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MODEL ESTIMATION OF LAND-USE EFFECTS ON WATER LEVELS OF NORTHERN PRAIRIE WETLANDS

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Abstract. Wetlands of the Prairie Pothole Region exist in a matrix of grassland dominated by intensive pastoral and cultivation agriculture. Recent conservation management has emphasized the conversion of cultivated farmland and degraded pastures to intact grassland to improve upland nesting habitat. The consequences of changes in land-use cover that alter watershed processes have not been evaluated relative to their effect on the water budgets and vegetation dynamics of associated wetlands. We simulated the effect of upland agricultural practices on the water budget and vegetation of a semipermanent prairie wetland by modifying a previously published mathematical model (WETSIM). Watershed cover/land-use practices were categorized as unmanaged grassland (native grass, smooth brome), managed grassland (moderately heavily grazed, prescribed burned), cultivated crops (row crop, small grain), and alfalfa hayland. Model simulations showed that differing rates of evapotranspiration and runoff associated with different upland plant-cover categories in the surrounding catchment produced differences in wetland water budgets and linked ecological dynamics. Wetland water levels were highest and vegetation the most dynamic under the managed-grassland simulations, while water levels were the lowest and vegetation the least dynamic under the unmanaged-grassland simulations. The modeling results suggest that unmanaged grassland, often planted for waterfowl nesting, may produce the least favorable wetland conditions for birds, especially in drier regions of the Prairie Pothole Region. These results stand as hypotheses that urgently need to be verified with empirical data.

Key words: grassland management; grazing; landscape condition; land use; Prairie Pothole Region; prairie wetland; waterfowl management; wetland ecology; wetland hydrology; wetland modeling; wetland water budget; wetland water level.

INTRODUCTION

Wetlands in the Prairie Pothole Region (PPR; Fig. 1) are ecologically and economically important, as these wetlands provide many ecosystem goods and services, including surface-water retention, groundwater recharge, rich biodiversity including 50–80% of North American duck production, outdoor recreation, and water and forage production for agriculture (Batt et al. 1989, van der Valk and Pederson 2003). Prior to settlement, an estimated 12.6 million wetlands (van der Valk and Pederson 2003) occurred in the nearly 800 000-km^2 Prairie Pothole Region (Kantrud et. al 1989*b*, Krapu and Duebbert 1989) of North America. Since then, over one-half of the original wetland area of the PPR has been lost by drainage, due mostly to agriculture (Tiner 1984, Dahl 1990, 2000, Dahl and Johnson 1991).

Most prairie wetlands are imbedded in a matrix of farmland; nearly every wetland is affected either directly or indirectly by human activities (Kantrud et al. 1989*a, b*). Much has been written about the negative effects of agricultural practices on the abundance and quality of these wetlands, especially wetland drainage (e.g., Dahl 2000), sedimentation, and nutrient and biocide pollution (Cooper and Moore 2003). Hochbaum (1960) noted long ago that drainage in Canada and the United States threatened to permanently remove most of the small nesting marshes from the agricultural range, the same farmland wetlands that supported more of the breeding waterfowl than the very large marshes. Since European settlement, nearly all of the tallgrass prairie and ~60% of the mixed grass prairie that surrounded wetlands in the northern Great Plains of the United States has been converted to cropland (Higgins et al. 2002). For example, cropland now surrounds 73.2% of the wetland basins in the glaciated portion of North

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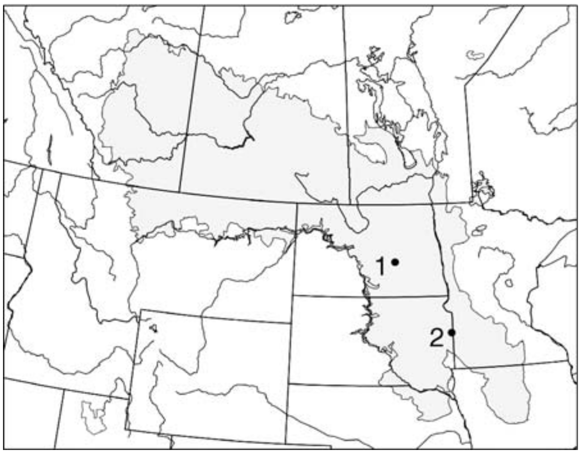

FIG. 1. Extent of Prairie Pothole Region in North America. The figure was adapted by combining ecoregion boundaries from various sources: Wilken (1986), CEC (1997), Omernik (1987), and EPA (1997). Also shown are the study site locations: (1) Cottonwood Lake Area and (2) Orchid Meadows.

Dakota (Austin et al. 2001). A Canadian study examining the impacts of agriculture on wetland habitats found that of the nearly 10 000 wetlands studied a mean of 58.9% of the wetland basins and 79.2% of the wetland margins were degraded by agriculture (Turner et al. 1987).

The management of wetlandscapes for agriculture has important implications for wetland function and habitat suitability for wildlife. In a study of the Canadian PPR, Podruzny et al. (2002) found, at a prairie-wide scale, that Northern Pintail (*Anas acuta*) settling was negatively associated with cropland area. They further found that pintail settling was better explained by information on specific agricultural practices than by overall increases in farmed area. Recent management has emphasized converting farmland in wetland watersheds to grassland habitat to improve nesting conditions for wetland waterbirds. Large, unfragmented landscapes with intact grasslands surrounding wetland complexes reduce predation and increase nesting success (Ball et al. 1995, Sovada et al. 2000, Hoekman et al. 2002, Horn et al. 2005). The consequences of reversions of cultivated farmland to grassland, while of unchallenged benefit to upland nesting success of waterbirds, have not been evaluated relative to their effect on the water budgets of associated wetlands.

Several effects are possible. While reversion of cultivated fields to grassland would reduce wetland sedimentation and filter biocides, it may also reduce runoff and water yield to downslope wetlands. Van der Kamp et al. (1999) published a striking account of grassland reversion that caused wetlands to dry up. Their study raised the possibility that grassland restoration may be a double-edged sword for some waterbirds, in that reversion to grassland can provide upland nesting habitat, but may cause wetlands to become drier. Another possibility is that some crop types may produce different water levels than others as a result of differential crop water use efficiencies and surface runoff. The possible trade-off between upland nesting and wetland habitat, mediated by watershed hydrologic processes, needs to be further explored by PPR wetland scientists and managers.

This research was undertaken to estimate the magnitude of the effect of land cover on wetland ecosystem dynamics. We wanted to better understand the potential for land-use decisions to affect wetland hydroperiod and water level rise and fall, the processes that drive wetland ecological functions. In the absence of empirical studies of land-use and wetland interactions, we chose a modeling approach using the single-basin wetland hydrologic and vegetation dynamics model WETSIM (Poiani et al. 1993*b*), modified to perform land-use simulations. WETSIM 1.0 and 2.0 were shown to accurately simulate the hydrology and vegetation dynamics of a semipermanent prairie wetland at the Cottonwood Lake site in North Dakota, USA (Fig. 1) (Poiani and Johnson 1993*b*, 2003, Winter 2003). Other applications of WETSIM explored the potential impacts of climate change on prairie wetlands (Poiani and Johnson 1991, 1993*a*, Poiani et al. 1995, 1996, Johnson et al. 2005). In previous applications of WETSIM, watershed cover was not a variable. The goal of this application of WETSIM was to simulate the effect of changing agricultural land-use cover type on the hydrology and vegetation of a semipermanent wetland at a new site in eastern South Dakota (Fig. 1). The specific objectives of this study were to (1) parameterize and calibrate the WETSIM 3.2 model for semipermanent wetland SP4 at the Orchid Meadows site in Deuel County, South Dakota (Fig. 1) using available field and literature data, (2) evaluate the WETSIM 3.2 model performance by comparison of the spring rise and fall drawdown dynamics to that of the monitored semipermanent wetland SP4, and (3) utilize WETSIM 3.2 to simulate the effects of agricultural land-use cover types on prairie wetland hydrology and vegetation.

