JOURNAL OF
ENVIRONMENTAL HYDROLOGY

The Electronic Journal of the International Association for Environmental Hydrology
On the World Wide Web at http://www.hydroweb.com

VOLUME 19 2011

FIELD-SCALE CHANGES IN SOIL WATER AND RECHARGE FOLLOWING RESTORATION OF A CULTIVATED FIELD TO PRAIRIE

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Restoration of large tracts of cropland to tallgrass prairie in north-central USA suggests that conversion will reduce runoff, infiltration, and groundwater recharge. In northwestern Minnesota, U.S.A., physically similar, adjacent native prairie (control) and cultivated sites were instrumented with time-domain reflectometry probes at depths ranging from 0.15-0.60 m and water-table piezometers. Following the end of cultivation in 2001 and restoration with native grasses, monitoring from 2002 through 2007 showed differences and trends in soil hydrology. Compared to the native prairie site, the former cropped location revealed larger and more rapid changes in soil moisture and a 0.2 m lowering of the water table during the five-year period. The native prairie retained comparatively greater soil moisture during the driest periods. If the conditions at this site are representative of those at a larger scale, then prairie restoration will not only "dry" the landscape, but may also retain greater soil moisture during drought.

INTRODUCTION

Worldwide, temperate grassland constitutes the most fragmented and endangered terrestrial biome (Hoekstra et al., 2005). For example, since the onset of agriculture in about 1860, approximately 98% of the tallgrass prairie in the northern United States and south-central Canada has been either developed or converted to cropland (Samson and Knopf, 1994). This conversion of land cover has affected hydrological processes to an unknown degree, but the change has been shown to have increased runoff over large regions, for example, the upper Mississippi River basin (Knox, 2001; Zhang and Schilling, 2006a) and the Red River Valley (Gerla, 2007). Results of monitoring (Zhang and Schilling, 2006b) and various recent examples of numerical modeling (e.g. Rodriguez-Iturbe, 2000; Laio et al., 2001; Guswa et al., 2002) confirm that for similar soils, one barren of vegetation will produce greater runoff when precipitation exceeds the infiltration rate and more recharge following infiltration, compared to soils supporting more dense vegetative cover. Because of a lack of vegetative cover during most of the year and a short-lived, non-perennial root system, cultivation of annual crops will likely have a similar effect on hydrology.

For example, van der Kamp et al. (2003) show empirically a major reduction in surface water storage following the establishment of smooth brome (*Bromus inermis* Lyess.) in a 4 km^2, formerly cultivated area near Saskatoon, Canada. Bodhinayake and Si (2004) conducted infiltrometer measurements in the same area after the smooth brome was established and found four times more water-conducting macropores and significantly greater hydraulic conductivity at a soil tension of -0.3 kPa. The net effect of the permanent cover of undisturbed tallgrass is to trap snow effectively and increase infiltration of snowmelt and rain into the soil, where most of it is used to supply transpiration by the deep-rooted grass (van der Kamp, 2003). Soil structure controls in large measure the infiltration and storage of water, but more rapid, significant changes in hydrological processes are likely as perennial grasses develop, affecting conditions both above and below the soil surface (Zuazo and Pleguezuelo, 2008).

In recent years, large tracts of cropland in the U.S. Midwest have undergone conversion to grassland, either through the U.S. Department of Agriculture's Conservation Reserve Program or through the conservation efforts of government agencies and non-profit organizations. Examples include prairie reconstruction at Nachusa Grassland and Midewin Prairie, Illinois (1,200 and 7,700 ha), Neal Smith National Wildlife Refuge, Iowa (2,000 ha), and The Nature Conservancy's Glacial Ridge Project in northwest Minnesota (10,000 ha). Similar grassland projects are underway in central Europe (Rosenthal et al., 2004). Restoration projects of this magnitude will likely affect runoff, infiltration, soil moisture, and groundwater flow. One of the first steps in predicting the effect of cropland to grassland conversion on the watershed scale is to better understand the processes occurring at the plot and field scale. For example, the data obtained at this scale are integral to improving conceptual and numerical models (Silberstein, 2006; Voldseth et al., 2007).

