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Chapter 14

PROFILING COVER CYCLE DYNAMICS FOR PRAIRIE POTHOLE WETLAND LANDSCAPES

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ABSTRACT

Over 3 million wetlands populate the U.S. portion of the Prairie Pothole Region (PPR), where conservation goals include restoration and preservation of the cover cycle. The cover cycle is characterized by seasonal and annual changes in vegetation and open water and is closely coupled to climate and natural ecosystem functions. A complete cover cycle include periods of time when high waters drown hydric vegetation during deluge and periods where hydric vegetation expands as waters dry-down during drought. Changes in wetland cover may occur on weekly, monthly, or annual time-scales. These dynamics contribute to a rich diversity of habitats that support more waterfowl than any other region in North America. In addition temporal dynamics, PPR wetlands rarely function as single entities because of shared surface and/or groundwater hydrology. This spatial interdependence requires PPR wetland functional assessments represent populations of wetlands, commonly referred to as "profiles." Synoptic data profiling cover cycle stage and return time for populations of wetlands would scaffold large-scale investigations of ecosystems services, habitat status, and sensitivity to climate change.

This chapter describes application of previously developed tools for synoptic delineation of wetland water and hydric vegetation cover to classify cover cycle for thousands of wetland basins within a single satellite image (10,000-30,000 km^2 of land area). Using satellite data layers in geographic information systems (GIS), wetland profiles developed using current (2007) wetland cover data are compared with profiles developed using National Wetland Inventory (NWI) data from 1980. Results underscore the dynamic nature of these ecosystems and the need for current observations when setting conservation goals, monitoring restoration effectiveness, and evaluating anthropogenic impacts.

INTRODUCTION

Knowledge of how disturbances impact wetland condition for a diversity of wetland types and water regime classes is limited by a spatiotemporally narrow range of ecologically-relevant observations. Comprehensive analyses of wetland condition in the Prairie Pothole Region (PPR) is particularly problematic because the region is vast (879,000 km^2), the average wetland basin is small (5 ha), wetland density is high (7 wetlands km^{-2}), and water levels respond rapidly to changes in weather (Johnson et al., 2004). Long-term datasets are available for only a small number of wetland types, water regime classes, and hydrogeomorphic or hydrologic landscapes. Typically, data collected for a large number of wetlands are short-term and do not include the long-term patterns of variability in hydrologic and vegetation parameters seen in almost all wetland types (Bedford, 1996). Since development and persistence of wetland ecosystems is a function of long-term hydrologic patterns, a time-series of synoptic observations would facilitate comprehensive watershed analyses and conservation assessments among dense populations of wetlands in the PPR.

Climate drives PPR wetland hydrology, and hydrology drives the wetland cover cycle and subsequent ecological processes (Johnson, 1998). Therefore, PPR wetland condition and function is closely coupled to climate (Johnson et al., 2005). These natural wetland dynamics result in a diversity of wetland habitats critical to waterfowl populations on a continental scale. While other factors also influence wetland condition and function, such as anthropogenic activities, these effects can rarely be understood without knowledge of natural hydrologic variability. The close coupling between climate, hydrology, and habitat is well established. Less known is how these combined factors alter wetland status for a diversity of water regime classes across multiple watersheds. Here, we suggest a mechanism for advancing knowledge of wetland cover from a single point in time to a historical synopsis for a variety of wetlands populating a hydrologic landscape (Wolock et al., 2004).

The National Wetlands Inventory (NWI) is the most geospatially complete database for wetlands in the U.S (Tiner, 1997). In the PPR, NWI data are widely used to map wetland type and water regime, as these variables provide some indication of habitat potential, water depth and duration (Cowardin et al., 1979). For example, the most common PPR wetland type is palustrine emergent (PEM), which can be divided into four water regime classes: temporary, seasonal, semi-permanent, and permanent. Water regime class was recorded for all wetlands at the time of the NWI (circa 1980), and these data are still invoked in wildlife management plans because water regime is closely tied to wetland habitat. Current conditions, however, are difficult to determine for over 3 million wetlands populating the U.S. portion of the PPR (Millet, 2004). The addition of remote sensing-based observations in Geographic Information Systems (GIS) would provide a vehicle for evaluating current condition to better constrain how local and large scale processes (e.g. land use and climate change) might influence the current spatial distribution of wetland habitats.