METHODS

Field site

The Orchid Meadows site is a 65-ha tract of tallgrass prairie that is managed by the U.S. Fish and Wildlife Service as the Severson Waterfowl Production Area. It is located ~16 km east of Clear Lake, South Dakota, USA on the Prairie Coteau (Johnson et al. 2004). The Orchid Meadows database has 17 years (from 1987 to the present) of water level data from wetlands and associated wells. These data were collected every two weeks during the ice-free season. Wetlands of temporary, seasonal, and semipermanent classes (Stewart and Kantrud 1971) occur throughout the landscape in depressional lows. Semipermanent wetland SP4 is ~2.2 ha in areal extent and is one of 10 monitored wetlands at the site. The Orchid Meadows site is characterized by rolling hills of 4–16% slope; some areas are up to 25% slope or more.

TABLE 1. Taxonomy and approximate landscape position of soils at Orchid Meadows, South Dakota, USA.

Soil series	Taxonomic class	Approximate landscape position
Barnes	fine-loamy, mixed, superactive, frigid, Calcic Hapludolls	upland, level to undulating, summits, 0–25% slopes
Buse	fine-loamy, mixed, superactive, frigid, Typic Calciudolls	upland, strongly convex slopes, shoulders, 3–60% slopes
Svea	fine-loamy, mixed, superactive, frigid, Pachic Hapludolls	upland, concave positions, toe-slopes, 0–25% slopes
Flom	fine-loamy, mixed, superactive, frigid, Typic Endoaquolls	wetland, level to mildly concave locations around and in temporary basins, 0–3% slopes
Vallers	fine-loamy, mixed, superactive, frigid, Typic Calciaquolls	wetland, very slightly convex to concave locations around and in seasonal and semipermanent basins, 0–3% slopes
Parnell	fine, smectitic, frigid, Vertic Argiaquolls	wetland, depressions of temporary and seasonal basins, 0–3% slopes
Southam	fine, smectitic, calcareous, frigid Cumulic Vertic Endoaquolls	wetland, deep depressions of semipermanent basins, 0–1% slopes

Note: The table is derived from information in Hubbard (1988), Millar (1990), and Miller (1997).

Soils are typified by Mollisols with calcareous or clay subsoils underlain by glacial till (Table 1). Uplands are dominated by native grassland with components of non-native smooth brome (*Bromus inermis* L.) and bluegrass (*Poa pratensis* L.). This site is grazed occasionally. Mean annual precipitation was 663 mm and the mean annual temperature was 7.4°C for this location based on a 41-year (1961–2001) composite data set compiled from the site and the National Oceanic and Atmospheric Administration (NOAA) weather stations at Clear Lake, South Dakota and Canby, Minnesota, USA. Further details on the ecological setting of the Orchid Meadows site can be found in Johnson et al. (2004).

Model description

WETSIM version 3.2 is a single-basin hydrologic and wetland vegetation dynamics model based on earlier model versions 1.0–2.0 (Poiani and Johnson 1993*a, b*, Poiani et al. 1996). Incorporated into WETSIM 3.2 are hydrologic functions and upland agricultural land-use components (Fig. 2). This deterministic model includes watershed-surface processes, watershed groundwater, wetland-surface processes, and wetland-vegetation dynamics (Fig. 3). WETSIM 3.2 calculated upland water contributions to the wetland, wetland water balance, wetland water level, and wetland vegetation cover daily from May through September for the simulation period (1961–2001). The vegetation cover types simulated

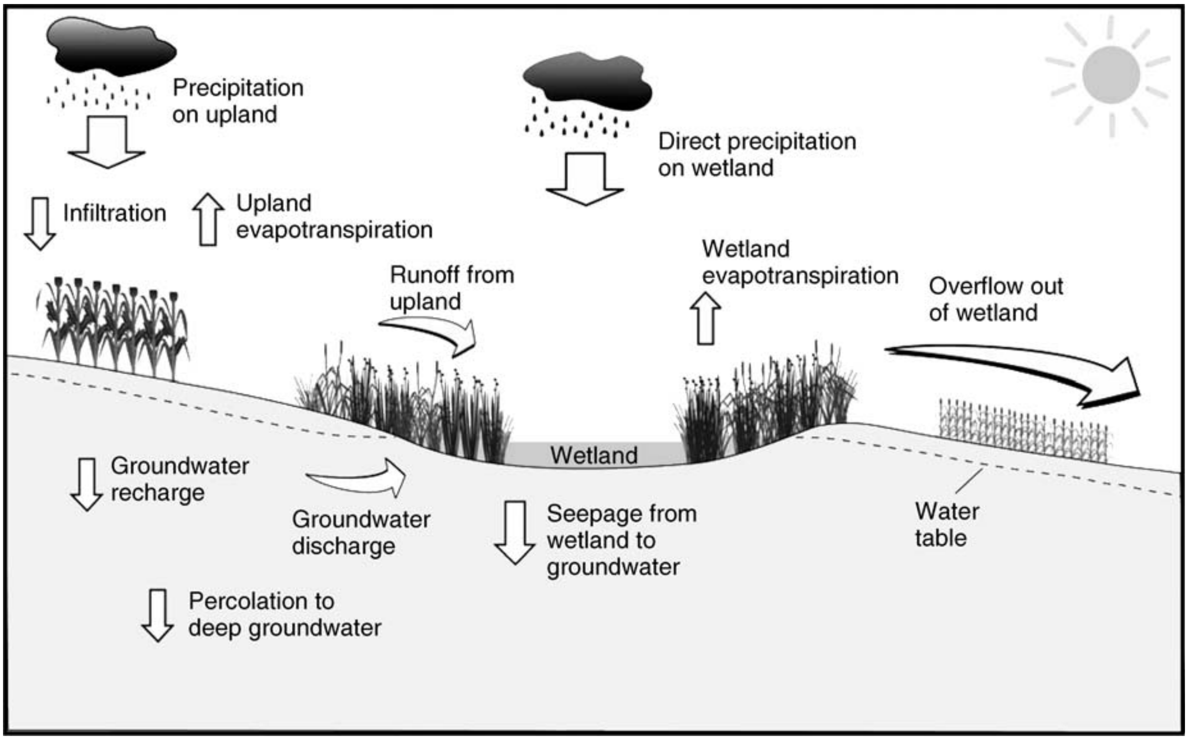

FIG. 2. WETSIM 3.2 hydrologic model conceptualization illustrating wetland water-budget inputs and outputs.