This report compares five years of soil moisture and infiltration monitoring at an adjacent cropped and native tallgrass prairie site in northwest Minnesota. The cropped location had been cultivated for at least several decades and then in 2001 restored to perennial, native grass species. Monitoring reveals the progressive changes in hydrology since prairie reconstruction. The other location, which lies 135 meters away and serves as the control, always has been native grassland. The two monitoring points selected have nearly identical physical characteristics — similar soil, slope, and aspect, suggesting that the same hydrological conditions and processes would prevail if it were not for the difference in land cover.

METHODS

Location and Site Characteristics

The monitoring location lies on the boundary between the Pembina Trail Scientific and Natural Area, owned by The Nature Conservancy (TNC) and administered by the Minnesota Department of Natural Resources, and TNC's Glacial Ridge Project (Figure 1), which is an extensive northern tallgrass prairie-wetland restoration. This part of the Glacial Ridge site was cultivated and cropped in small grain / soybean rotation prior to August 2001 and then planted with native grasses and forbs, dominated by big bluestem (*Andropogon gerardii* Vitman). The location lies at 47º 20' 52" N and 96º 41' 35" S, in the northeast one-quarter of section 30, Township 149 North, Range 44 West, Polk County, Minnesota.

The monitoring site in recently restored cropland had been continuously cultivated since at least 1939, the date of the earliest available aerial photograph, and is likely to have been cropped for at least two decades prior to that year. In 2002, this site was seeded with native species, but non-native and invasive weeds dominated the cover during the first few years while native grasses became increasingly established.

Lying 135 m to the southwest (Figure 1), the non-cropped site has been managed as native prairie since 1975, when it was purchased by TNC. Prior to that time, the site was grazed and hayed for 80-90 years, but never plowed or cultivated (B. Winter, personal communication, 2008). Both the former cropland and native sites were burned in spring 2004 to control weeds and encourage native grasses and forbs.

Both sites lie on a nearly level, east-southeast facing slope of a ~10,000-year-old beach deposit formed along glacial Lake Agassiz (Clayton, 1983). At both sites, Sandberg sandy loam within the Sandberg-Radium association comprises the soil (Saari and Heschke, 2003), which is moderately to excessively drained and formed on coarse textured beach deposits. Taxonomically, the soil is a sandy, mixed, frigid, Calci Hapludoll with a 0.2 - 0.4 m mollic epipedon. The depth class is very deep and excessively drained; silty-clay, Wisconsinan-age till lies at a depth of about 2-3 m.

Groundwater flows toward and discharges in a wetland along the west side of the beach ridge, lying 150 m west of both monitoring sites (Figure 1). The gradient is about 0.005 and hydraulic conductivity estimated from slug tests and soil survey data (Saari and Heschke, 2003) ranges from 0.5 to 2.5×10^{-4} m s^{-1}. Depth to the water table ranges from approximately 1 m during the spring and wet periods to about 1.8 m during unusually dry conditions. The study site lies at an elevation of 325 m. Cold winters and warm summers prevail at this mid-continental, semi-arid location, with an average 0.5 m of precipitation occurring per year, most of which falls as rain during the summer months.

Monitoring and Analysis

The two sites were instrumented to continuously monitor soil moisture and precipitation during the growing season. To track the level of the water table, wells were installed at the two monitoring sites and elsewhere in the vicinity. Soil texture, organic carbon content, and variably saturated hydraulic conductivity were characterized before monitoring began.

Volumetric Soil Water Content

Soil moisture was monitored using Campbell Scientific time-domain reflectometry (TDR) probes (CS616) connected to a CR10X data logger. Developed over the last 25 years, TDR