The frequency, duration, and timing of flooding or soil saturation are defining characteristics of PPR wetlands (Mitsch et al., 2000) and are the primary mechanisms for the cyclic vegetation dynamics collectively known as the wetland cover cycle. The cover cycle has been described as a successive progression of wetland stages, from high water during deluges (lake marsh stage) to low water and drying during droughts (dry marsh stage) that occurs on decadal time-scales or longer (van der Valk et al., 1978; Johnson, 1998). High waters found in the lake marsh stage eventually recede, which stimulates plant recruitment and productivity and moves the wetland into the regenerating marsh stage. Continued drought may dry down the wetland completely, leaving only marsh vegetation cover. When high waters return following drought, marsh plants decline, water levels rise, and the wetland enters the hemi-marsh stage. A complete cover cycle that ranges from open water to complete vegetation cover may result in a 20-fold variation in net primary production (Johnson et al., 2005). The number of completions through these four stages for semi-permanent PPR wetlands during a 95-year time period may range from zero to three (Johnson et al., 2005). Climatic variability is the primary driver to the cover cycle (Johnson et al., 2004), but the cover cycle stage for each wetland in space is unique, which contributes to a rich diversity of densely populated wetland habitats. Managing wetland landscapes to retain cover cycle/habitat spatial diversity is fundamental to PPR conservation and mitigation goals (Bedford, 1996).

It is not clear how often the cover cycle returns for the range of water regime classes in the PPR. Long-term monitoring at a single site has helped with understanding the specific interactions among prairie wetland biota and variable weather (Conly et al., 2001). However, long-term cover cycle data, including the diversity of PPR wetland classes and hydrologic landscapes, are lacking. Further, remote sensing-based observations are either so spatially fine that the area of coverage is limited to a few hectares (e.g. aerial photography) or so coarse that seasonal vacillations in hydrology and vegetation cannot be delineated [e.g. the 500-m Moderate Resolution Imaging Spectroradiometer (MODIS) or the 1-km Advanced Very High Resolution Radiometer (AVHRR) sensors]. Data retrieved from the Landsat, Advanced Spaceborne Thermal Emissions Radiometer (ASTER), and SPOT sensors are useful in this region because they collect data at 30, 15 and 10-m spatial resolutions, respectively. These data can now be modeled to delineate seasonal fluctuations in open water (Beeri et al., 2007) and marsh vegetation communities (Phillips et al., 2005) for thousands of wetlands within a single 10,000-30,000 km^2 image. These data, in combination with the NWI, can be used in a classification system to indicate wetland cover cycle stage. In the following, we describe the need for analyzing not only a single wetland but spatial relationships within and among populations of wetlands using synoptic, time-series data. Then, we illustrate how remote sensing-based observations can classify and track wetland cover information using an example dataset collected in central North Dakota. We conclude by suggesting how these new tools in GIS can support a framework for conservation and long-term monitoring in the PPR.

WETLAND PROFILES

The idea of evaluating a population of wetlands as compared to a single site was championed by Bedford (1996) in her description of wetland "profiles." Bedford described the need to evaluate multiple wetlands within a contiguous, hydrogeomorphic or hydrologic landscape because PPR wetlands interact through surface and/or groundwater flows (Winter, 2003). A wetland at the top of the watershed may recharge groundwater, whereas a lower elevation wetland may both receive groundwater discharge and recharge groundwater. Hydrologic connectivity, while difficult to quantify, is a PPR wetland feature, although data are lacking to determine the spatial extent of this phenomenon. Another reason for considering populations of wetlands is the diversity of wildlife habitats found among neighboring wetlands. A single management unit, e.g. a section of land, may include several wetland habitats (Weller et al., 1965; Murkin et al., 1997). Therefore, wildlife managers cannot manage the diverse array of wetlands as a homogenous unit. A profile, which summarizes ecologically-relevant variables within a common hydrogeomorphic or hydrologic landscape, may include tens or thousands of wetlands. Although the need to construct landscape profiles to evaluate populations of wetlands is clear, addressing this need is difficult without ecologically-relevant, synoptic data.

While synoptic data are needed for constructing wetland profiles, only recently have techniques become available for delineating open waters in the PPR using data from sensors onboard satellites. These techniques can address questions regarding long-term hydrologic dynamics at watershed and landscape scales (Beeri et al., 2007). By employing Landsat sensor data, data for each NWI wetland can be used to retrospectively calculate hydroperiod (at bi-monthly time-steps) since 1982. In addition, the area of marsh vegetation can also be delineated from graminoids or grain crops using data available from the satellite-based Landsat, ASTER, and SPOT sensors. This chapter outlines how these combined techniques delineate those wetland properties associated with the wetland cover cycle using satellite data. Further, we describe application of these data, and how an archive of geospatially explicit cover cycle estimates can be created to support change detection analyses. Following is a demonstration of this concept for a 100 km^2 area-of-interest (AOI) residing within hydrologic landscape region 8 (Wolock et al., 2004). In this example, wetlands are first mapped by water regime class, and then evaluated for the entire landscape using an 11-year time series. Current wetland cover classes are then mapped for the same AOI, as derived from satellite-based optical data only. We compare profiles, or distributions, of water regime classes to the current wetland cover classes for this 100 km^2 landscape.