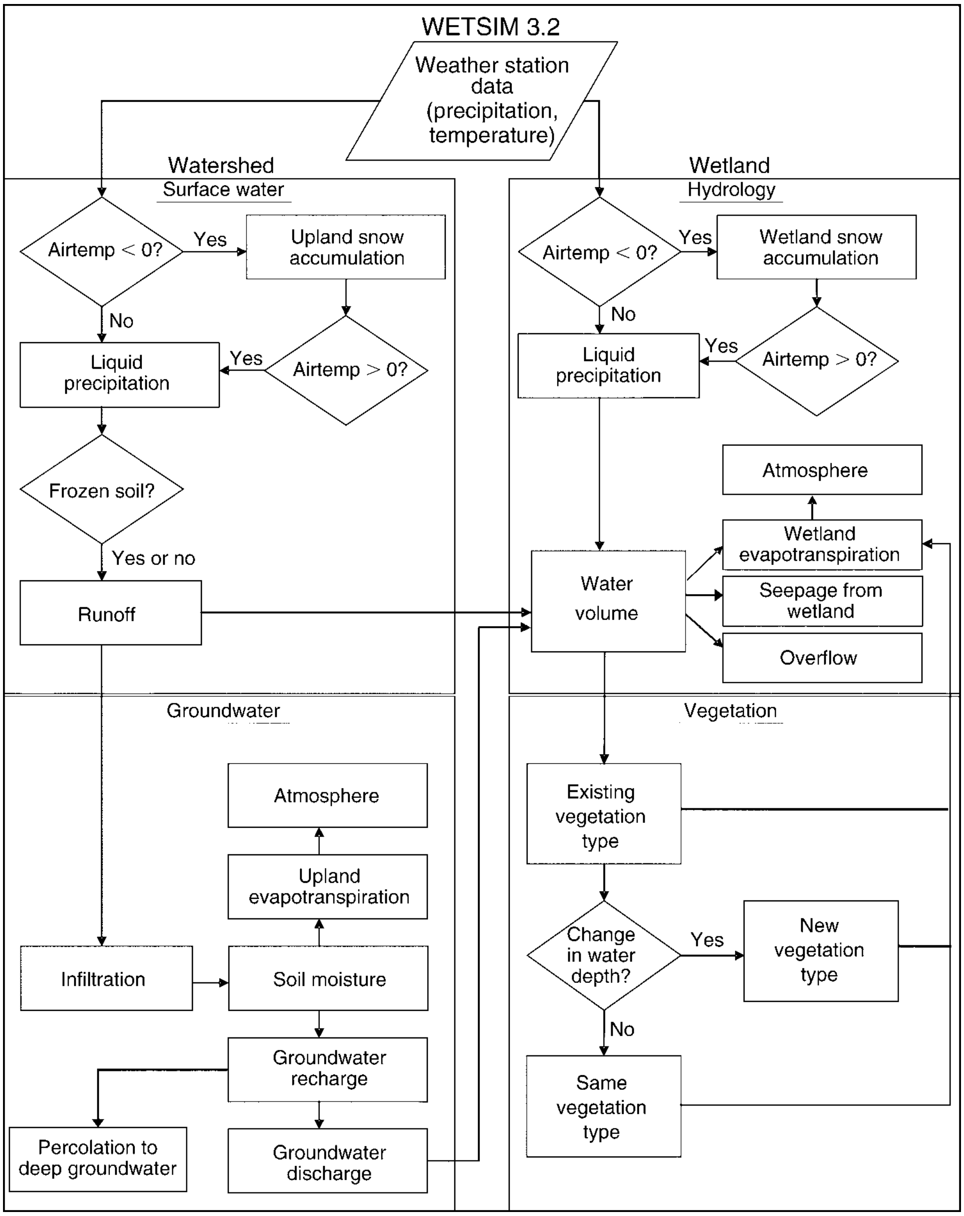

FIG. 3. Flow chart illustrating watershed and wetland hydro-ecological processes in WETSIM 3.2.

included open water, bare soil, seedlings, mixed plants, wetmeadow/shallowmarsh, and deepmarsh. Input required for WETSIM 3.2 were a daily precipitation and temperature file, a file of precipitation sums for each year of the simulation, a file of elevations representing the topography of the wetland catchment and basin, and a file of observed wetland water levels used for calibration. The model was programmed in Mathematica (Wolfram 1999).

Modifications made to the WETSIM model included (1) replacing Blaney-Criddle potential evapotranspiration (ET) with the Hargreaves potential ET (Hargreaves 1994) from the USDA's Erosion Productivity Impact Calculator (EPIC) model (Williams 1995), (2) replacing subsurface lateral flow with a calibrated ground-water function (Carroll et al. 2005), (3) employing independent upland- and wetland-snowpack accumulation and sublimation from EPIC (Williams 1995), and (4) incorporating land-use influences on runoff using the Soil Conservation Service's (SCS) Runoff Curve Number Method (USDA-SCS 1972) and upland evapotranspiration based on a simple temperature- and precipitation-adjusted leaf area index (LAI) growth-curve function for determining crop transpiration, along with soil evaporation from EPIC (Williams 1995). Mean annual ET for each land use was calibrated using a coefficient to match mean annual ET produced using EPIC (Williams 1995) for corresponding land uses.

TABLE 2. Land-use type and land-treatment considerations used to determine the runoff curve number from the National Engineering Handbook (USDA-SCS 1972).

Land-use type	Curve number	Land treatment
Native grass	62	uncultivated; good hydrologic condition
Moderately heavily grazed native grass	79	uncultivated; poor hydrologic condition (some bare patches, little mulch, compaction)
Spring-burned native grass	80†	uncultivated; poor hydrologic condition (no mulch)
Smooth brome grass	63	previously cultivated; good hydrologic condition
Small grain	75	conventional contour tillage; good hydrologic condition
Row crop	78	conventional contour tillage; good hydrologic condition
Alfalfa	73	recently cultivated; good hydrologic condition

Note: Land-treatment considerations common to all land-use types are hydrologic soil group B soils, slope, and inclusions of group C and D soils.

† Curve number for spring-burned native grass is estimated because no options exist for burned grass in the National Engineering Handbook.

EPIC (Williams 1995) is a mathematical, field-scale, physically based model that is used to simulate the long-term effects of erosion on soil productivity on a daily time step. We chose to use components of EPIC in WETSIM 3.2 because EPIC is rather robust and has been well tested and reviewed. EPIC has been used in numerous modeling studies including studies of land use and climate change (e.g., Huszar et al. 1999, Thomson et al. 2005). The SCS curve number method (USDA-SCS 1972) used in EPIC is a versatile, efficient, and widely used procedure for determining the approximate amount of runoff from rainfall events in a particular area. It is widely used because it can provide consistently usable results over a range of soils, land uses, and geomorphic settings. The method includes several important properties of the watershed including soil type (hydrologic group or textural class), hydrologic condition (vegetation ground cover, mulch, compaction), and land-use practices (crop type and conservation practice with slope considerations). Runoff potential is expressed as a curve number ranging from 0 to 100, with 100 being an impervious surface with the greatest runoff capability. Our curve number selections (Table 2) were based on land-use type and land-treatment descriptions given in the National Engineering Handbook, Section 4 (USDA-SCS 1972).