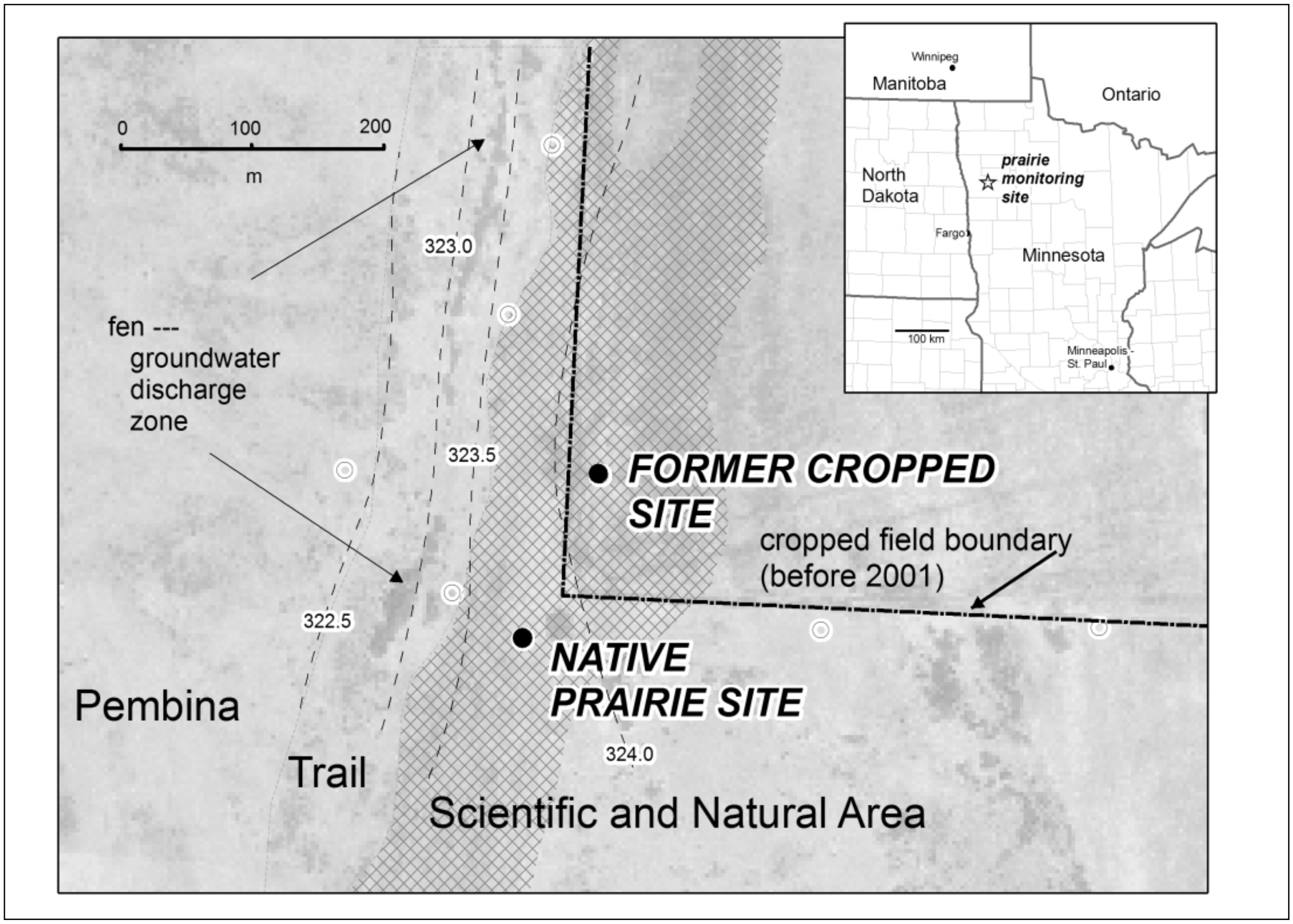

Figure 1. Map showing the spatial relationship of the native prairie and former cropped monitoring locations to water-table elevation (dashed contour lines, mid-July, 2005), the native prairie (west and south), and former cropped field (northeast). Open gray circles show additional groundwater control points. The insert shows the location in northwestern Minnesota, U.S.A.

provides an accurate and automatable method to measure soil moisture (Noborio, 2001; Jones et al., 2002). The TDR probes were permanently installed in the summer of 2001 by excavating a small diameter pit and inserting the 30-cm rods of the probe diagonally at 60° into the wall of the hole. Individual probes were installed at 0.15 - 0.30, 0.30 - 0.45, and 0.45 - 0.60 m depth intervals at one location at both sites. The pit was then tamped as it was filled, thereby minimizing soil disturbance. Hourly TDR data were collected during the 2002-2007 growing seasons and calibrated initially by using gravimetric measurements of volumetric water content.