WETLAND PROFILE DEMONSTRATION

We chose a hydrogeomorphically similar, 100 km^2 AOI located between Bismarck and Minot, North Dakota to demonstrate how the landscape profile for water regime class differs from the landscape profile for current wetland cover class for the same group of wetlands. This AOI is characterized by hilly and irregular terrain, with deep glacial and fluvial deposits consisting of till, clay, rocks, sand and gravel (Bluemle, 1991). It is located in the mixed-grass prairie physiographic region, where grasslands are now comprised of *Bouteloua gracilis* [(Willd. ex Kunth) Lag. ex Griffiths], *Poa pretensis* (L.), *Carex sp.* (L.), *Pascopyrum smithii* [(Rydb.) A. Löve], and *Melilotis officinalis* (L.) (Beeri et al., 2007). Most of the AOI is privately owned and used for annual crop production (~30%) and livestock grazing (~70%). Average annual precipitation recorded over the last 30 years is 434 mm as rainfall and 78 mm as snowfall (Turtle Lake Weather Station; 47°31′N, 100°54′W). For the purpose of this demonstration, we selected only the palustrine emergent wetlands (PEM) because this type comprises over 97% of the wetlands in our AOI (U.S. Fish and Wildlife Service, 2008).

The NWI lists 2627 PEM wetlands within our AOI, and most of these (72%) are classified as seasonal (Figure 1). Seasonal wetlands are usually ponded for extended periods (commonly through June), while temporary wetlands are ponded only briefly during the growing season.

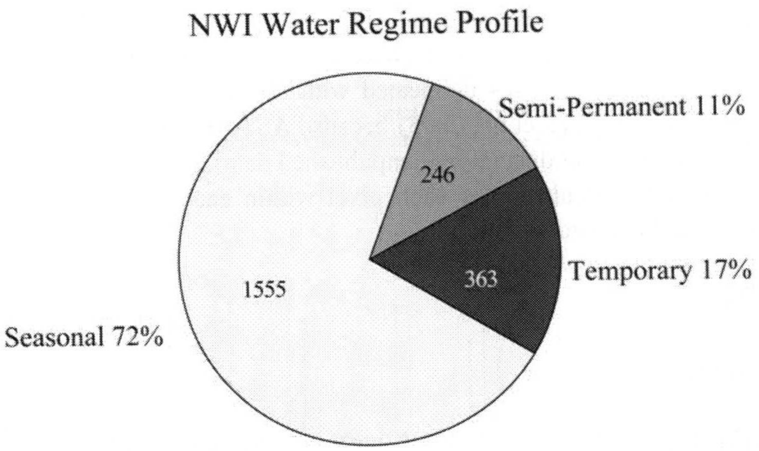

Figure 1. The distribution of water regime classes for palustrine emergent wetlands found within a 100 km^2 area-of-interest located in central North Dakota, according to the National Wetland Inventory (U.S. Fish and Wildlife Service, 2008).

Semi-permanent wetlands are ponded throughout most years but may dry up during extended drought (Cowardin et al., 1979). This water regime classification profiles the distribution of water regime classes as recorded in April or May between 1979 and 1982. What is not known is how water ponding or the area of water coverage may have changed for each water regime class from 1997 to 2007. Moreover, it is unclear if ponding changes in temporary wetlands are spatially distributed in a manner that is distinct from seasonal or semi-permanent classes. In other words, we might expect most temporary wetlands in a landscape to pond in spring each year, while we might expect most seasonal wetlands to pond in spring and summer only.

To determine seasonal changes in actual ponding we modeled Landsat data collected in spring (April-May), summer (June-July), and fall (August-September) between 1997 and 2007 to delineate the area of open water in each NWI polygon (Beeri et al., 2007). Using optical data and the technique described in Beeri et al. (2007), we mapped the proportion of open water to total wetland area in spring, summer and fall for each NWI wetland from 1997 to 2007. Briefly, Landsat reflectance for each spectral band was calculated for each pixel within each NWI polygon and mapped as follows:

If $B4 + B5 + B7 < 0.188$

Or $[(B5 + B7) - (B2 + B3)] / [(B5 + B7) + (B2 + B3)] < -0.457$

Or $[(B5 + B7) - (B1)] / [(B5 + B7) + (B1)] < 0.04$

Then classify as open water.

where B1= Landsat Band 1 (blue, 450-515 nm); B2= Landsat Band 2 (green, 530-610 nm); B3= Landsat Band 3 (red, 630-695 nm), B5= Landsat Band 5 (short-wave infrared, 1570-1780 nm); B7= Landsat Band 7 (short-wave infrared, 2090-2350 nm). Only wetlands with areas exceeding the model detection limit (0.2 ha) were included (Beeri et al., 2007). Consequently, 196 temporary and seasonal wetlands (7.4% of the total) were excluded from this analysis. Marsh vegetation was delineated with optical data derived from the ASTER sensor in August 2007 (Phillips et al., 2005) because ASTER data more accurately delineate marsh vegetation than Landsat data (Beeri, unpublished data). Briefly, ASTER reflectance for each spectral band was calculated for each pixel within each NWI polygon that was not classified as water and mapped as follows:

If $B1 + B2 + B4 < 0.303$

Then classify as marsh vegetation

where B1=ASTER Band 1 (green, 516-600 nm); B2=ASTER Band 2 (red, 629-689 nm); B4=ASTER Band 4 (short-wave infrared, 1610-1706 nm). The area of marsh vegetation was mapped for each wetland and the proportion of marsh vegetation to total wetland area calculated. Current wetland cover was determined as follows, after Johnson et al. (2005): Dry marsh stage (no detectable water from spring to fall and marsh vegetation present); Hemi-marsh stage (<75% but >0% open water at any time between spring and fall); Lake marsh stage (>75% open water from spring to fall); Dry/no marsh stage (no detectable water from spring to fall and no marsh vegetation present). Results were mapped for each NWI wetland in our 100 km^2 AOI and summarized by water regime class and by current wetland cover class.

RESULTS AND DISCUSSION

The proportion of open water to total wetland area between 1997 and 2007 was (on average) less than 0.1 for temporary (Figure 2), less than 0.2 for seasonal (Figure 3), and less than 0.8 for semi-permanent wetlands (Figure 4). However, the standard deviation at any one of the 33 points in time exceeded the mean value in almost all cases (Figures 2-4). We found evidence of open water in spring, summer and fall for all water regime classes. Given eleven years of data, we expected temporary and seasonal wetland open water levels to be high in spring and to decline in summer and fall (Cowardin et al., 1979). However, water regime classes mapped for this landscape profile did not fit archetypes for temporary (Figure 2), seasonal (Figure 3), and semi-permanent (Figure 4) wetlands. For example, temporary and seasonal wetland ponding occurred not only in spring and summer, but also in fall. Semi-permanent wetland ponding persisted despite extreme drought conditions in recent years. We suspect that this inconsistency is an artifact of the one-time inventory. Recorders may have presumed those basins with a relatively small amount of open water in spring were temporary (see Figure 2) and expected these to quickly dry out. Similarly, they may have presumed those basins with a relatively high amount of water in spring were semi-permanent (see Figure 4) and expected these to dry out during drought. These time-series data indicate we cannot conclude a particular water regime class will follow classical ponding patterns, especially when profiling populations of wetlands. These results, garnered from newly available synoptic observations (Beeri et al., 2007), point to the need for expanding our knowledge base to include historical water level observations for individual and populations of wetlands.

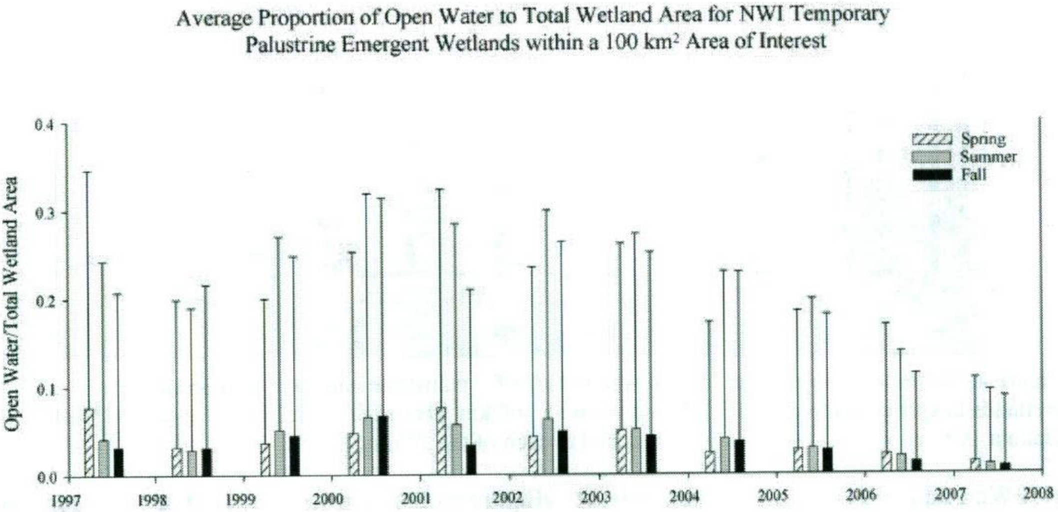

Figure 2. The ratio of open water to total wetland area for palustrine emergent temporary wetlands in spring, summer and fall found within a 100 km^2 area-of-interest located in central North Dakota. A total of 2612 wetlands were mapped at each of the 33 time points.