Wetland water volume was calculated daily via mass balance. Evaporation from the open water wetland surface and evapotranspiration from the vegetated portion of the wetland were estimated using the modified Hargreaves ET equation from EPIC (Williams 1995). Water level was calculated from a water level–volume relationship based on empirical wetland data. Water that exceeded the wetland outlet elevation was lost as overflow discharge. The seepage factor for wetland SP4 was set to zero. ET demand was allowed to continue after the wetland went dry; however, the water table was not tracked below the wetland bottom. The water level in this semipermanent wetland rarely dropped below the wetland bottom during our observation period.

Model parameterization, calibration, and testing

The precursors to WETSIM 3.2 were all calibrated using literature and site data for semipermanent wetland P1 at the Cottonwood Lake Area in North Dakota, USA (Fig. 1). In this study, the model was "moved" and recalibrated using literature and site data for wetland SP4 at the Orchid Meadows site (Johnson et al. 2004). During this process, it was found that adjustments were needed to groundwater contribution and to evapotranspiration to improve the fit between observed and simulated water levels. During model calibration, adjustments were made to the timing (period of time during the year) of the upland and wetland snowpack melt, timing of soil frost thaw, soil moisture balance, groundwater recharge, potential evaporation, upland evapotranspiration, open water evaporation, and wetland evapotranspiration. Model processes calibrated using scalars were upland evapotranspiration, open water evaporation, and both dry- and wet-emergent-vegetation evapotranspiration. Snow-pack accumulation and sublimation are temperature based. The timing of snowpack melt and soil frost thaw were adjusted by calibrating to a 10-day mean temperature threshold.

Land use was incorporated into WETSIM 3.2 to explore the potential impacts of upland agriculture on wetland hydrologic and vegetation processes. Seven land-use cover types were evaluated: "managed native grassland" ([1] continuous, moderately heavily grazed native grass and [2] spring burned native grass), "unmanaged grassland" ([3] native grass and [4] smooth brome grass; no mowing, haying, burning, grazing, or tillage), "cultivated crops" ([5] row crop, e.g., corn, and [6] small grain, e.g., spring wheat). Additionally, we simulated "alfalfa hayland" ([7] alfalfa as a 1-year-old stand with averaged cutting effects). Grassland cover types were considered native grassland for the location, except in the case of smooth brome, which fit best with the Conservation Reserve Program (CRP) categorization.

In WETSIM 3.2, differences in land-use cover types were simulated by varying three main components of the water budget: runoff, infiltration, and upland evapotranspiration. Runoff was calculated from liquid precipitation based on the SCS runoff curve number method (USDA-SCS 1972). Infiltration and ET were determined as follows. Infiltration was the amount of precipitation remaining after runoff was removed.

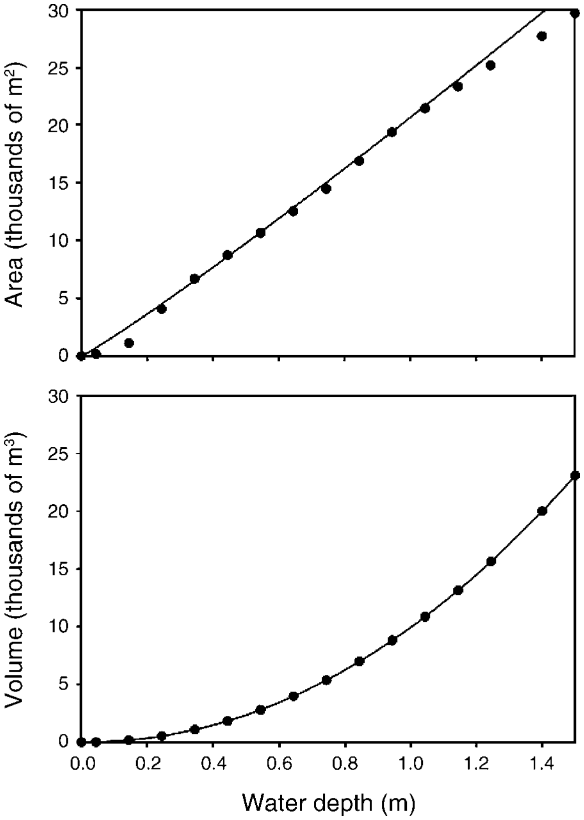

FIG. 4. Area–depth (Eq. 1) and volume–depth (Eq. 2) power functions of semipermanent wetland SP4. Curves indicate the power functions, and solid circles indicate data points.

Simulated evapotranspiration in the upland was dependent on plant LAI and soil moisture. An LAI "growth" curve was developed as a function of 10-day mean temperature, annual precipitation for that year, and a maximum LAI (Voldseth 2004). The maximum LAI value was determined with the equation LAI = 0.00698 × mean annual precipitation in millimeters (B. Lauenroth, *personal communication*). This equation was developed from grassland sites across the central Great Plains, based on data from Lane et al. (2000). Maximum LAI for both grassland and crops was set not to exceed 4 m^2/m^2 (B. Lauenroth, *personal communication*). The range of maximum LAI values used was further corroborated by published data (Scurlock et al. 2001).

With LAI responding to temperature and precipitation, scalar coefficients were developed to adjust the model LAI-based ET to specific estimates of ET simulated with EPIC (Williams 1995) for each land-use cover type. Evapotranspiration estimates for smooth brome, corn, spring wheat, and alfalfa were determined for the study area using EPIC version 5300. Because EPIC does not have a cover category corresponding to northern native tallgrass prairie, we adjusted the evapotranspiration coefficient for native grass at Orchid Meadows to 75% of the smooth brome mean ET calculated by EPIC to better represent grass-production curves for South Dakota (Derscheid et al., *no date*). ET for continuously grazed native grass was calculated as a 50% reduction in LAI representing the "take half–leave half" rule of thumb for grazing (Tanner 1988, Poole 2002). A 50% reduction in LAI is typically considered of moderate grazing intensity; however, we combined the reduction of LAI with a high runoff curve number that is representative of a heavy grazing class. We consider our grazing class to be moderately heavy. The curve number for burned grassland is set similar to that for heavy grazing because mulch ground cover does not develop during the model simulation. Therefore, very little mulch, as represented by the curve number, is present during spring snowmelt runoff. LAI functions the same throughout the season for burned grass as it does for unmanaged native grass, without the reduction that occurs in grazed grass. ET for burned grassland was calculated as 23.3% higher than unburned native grass ET (Bremer and Ham 1999). ET from the wetland was divided into open water and emergent vegetation components and was calibrated with a scalar applied to Hargreaves potential evaporation.

