Palmer Drought Severity Index (PDSI), which demonstrated a strong correlation between counts of inundated potholes and historical climatic record, indicated that the forecasted warming of the region would reduce the number of inundated ponds by 38 to 54 % in 2060 [48].

There is a strong spatiotemporal relation between the region's climate and wetland hydrology highlighting the future consequences of climate change. According to seasonal water budget studies [5,72], the depressions fill with water from spring runoff (RO) and dry-out in the summer because of the ET, which exceeds the precipitation. A substantial increase in air temperature would cause the wetlands to dry even sooner [35,36]. For instances, in PPR, the north-south and east-west temperature (T) and precipitation (P) gradients have structured the hydrology of depressional wetlands such that the densities increase from south-to-north [7]. It also structured wetlands hydrologic connectivity such that the frequency increases from west-to-east [39] indicating impacts of climate change on the spatial distribution of depressional wetlands.

6. Wetlands Restoration

Hundreds of wetlands have been restored, since the 1980th; in the Midwestern United States following the 1977th "no net loss" legislation enacted by US congress. Wetlands restoration, which in essence is restoring the hydrology, was carried out to compensate for wetlands that are lost due to avoidable and unavoidable development projects. The restoration and conservation policies have slowed the rate of wetland losses since 1980 and restored some wetlands. One percent of the wetlands lost in Minnesota and Iowa have been restored [35].

However, the restoration efforts have not fully replenished the original functions of the wetlands' ecosystem [18,73,74,75]. According to [73], the overall plant community evenness, richness and relative abundance of the restored wetlands were the same as neighboring natural wetlands, though restored wetlands lacked as well-developed community of sedge-meadow. Similarly, the study [74]) found similar recovery for semi-permanent wetlands and those located geographically closer to their corresponding natural wetland, but not seasonal and temporary wetlands. Also, restoration of wetlands disturbed by fire, grazing, and alternating drought and deluge did not fully recover their natural plant community functions [75], through amphibian and waterfowl communities were recovered [18]. Therefore, restoring wetlands' is not an end by itself. A continued management of the wetlands ecosystem is critical for its holistic functional restoration. The restoration efforts must also include improving ecosystems resilience and/or facilitation [76]. Ecosystem resilience entails a management of the ecosystems such that the climate change does not bring directional changes in equilibrium states. Facilitation is mitigation processes that assists, or encourages adaptions to environmental changes.

7. Conclusion

In conclusion, there is a significant understanding in the distribution, formation, dynamics, functions, services, conditions, vulnerability and mitigations of depressional wetlands. Accordingly, depressional wetlands are formed as consequences of physiographic characteristics (i.e., topographic depressions, slope breaks and flat landscapes), and geologic settings having low hydraulic conductivity. Atmospheric waters are responsible for the hydrology that forms depressional wetlands that collect and retain snowmelt and rainstorm water to form wetlands with varying hydro-periods (i.e., Ephemeral, Temporary, Seasonal, Semi-permanent and Permanent Wetlands). The wetlands are habitats for diverse flora and fauna including those endangered, threatened and vulnerable wildlife species and focal point for groundwater recharge, which are the sources of potable water for millions of prairie inhabitants. Additionally, they filter surface water loads (i.e., sediments and nutrients) thereby improving downstream water quality and also controlling floods by storing the floodwater, checking the momentum and reducing hazard to life and property. The wetlands are valued as a potential sink of GHGs, while providing various goods and services beneficial to mankind such as, but not limited to, aesthetic, recreation, hunting, fishing, cultural heritage, and educational services.

Despite these functions and services, the wetland is enduring various forms of natural and anthropogenic stresses. For example, in PPR, the agricultural suitability of the land coupled with rising demands for biofuels and food & fiber, for the ever increasing population, will continue to present a difficult dilemma of protecting wetlands for their environmental functions or developing them for economic growth. Besides, the region's forecasted climate change characterized by milder winter, early springs onsets, and warmer summer will impact atmospheric water, which is a major source of water for the wetland formation. Hundreds of depressional wetlands are being created or hydrologically restored to offset the lost wetlands, even though the efforts have not fully restored their original functions.

There are areas of depressional wetland's studies that require further investigations. The sediment and nutrient filtering functions should as well unravel the side effects of this process on other functions such as biodiversity. Besides, the groundwater recharge function and its contribution to overall water-balance should be established for the wetlands that are formed on other geological settings (e.g., outwash and lacustrine deposits) as it has been done for glacial tills. The recharge/discharge impacts of the underlying organic soils, irrespective of bedding mineral soils, need to be understood better. The hydrologic controls of pond depth, topography, shore width, and catchment areas are not fully understood. The current classification scheme emphasizes on hydrologic permanencies, not chemistry (i.e., salinity parameters) although salinity controls certain ecosystem functions. The GHG sequestration function must account the seasonal hydrodynamics and surrounding land use practices. Last but not least, the functional differences of restored and natural wetlands, which mainly focused on habitat functions, should consider other ecosystem functions such as, but not limited to, recreation, water quality, and carbon sequestration. Besides, the customary dual comparisons of natural vs restored wetlands do not adequately explain the opportunity cost of wetland restoration. Triplet comparisons of natural, restored and abandoned wetlands must be done to have a comprehensive understanding of the restoration activities, outcomes and costs.

Acknowledgement

I thank Dr. Assefa M. Melesse, Professor of water resources engineering at Florida International University and Dr. Bharat Pokharel, Research Assistant Professor of Forest Resource Monitoring at Tennessee State University for reviewing the manuscript. The manuscript is based on a literature review made for a grant project entitled; "a geospatial assessment of environmentally sensitive areas of Tennessee". Efforts were made to incorporate recent findings on geographically isolated wetlands ecological functions and values, and the knowledge gaps that would enhance the understanding of ecosystem stressors and restoration values.

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