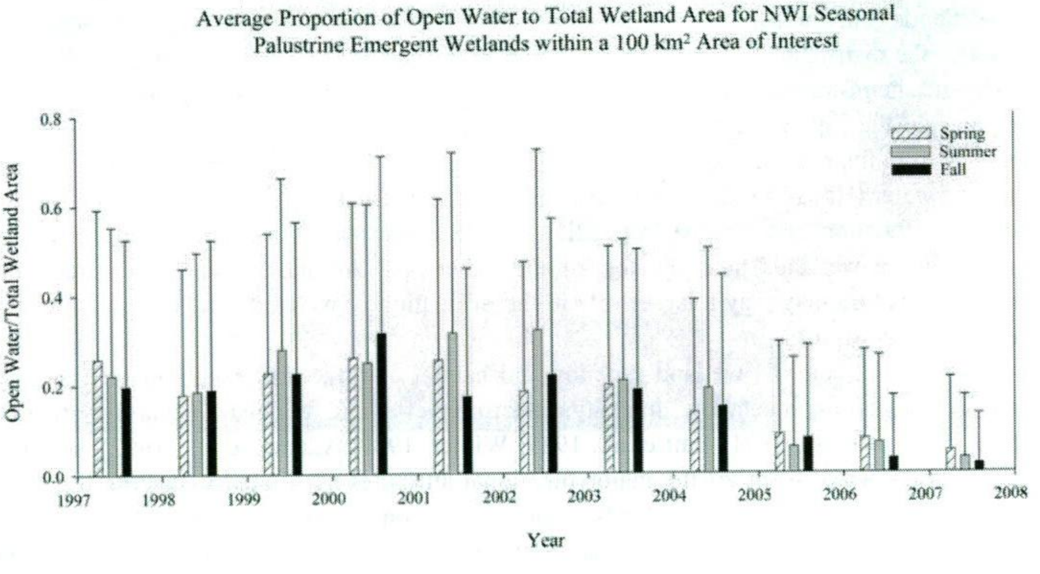

Figure 3. The ratio of open water to total wetland area for palustrine emergent seasonal wetlands in spring, summer and fall found within a 100 km^2 area-of-interest located in central North Dakota. A total of 2612 wetlands were mapped at each of the 33 time points.

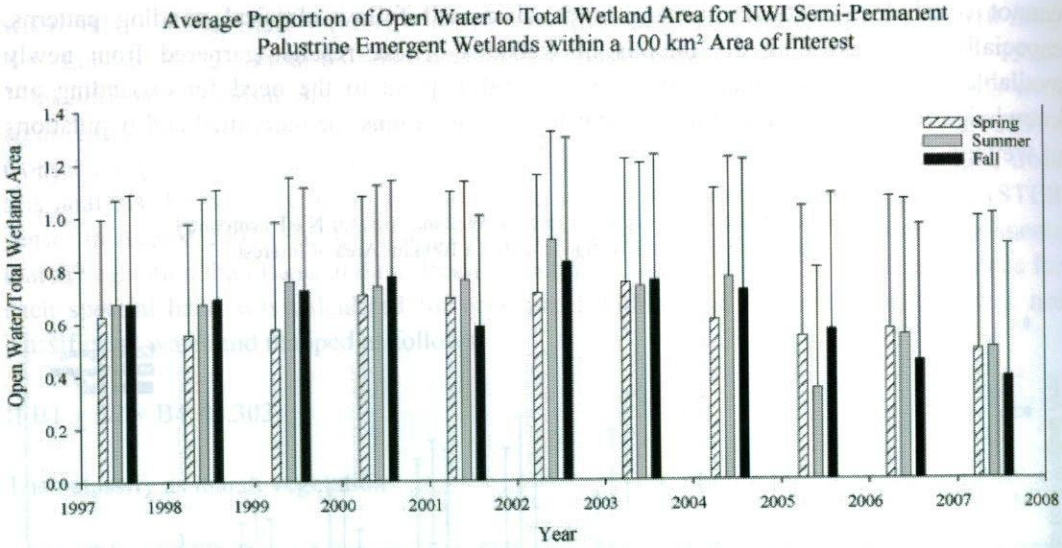

Figure 4. The ratio of open water to total wetland area for palustrine emergent semi-permanent wetlands in spring, summer and fall found within a 100 km^2 area-of-interest located in central North Dakota. A total of 2612 wetlands were mapped at each of the 33 time points.

We mapped NWI water regime classes (Figure 5) and wetland cover classes (Figure 6) for a subset of our AOI to illustrate how these attributes differ in space for the same wetlands. During the NWI, most of this landscape was populated by seasonal wetlands (Figure 5), as described by Cowardin et al. (1979). Our current wetland profile (Figure 7) indicates many wetlands now lack classical wetland characteristics, e.g. ponded water and marsh vegetation. In 2007, most seasonal and temporary wetlands are in the dry marsh or dry/no marsh stages. Many of the semi-permanent wetlands are in the dry marsh or hemi-marsh stages, with only a few wetlands remaining in the lake marsh stage. Current wetland cover for our entire AOI illustrates the distribution of cover classes in space with respect to elevation (Figure 8). Lake marsh and hemi-marsh stages are more abundant in the darker, lower-elevation areas, compared to the lighter, higher-elevation areas. This is not surprising considering overland flow is the dominant hydrologic flowpath (Wolock et al., 2004), and snowmelt is the primary source of water (Hayashi et al., 1998). However, these geospatial population data suggest that hydrologic function may be tied to position on the landscape, with a greater probability of drier, recharge wetlands near the top of the watershed. Additional work is needed, but landscape position may play a larger role in the evaluation of wetland condition and services than previously discussed.