The calibration of the model to wetland SP4 was based on the existing wetland outlet level of 1.17 m, a level lower than the original natural outlet due to ditching. After calibrating and testing, it was found that SP4 with the 1.17-m outlet produced and maintained little open water habitat. After calibration, a 1.4-m outlet level was set to better represent pre-ditched conditions. All subsequent simulations with upland land-use cover types were conducted using a 1.4-m outlet level. The selection of SP4 was not intended to represent the average prairie pothole wetland. Rather, we chose wetland SP4 due to its location, moderate size, and the long record of observations. Many wetlands in areas dominated by agriculture have had their outlets lowered. A closed basin wetland similar to SP4 with a higher outlet level would retain more water and would likely be more dynamic. The relationship of volume, area, and depth in SP4 was derived from a bathymetric map. We developed the area and volume relations (Fig. 4) for SP4 as simple power functions given by

$$V = aD^b \qquad (1)$$

$$A = abD^{b-1} \qquad (2)$$

where V is wetland volume (m^3), D is water depth (m), A is wetland surface area (m^2), $a = 9937.779346$, and $b = 2.080364437$. Hayashi and Van der Kamp (2000) provided equations that represent volume–area–depth relationships of shallow wetlands in small topographic depressions. In their study, two parameters are defined, s and p, which reflect the size and geometry, respectively, of small wetlands in the northern PPR. In the context of a large number of northern prairie wetlands (see

Hayashi and Van der Kamp 2000), wetland SP4 at Orchid Meadows exhibits a somewhat concave morphometry ($p = 1.85$) and has a water surface area, or s, equal to 20 674 m^2 when depth of water at the deepest point in the wetland is 1 m.

WETSIM 3.2 was calibrated to field data of wetland water levels from 1993 to 2001. Three years of field data after 2001 were used to test the model beyond the calibration period. The goal of calibration was to capture the key dynamics of prairie wetlands: spring rise, summer drawdown, and longer weather cycles of drought and deluge. The goal could not have been to replicate water level observations exactly because much of the weather input data was not available from the site but rather offsite from the nearest NOAA weather stations ~15 km away.

Water level sensitivity

After calibrating the model with existing grassland conditions at Orchid Meadows, several parameters were varied to evaluate their proportional impact on water levels. Contributions to wetland water levels were affected foremost by the amount of precipitation received in the upland watershed, particularly as snowpack during spring thaw, and secondly, as direct precipitation on the wetland. Reductions in wetland water levels were due primarily to evapotranspiration directly from the wetland basin during the summer.

Wetland water levels simulated by WETSIM 3.2 were sensitive to factors affecting runoff, particularly the type of land use and the timing of soil frost thaw in early spring. The timing of soil thaw was the most sensitive parameter affecting the amount of available snowmelt or early spring precipitation that reached the wetland. After spring thaw, wetland water levels were primarily affected by direct rainfall on the wetland and ET from the wetland. The amount of runoff that occurred during the soil frost-free period was dependent mostly on the unsaturated hydraulic conductivity of the upland soil and land use as it affected antecedent soil moisture through the amount of infiltration and upland ET. Significant runoff events during the summer were rare because antecedent soil moisture rarely approached saturation. Soil moisture balance affected runoff and the amount of available soil water that became groundwater recharge. Years with persistent water in the wetland during late summer and early fall were usually due to groundwater support provided through the model's groundwater recharge function. Groundwater recharge in WETSIM 3.2 is a function of infiltration, soil moisture balance, and a time lag function (Carroll et al. 2005).

Model simulations and analysis

One 41-year simulation, using weather data for 1961–2001, was run on a daily time step for each of the seven land-use cover types using an outlet level of 1.4 m. Runoff curve number and ET scalar coefficients remained the same for each year of the simulation. This provided a 41-year mean effect for land use based on actual weather data. The native-grass land-use cover type was used as the reference for comparison. Statistical analysis was conducted as a randomized complete block design with years as blocks and land use as treatments. The "proc mixed" procedure in SAS (SAS Institute 1999) was used with years considered as random effects. A least-square means comparison was conducted on land-use treatments ($P = 0.05$) to test for rejection of the null hypothesis that no differences exist between mean annual water levels. Several hydro-ecological metrics were also calculated for each land-use simulation because of their importance to ecological interpretation of wetland conditions. However, these metrics were not evaluated statistically.

RESULTS

Calibration and testing

The model simulation hydrograph with the 1.17-m outlet for unmanaged native grassland agreed with many of the observed values for both the calibration (1993–2001) and the post-calibration data sets (Fig. 5), demonstrating that the key fluctuations of spring water-level rise and summer drawdown, dynamics that drive prairie wetland functions, were simulated. Seasonal patterns of mean monthly observed and simulated wetland water level for 1993–2004 (Fig. 6) showed that the model overestimated both spring rise and fall drawdown.

WETSIM 3.2 accurately simulated wetland vegetation dynamics. Visual comparison of model maps and aerial photographs of SP4 (July 1994, July 1995, July 1996) shows a satisfactory match between the simulated and actual extent of wetland emergent vegetation and open water (Fig. 7).

Land-use simulations

Moderately heavily grazed and spring-burned native grassland produced the highest mean wetland water levels under the historical (41 years) climate, 0.85 m and 0.83 m respectively (Fig. 8). The mean water level for unmanaged native grass was 0.67 m, with unmanaged smooth brome only a fraction lower at 0.66 m. Row crop, small grain, and alfalfa had mean wetland water levels between these two extremes.

Mean water levels for the two categories of unmanaged grasslands did not differ significantly from each other, but they both differed significantly from the managed grasslands and crops (Fig. 8). The two cultivated crops were not significantly different from each other, and burned grassland was not significantly different from row crop or grazed native grass.

The differences among the treatments were quite large for several of the wetland metrics calculated. The percentage of years that the wetland experienced a dry period was lowest for the managed grasslands and highest for the unmanaged grasslands. Moderately heavily grazed native grass experienced 53% fewer

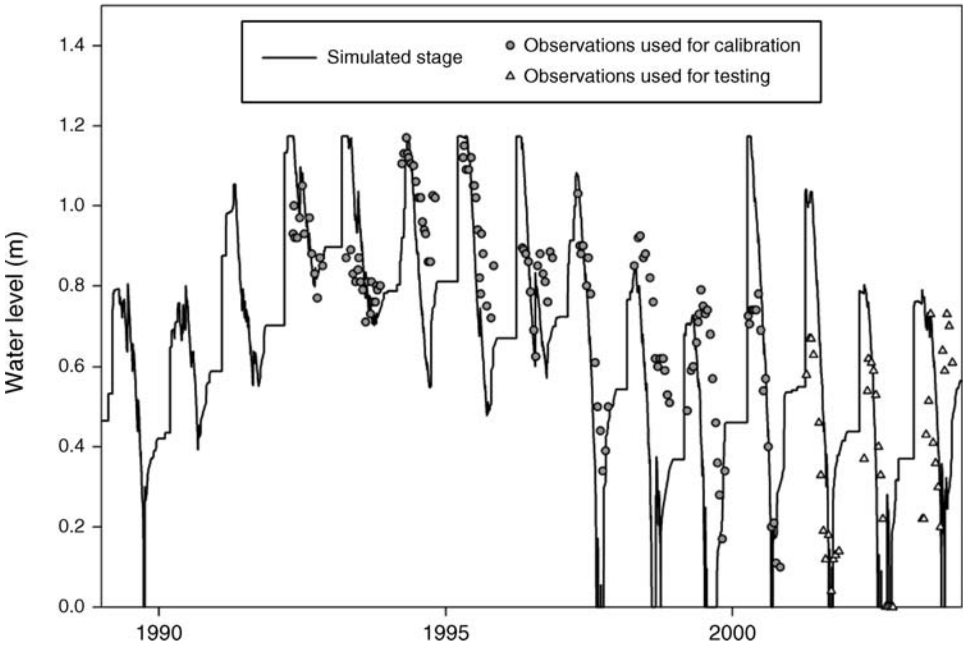

FIG. 5. Model simulation hydrograph (1990–2004) for semipermanent wetland SP4 with 1.17 m outlet level. Data from 1993–2001 were used for model calibration, and data from 2002–2004 were used for testing. The simulation was started in 1990 to allow the model to adjust to weather data for a few years before attempting calibration.