Hydroperiod controls wetland function and habitat quality with respect to productivity, water conservation, vegetation diversity, macro invertebrate populations, and waterfowl habitat (Stewart et al., 1971; Batt et al., 1989; Winter, 1989; Adamus et al., 1992), so cover cycle stage indicates many of the major functional attributes associated with PPR wetlands. When profiling populations of wetlands, relative elevation may also covary with cover cycle and further clarify wetland function at a watershed level. Wetland cover profiles and subsequent cover changes are critical to conservation assessment and should be built into regional wetland and water quality monitoring programs.

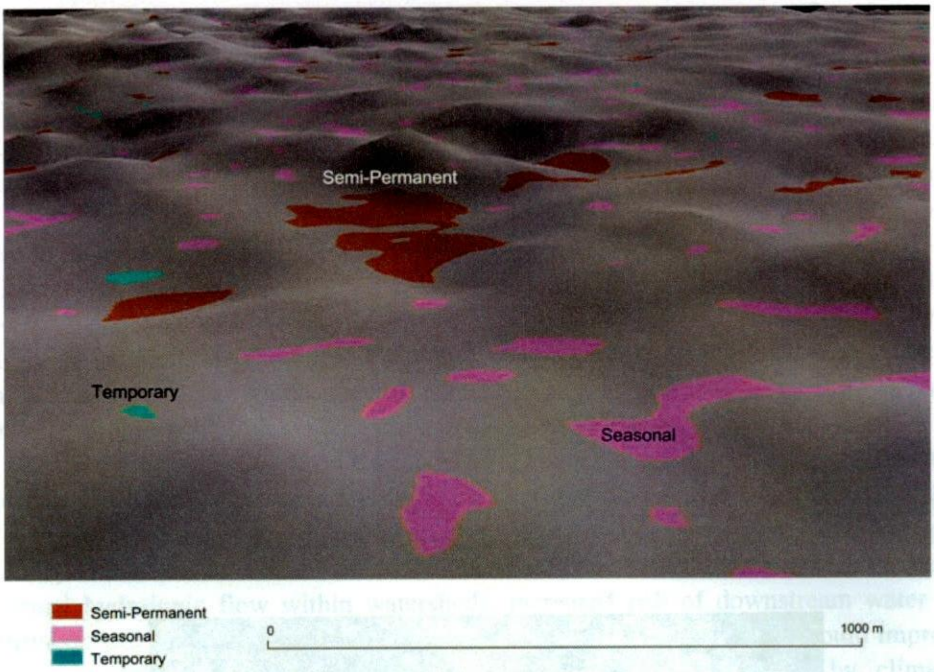

Figure 5. Temporary, seasonal and semi-permanent water regime classes, as recorded by the NWI (U.S. Fish and Wildlife Service, 2008), mapped on elevation.

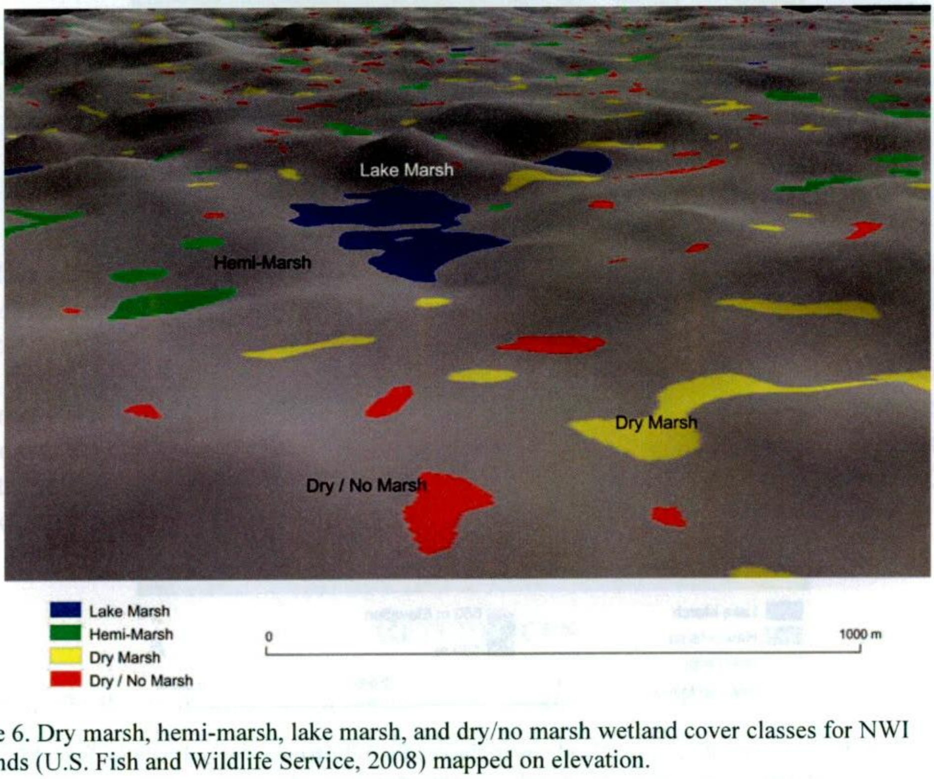

Figure 6. Dry marsh, hemi-marsh, lake marsh, and dry/no marsh wetland cover classes for NWI wetlands (U.S. Fish and Wildlife Service, 2008) mapped on elevation.