drought years than unmanaged native grass (Table 3). The wetland went dry 70% more often under unmanaged native grass than under grazed native grass (Table 3). Other metrics showed smaller differences, yet may be important ecologically. For example, the number of days that the wetland had ponded water (depth $>$ 10 cm) was highest for managed grassland and lowest for unmanaged grassland (Table 3). The mean number of consecutive dry days was highest for the unmanaged grasslands (Table 3).

Water budgets varied by land use. Runoff and ET from the wetland were the dominant factors in the wetland water budget (Table 3). Land use affected the water budget largely by impacting runoff. Runoff was greatest for the managed grasslands and least for the unmanaged grasslands.

The occurrence of hemi-marsh conditions (25–75% of the wetland area in emergent vegetation cover) varied by land use (Table 3). All land-use cover types experienced ~10% or more of the simulation period in the hemi-marsh phase. The time spent in hemi-marsh conditions was greatest for managed grassland and least for unmanaged grassland. The full open phase (open water area $>$ 75%) did not occur in this wetland as depth was limited by the outlet level.

Land use affected the mean proportion of wetland vegetation cover types. The most open water was created through the managed grasslands, while the least by the unmanaged grasslands (Fig. 8). The mixed-plants class did not appear in any of the simulations.

DISCUSSION

Land use, water levels, and wetland dynamics

Land use that alters the vegetation cover and surface roughness in the uplands affects precipitation routing to the wetland. Precipitation that falls on the landscape will be intercepted by plant material, run off the soil surface, infiltrate the soil, evapotranspire, drain to shallow groundwater and migrate to the wetland basin, or percolate to deep groundwater. Our modeled land-use cover types predominantly affected the hydrologic factors of infiltration, runoff, and evapotranspiration. Conceptually, vegetation cover and plant residues provided unmanaged grassland with interception that reduced runoff in the model (USDA-SCS 1972). In

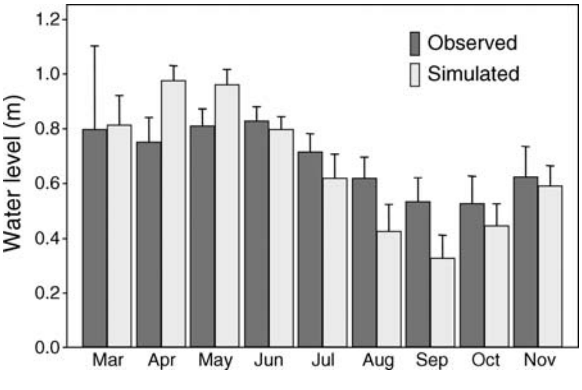

FIG. 6. Comparison of mean (+SE) monthly observed and simulated wetland water level for native grass (1993–2004).

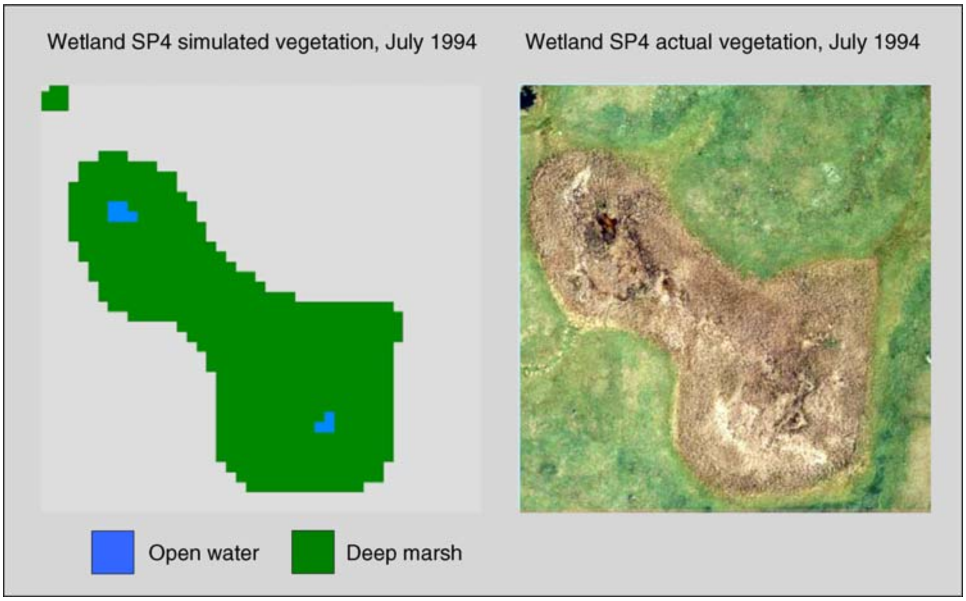

FIG. 7. Semipermanent wetland SP4 simulated vegetation vs. actual vegetation. The legend applies to model-simulated vegetation only. The green portion of the wetland in the simulated depiction (left) and the light brown/tan component on the aerial photo (right) are both deep-marsh vegetation. The two dark patches in the aerial photo are open-water areas and are located in similar positions as the blue open-water areas on the simulated depiction.

addition, relatively high soil porosity in unmanaged grassland, vis-a-vis soil structural development, soil organic matter, and root channel macropores, resulted in high infiltration. In contrast, cultivated fields typically have reduced organic matter, soil structure, and soil porosity when compared to uncultivated fields (Elliott and Efetha 1999, Unger 2001), resulting in reduced infiltration and greater runoff. An upland cover of cultivated crops may result in more water reaching the wetland than unmanaged grassland cover, but other factors, such as increased wetland sedimentation and alterations to water chemistry due to cultivation practices, are likely to have negative impacts on wetland condition and long-term permanence. Grazed grasslands have reduced vegetation cover and leaf area index resulting in lower interception of precipitation and transpiration producing increased surface runoff.

Field data do support less water yield to wetlands by unmanaged grassland compared to some crops. For example, in a wetland landscape in Saskatchewan, Canada, one-third of the wheatland acreage was converted to unmanaged smooth brome to provide nesting cover for waterfowl, while the other two-thirds remained in wheat (Van der Kamp et al. 1999, 2003). After a few years, all of the wetlands within grassed watersheds became dry and no longer produced

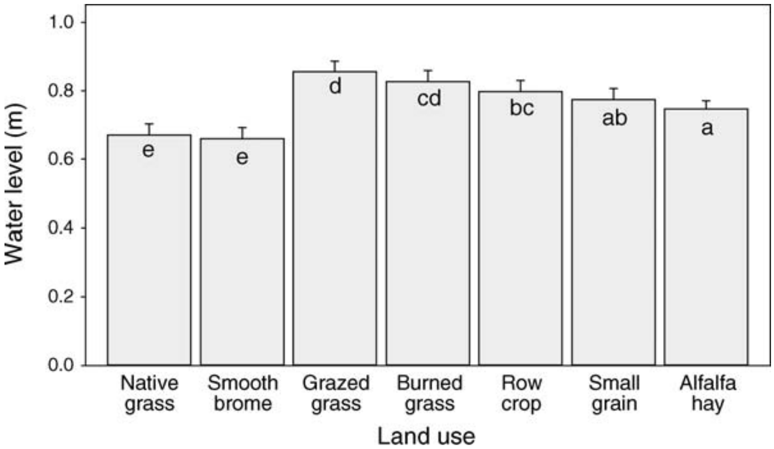

FIG. 8. Wetland water level (mean + SE) for land-use treatments simulated with WETSIM 3.2, based on the 41-year simulation period. Least-square means ($P = 0.05$) with the same lowercase letters (a–e, within the bars) are not significantly different.

TABLE 3. Summary table of hydro-ecological metrics for each land-use simulation.

Metric	Native grass	Grazed grass	Burned grass	Smooth brome	Row crop	Small grain	Alfalfa hayland
Runoff from upland (mm)	79	124	123	80	115	107	101
Infiltration in upland soil (mm)	580	536	537	580	545	553	558
Evapotranspiration in upland (mm)	457	313	590	604	588	493	532
Groundwater discharge from upland (mm)	25	26	21	22	22	23	23
Mean annual wetland water level (m)	0.67	0.85	0.83	0.66	0.80	0.77	0.75
Percentage of days inundated (>10 cm depth)	93	98	97	93	97	96	95
Mean number of consecutive days dry	15.5	17.8	17.3	16.1	12.5	15.5	16.1
Minimum number of consecutive days dry	1	1	2	1	1	1	1
Maximum number of consecutive days dry	75	58	73	76	55	89	93
Frequency of dry periods	60	18	23	61	31	38	43
Percentage of years with dry period (%)	46.3	22	22	48.8	26.8	34.2	34.2
Proportion of days in open phase	0	0	0	0	0	0	0
Proportion of days in hemi-marsh phase	0.10	0.21	0.19	0.10	0.14	0.12	0.12
Proportion of days in closed phase	0.90	0.79	0.81	0.90	0.86	0.88	0.88
No. switches between open and hemi-marsh phases	0	0	0	0	0	0	0
No. switches between hemi-marsh and closed phases	11	5	3	10	2	4	5
Runoff to wetland (m^3)	8963	13 990	13 831	9018	12 962	12 087	11 417
Direct precipitation on wetland (m^3)	9382	9382	9382	9382	9382	9382	9382
Groundwater discharge to wetland (m^3)	2784	2904	2386	2515	2423	2619	2571
Evapotranspiration from wetland (m^3)	19 822	23 402	22 919	19 640	22 387	21 989	21 445
Seepage from wetland (m^3)	0	0	0	0	0	0	0
Overflow from wetland (m^3)	1193	2735	2548	1167	2260	1979	1810

Notes: Metrics are mean annual values based on a 41-year simulation. Mean wetland area is 14 241 m^2. Mean annual precipitation is 663 mm.

standing water, while all of the wetlands that remained surrounded by cultivation maintained their former hydroperiods. This part of the PPR in Saskatchewan is quite dry with a mean annual precipitation of ~360 mm at Saskatoon (Van der Kamp et al. 1999, 2003); hence, these cover conversions may not have the same effect in wetter portions of the PPR. Also, these Canadian wetlands may be closer in permanence type to seasonal wetlands, rather than to semipermanent wetlands as simulated by WETSIM 3.2. In support of the Canadian study, however, results of WETSIM 3.2 simulations showed that mean wetland water levels for unmanaged smooth brome were significantly reduced compared to mean water levels for small grain cultivation in eastern South Dakota (Fig. 8).

The drying of the Canadian wetlands whose watersheds were converted to grassland indicated that runoff and precipitation into the wetland was less than evapotranspiration demands (Van der Kamp et al. 2003). The wetlands under grassland received less water through wind-blown snow and surface runoff than those surrounded by cultivation. Field measurements showed that often a greater amount of snow became trapped in the grassed upland and did not accumulate in the wetland basin as occurred in cultivated wetlands. The primary effect of the reversion from cultivation to grassland was the development of a soil macropore network over several years that resulted in increased infiltration of snowmelt into the soil, where it was primarily subjected to greater transpiration by the smooth brome and possibly to some loss by percolation to deeper ground water. At the St. Denis site in Saskatchewan, Canada (van der Kamp et al. 1999, 2003), macroporosity was 10% for cultivation, 17% for native grassland, and 20% for brome grassland (Bodhinayake and Si 2004). Van der Kamp et al. (2003) found that soil moisture down to a depth of 0.9 m was much lower under smooth brome compared to cultivated landscapes in this semiarid prairie region. This presumably was the net result of the inability of the climate in this part of the PPR to overwhelm the cumulative soil moisture deficit caused by the transpiration demand of the smooth brome.

The parameterization and testing of WETSIM 3.2 benefited from the longest and most extensive prairie–wetland data sets in the United States; water level and piezometer monitoring, among other measures, have continued over 26 years for wetland P1 and for 17 years for the wetland SP4 at the Orchid Meadows site. While these robust data sets allowed for the development of a functional wetland model, we found field hydrologic data from prairie wetland watersheds (i.e., runoff, infiltration, and the like) essentially lacking, making it difficult to assess the watershed portion of the model. The WETSIM 3.2 model was slightly more dynamic than the actual wetland, overestimating both spring rise and fall drawdown. This occurred because the water table was not tracked below the wetland bottom during dry periods. Overestimation of spring rise and fall drawdown, however, was constant across land-use conditions and did not differentially affect the simulated differences due to land cover types.

Model simulations using WETSIM 3.2 indicated that agricultural land use significantly affected wetland water levels and vegetation dynamics. Land use altered the dynamics of wetland inflows. Changes in the amount of water reaching the wetland in turn altered the hydro-ecological processes of spring rise, summer drawdown, occurrence of dry periods, and vegetation reproduction, establishment, and mortality. The primary factor responsible for higher water levels was increased runoff under crop cultivation and managed grasslands.

Some land-use cover types had greater effects on wetland water levels and vegetation dynamics than did others. For example, unmanaged native grassland and smooth brome grassland produced drier wetland conditions than did cultivated crops or managed grassland. Moderately heavy grazing caused significantly higher wetland water levels compared to unmanaged grassland. Moderately heavy grazing resulted in both a 10% greater proportion of days in hemi-marsh conditions and four times the proportion of wetland area in open water conditions on average when compared to unmanaged native grassland. We did not simulate moderate to light grazing in our original work with WETSIM 3.2. However, a recent simulation with moderate grazing (R. A. Voldseth, *unpublished data*) produced results nearly identical to those for our alfalfa hayland simulation.