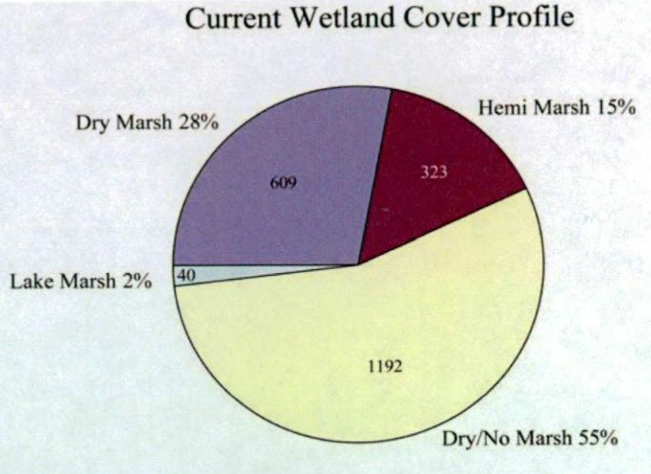

Figure 7. The distribution of wetland cover classes for palustrine emergent wetlands found within a 100 km^2 area-of-interest located in central North Dakota (U.S. Fish and Wildlife Service, 2008).

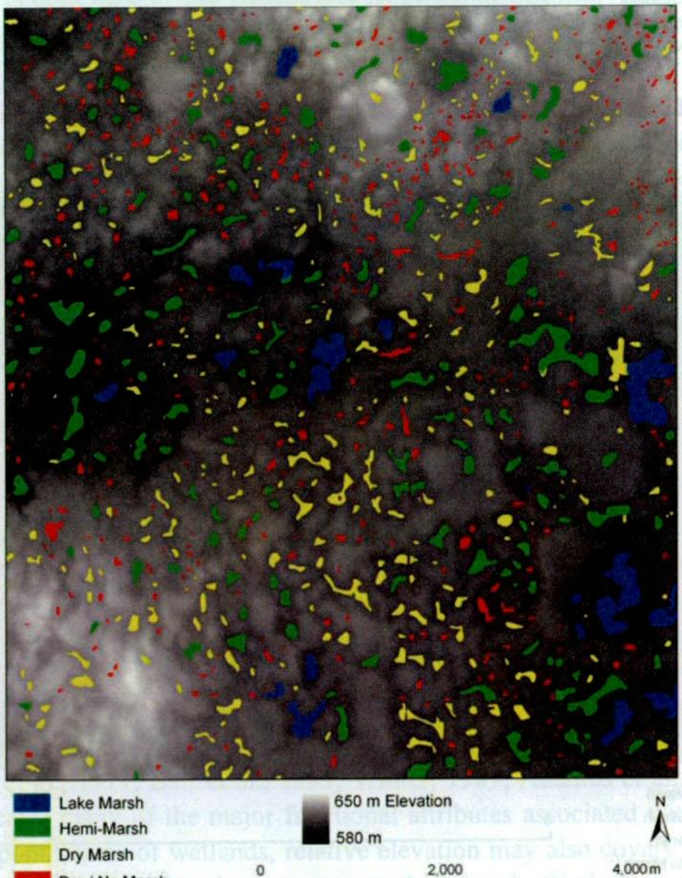

Figure 8. The spatial distribution of wetland cover classes for palustrine emergent wetlands within a 100 km^2 area-of-interest located in central North Dakota mapped on elevation.

CONCLUSION

The Cowardin et al. (1979) water regime classification is an extremely useful attribute included in the NWI map. However, these data are static and do not represent hydrologic dynamics associated with these climatically-sensitive wetlands. We suggest application of new satellite-based observations in GIS will improve our understanding of wetland condition by complementing existing knowledge with current cover data. What we know about spatiotemporal variability in the PPR is based on data generated from a few field sites, and the error associated with extrapolating results from a few sites across 3 million wetlands could be formidable. Mapping actual wetland cover over time could provide insight needed to monitor natural versus anthropogenic stressors among wetland populating a common hydrogeomorphic or hydrologic landscape (Wolock et al., 2004).

The need for tracking wetland condition goes beyond enhancing the knowledge base with up-to-date, ecologically-relevant data. Wetlands in the PPR are ecosystems at risk from losses due to changes in land use (van der Kamp et al., 1998) and climate (Winter, 2000; Johnson et al., 2005). Consequences of wetland losses, besides habitat fragmentation, include disruption of normal hydrologic flow within watersheds, increased risk of downstream water quality impairment, and losses to waterfowl populations. Tracking wetland cover could improve our capacity to estimate how populations of wetlands may be impacted by climate and anthropogenic stressors for thousands of wetlands in real time. Wetland cover cycle information could specifically advance efforts to tease out predicted effects of climate (Johnson et al., 2005) from effects of land use for multiple wetland basins. By mapping wetland cover regularly in GIS, condition assessments can capture current and historical wetland dynamics that drive ecological processes, including habitat structure for these sensitive and endangered ecosystems.

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REFERENCES

Adamus, P. R.; Leibowitz, S. *A process for regional assessment of wetland risk;* U.S. Environmental Protection Agency: Corvallis OR., 1992; 180 pp.

Batt, B. D. J.; Anderson, M. G.; Anderson, C. D.; Caswell, F. D. The use of prairie potholes by North American ducks in Northern Prairie Wetlands. In *Northern Prairie Wetlands;* Iowa State University Press: Ames, IA, pp 204-227.

Bedford, B. L. *Ecol. Appl.* 1996, *6,* 57-68.

Beeri, O.; Phillips, R.; Hendrickson, J.; Frank, A. B.; Kronberg, S. *Remote Sensing Environ.* 2007, *110,* 216-225.

Beeri, O.; Phillips, R. L. *Global Change Biol.* 2007, *13,* 897-920.

Bluemle, J. P. *The Face of North Dakota;* North Dakota Geological Survey: Bismarck, ND, 1991; 177 pp.

Conly, F. M.; van der Kamp, G. *Environ. Monitor. Assess.* 2001, *67,* 195-215.

Cowardin, L. M.; Carter, V.; Golet, F. C.; LaRoe, E. T. Classification of wetlands and deepwater habitats of the United States. In *U.S. FWS, Office of Biol. Ser. (FWS/OBS-79/31).* 103 pp.

Hayashi, M.; van der Kamp, G.; Rudolph, D. L. *J. Hydrol.* 1998, *207,* 42-55.

Johnson, W. C. *S. Dakota Conservation Digest* 1998, *65,* 10-11.

Johnson, W. C.; Boettcher, S. E.; Poiani, K. A.; Guntenspergen, G. R. *Wetlands* 2004, *24,* 385-398.

Johnson, W. C.; Millett, B. V.; Gilmanov, T. G.; Voldseth, R. A.; Guntenspergen, G. R.; Naugle, D. E. *BioScience* 2005, *55,* 863-872.

Millet, B. V. Vulnerability of Northern Prairie Wetlands to Climate Change. Ph.D. Dissertation, South Dakota State University, Brookings, SD, 2004.

Mitsch, W. J.; Gosselink, J. G. *Wetlands;* John Wiley and Sons: New York, NY, USA, 2000.

Murkin, H. R.; Murkin, E. J.; Ball, J. P. *Ecol. Appl.* 1997, 1144-1159.

Phillips, R. L.; Beeri, O.; DeKeyser, E. S. *Wetlands* 2005, *25,* 21-35.

Stewart, R. E.; Kantrud, H. Classification of natural ponds and lakes in the glaciated prairie region. Resource Publication 92. Bureau of Sport Fisheries and Wildlife, U.S. Fish and Wildlife Service, Washington, DC, 1971: 57 pp.

Tiner, R. W. NWI Maps: What they tell us. *National Wetlands Newsletter.* 1997, *19,* 5-12.

U.S. Fish and Wildlife Service. National Wetland Inventory Maps. U.S. Fish and Wildlife Service; Washington, DC, 1977 to present. http://wetlandsfws.er.usgs.gov/wtlnds/launch.html

van der Kamp, G.; Hayashi, M. *Great Plains Res.* 1998, *8,* 39-56.

van der Valk, A. G.; Davis, C. B. *Ecology* 1978, *59,* 322-335.

Weller, M. W.; Spatcher, C. E. Role of Habitat in the Distribution and Abundance of Marsh Birds. *Agric. and Home Econ. Exp. Sta. Spec. Rep. No. 43. 31.* Iowa State University, Ames, IA, 1965.

Winter, T. C. Hydrologic studies of wetlands in the Northern prairie. In *Northern Prairie Wetlands;* Iowa State University Press: Ames, IA, 1989; pp 16-55.

Winter, T. C. *J. Amer. Water Resources Assoc.* 2000, *36,* 305-311.

Winter, T. C. *Hydrological, chemical and biological characteristics of a prairie pothole wetland complex under highly variable climate conditions - the Cottonwood Lake area, East-central North Dakota;* Professional Paper; U.S. Geological Survey: Washington, DC, 2003; 109 pp.

Wolock, D. M.; Winter, T. C.; McMahon, G. *Environ. Manage.* 2004, *34,* S71-S88.