Land-use effects and implications for management

Higgins et al. (2002) pointed out that grassland birds and waterbirds benefited from conversion of tilled landscapes to conservation grassland that provided nesting habitat and protection of wetlands from drainage. Simulations with WETSIM 3.2 indicated that converting managed grassland or cultivated crops to unmanaged native grassland or smooth brome grassland could produce reduced wetland water levels. Simulations with unmanaged grassland resulted in lower mean wetland water levels than the other land-use options. Reduced water levels often resulted in less dynamic cover and water conditions that could negatively affect productivity and biodiversity. These consequences could be especially significant in the drier portions of the PPR, where water levels are often marginal for waterfowl production, or in the future if the climate becomes effectively drier (Larson 1995, Johnson et al. 2005).

What are the implications of the Saskatchewan study results? While converting surrounding land use from small grain cultivation to unmanaged grassland improved upland nesting cover, it also seriously reduced wetland habitat under the Saskatchewan climate. The fact that these wetlands no longer maintained surface water after conversion of the upland from cultivation to grassland suggests that under historical natural grassland conditions, these wetlands were of the temporary or ephemeral type or were grazed sufficiently to increase runoff and lower ET such that they responded as seasonal wetlands under the climate regime. Conversion of the historical landscape to small-grain cultivation would have lengthened the wetland hydroperiod. While improving wetland water levels would have been beneficial to some life-history stages of waterfowl, extensive cultivation of the upland would also have greatly reduced nesting cover. Management of the uplands in wetlandscapes appears to have trade-offs for waterfowl production: too little grass reduces nesting while too much grass, if unmanaged, can dry up more labile wetlands.

Our simulations of wetland dynamics and hydroperiod revealed similar management implications for semipermanent wetlands in eastern South Dakota. Wetland water levels under unmanaged grassland were much lower than water levels under managed grassland or cultivation. Even if the wetlands do not dry out completely, land use could affect water levels such that hemi-marsh conditions and vegetation cycling are reduced or no longer occur. When small grain was converted to brome grass cover types in our simulations, the frequency of dry periods and percentage of years with dry periods increased by 61% and 43%, respectively (Table 3). Correspondingly, both open water and bare soil conditions in the wetland decreased (Fig. 9), indicating ecologically significant changes in wetland conditions.

Temporary and seasonal wetlands are often the primary sources of open water feeding habitat for migrating waterfowl in early spring, as they fill with snowmelt prior to the ice thaw on semipermanent wetlands (Swanson et al. 1974). Because of their hydrology and vegetation dynamics, small wetlands are important in nutrient cycling and in the maintenance of biodiversity (Semlitsch and Bodie 1998). The implications for temporary and seasonal wetlands under conversion from cultivation or managed grassland to unmanaged grassland are that they will likely go dry and remain dry with a greater frequency and duration. This could result in reduced wetland productivity, nutrient recycling, and biodiversity.

Higgins et al. (2002) made the case that wetlands within grazing landscapes were generally at low risk of drainage and that the most effective means for the conservation of waterbird habitat in the northern Great Plains would be stewardship incentive programs for family ranchers. Results from WETSIM 3.2 model simulations suggest that grazing management that reduces upland plant leaf area and ground cover would increase the water levels and hydroperiod of semipermanent wetlands. However, management planning would need to consider the impacts of grazing on soil compaction and surface litter loss. For wetlands in need of increased hydroperiod and open water conditions, grazing particular portions of the landscape and/or grazing only certain years or particular times of the season could produce more favorable wetland hydroperiod and function, while also providing some options for upland nesting cover.

CONCLUSIONS

The condition and management of a landscape with embedded wetlands can affect the quality and quantity of wetland ecosystem services. Simulations using WETSIM 3.2 indicated that wetland water levels and function are affected by agricultural land use in the upland.

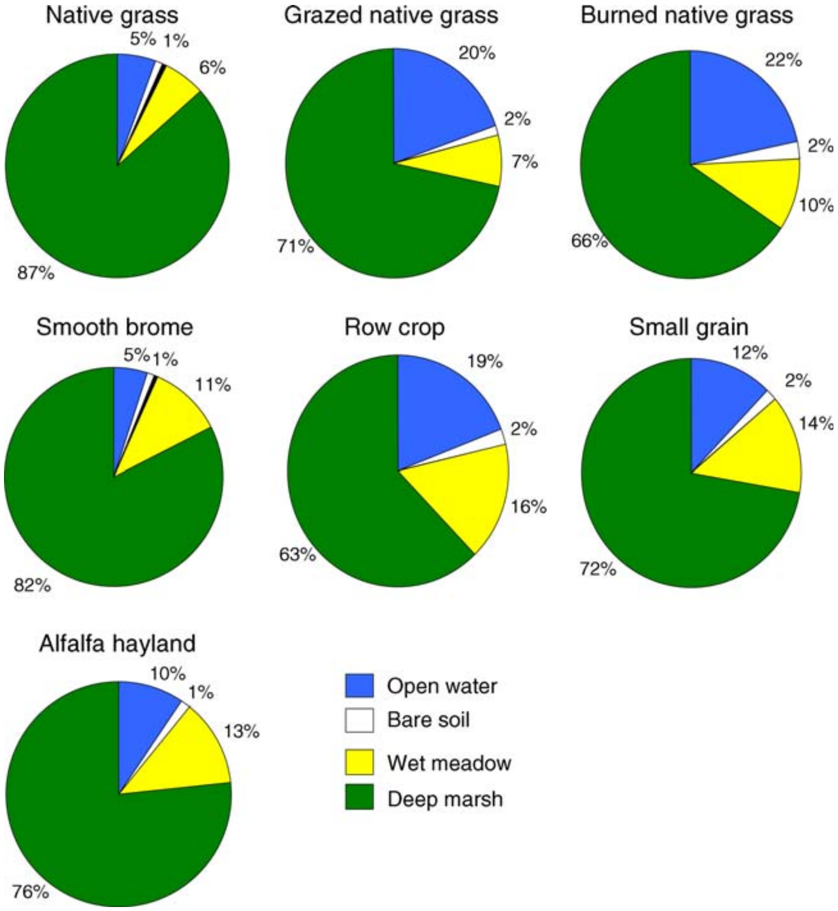

FIG. 9. The dynamics of wetland cover for the seven land-use treatments simulated by WETSIM 3.2. Shown are mean percentage of wetland cover types under the reference climate. Seedlings, mixed plants, and mixed emergent categories totaled <1% and do not appear or appear as a thin black segment.

Reversion of cultivated farmland to unmanaged grassland resulted in lower wetland water levels and reduced wetland vegetation, illustrating that land use and its effects on watershed hydrologic processes are important considerations for land managers when planning habitat restoration and rehabilitation efforts.

Model simulations using WETSIM 3.2 have provided insight into the effects of land use on northern prairie wetlands. These simulations have demonstrated that wetland water levels affected by adjacent land use can be managed to some extent by altering the land use. The results of this modeling study are hypotheses which urgently need to be verified with field observations. Few field studies have been conducted that can provide empirical data for validation of land-use simulations. There is a need for well designed and monitored empirical field studies on the effects of land use and wetland water levels, paying particular attention to soil moisture dynamics.

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