Variability of the Water Table

The water table elevation was monitored at both sites using single wells constructed of 1-meter long, 3-cm diameter stainless-steel-screen sand points, driven to about 1.5 m below the average water table. Water levels were logged hourly for one year, beginning in late summer 2002, by using an In Situ, Inc. barometrically corrected, unvented pressure transducer positioned near the base of the sand point. After 2002, water levels were measured every few weeks using an electronic water-level probe. Additional information on the water-table elevation was obtained from seven other wells within 0.5 km. Precipitation was recorded with a TE525WS-L Texas Electronics tipping bucket rain gage and checked for consistency with records obtained from the NRCS Glacial Ridge SCAN weather station 3 km to the northeast.

In this study, a distinction is made between *apparent* and *effective* specific yield. Apparent specific yield pertains to the ratio of water table rise in response to the depth of precipitation generated by a storm. As such, apparent specific yield will vary greatly, depending on the temporal moisture regime and varying position of the water table within the soil at the monitoring location, along with seasonal and spatial differences in interception and evapotranspiration. Effective specific yield refers to the fraction of soil pore space near the water table that can be filled or drained, and estimated by the ratio of water-table rise to the depth of infiltration that actually reaches the water table. Groundwater recharge can be estimated by multiplying the rise of the water table times the effective specific yield (Gerla, 1992; Healy and Cook, 2002). The effective specific yield may vary depending on antecedent moisture conditions, textural heterogeneity of the soil profile, and the level of water table (Scanlon et al., 2002), but it varies less than apparent specific yield. For the analysis presented here, effective specific yield is assumed constant and best represented by the ratio of water-table rise to the depth of rainfall that occurs during moderate storms when vegetation is senescent.

The non-parametric Mann-Kendall statistical test for a trend (Helsel and Hirsch, 1992; Kendall, 1938) was applied to determine if the observed changes in water levels are statistically significant and to assure that data for the native prairie / control site do not reveal a significant trend. To perform the test, all temporal pairs of measurements are compared and analyzed using the relationship

$$S = \sum_{i=2}^{n} \sum_{j=1}^{i-1} sign(x_i - x_j) \tag{1}$$

where n is the number of observations and sign $(x_i - x_j)$ is -1 for $x_i - x_j < 0$, 0 for $x_i - x_j = 0$, and 1 for $x_i - x_j > 0$. If no trend exists, then S is expected to be zero and has variance $\mathrm{Var}(S) = n(n-1)(2n+5)/18$. Because the number of observations $n > 10$, the test statistic $Z = S/SE(S)$ is compared against critical values from the Standard Normal Table.

Other Soil Properties

Soils were sampled at depth intervals of 0 - 15, 15 - 30, and 30 – 45 cm at four locations within 5 m of each site. Standard methods described by Carter (1993) were used to determine organic matter (oxidized using 55% hydrogen peroxide - H_2O_2) and grain-size distribution (sieve and hydrometer) of the samples.

To compare variably saturated hydraulic conductivity, a tension infiltrometer (Soil Measurement Systems, 2011) was used to estimate unsaturated hydraulic conductivity at five random locations within 5 m of each monitoring station. To provide adequate disk - soil contact, a 20-cm ring was set on a smooth, leveled soil surface and filled with a thin layer of fine silica sand, onto which was placed the permeable disc. Measurements of the volume of water entering the soil per unit time at steady-state infiltration were made at four tension heads (h): 3 cm, 6 cm, 10 cm, and 15 cm. Infiltration data were used to estimate α and saturated hydraulic conductivity (K_{sat}), which are approximately related to unsaturated hydraulic conductivity (K_{unsat}) (Gardner, 1958; Wooding, 1968) as

$$K_{unsat} = K_{sat} \exp(\alpha h) \tag{2}$$

RESULTS

Comparison of Soil Physical Properties

Characterizing the effects of land-cover change on hydrological conditions requires close similarity in physical properties of the soils at the two monitoring sites. Results of grain-size analysis show similar distribution for 24 samples (Table 1). Most sand is medium to coarse, and texturally the soils at both sites are loamy sand for the samples obtained from 0-30 cm and sand for the samples taken from 30-60 cm. Average unsaturated hydraulic conductivity in all cases is lower in the former cropped soil (Table 1), but the difference is small and insignificant for tensions of 15, 10, and 6 cm. The greatest difference, (88 versus 18 cm hr^{-1}) was observed at the lowest tension (3 cm).

The measured weight percent of organic matter was greatest at 0-15 cm (5.5%-7.4%), and decreased with depth for all of the samples. Average percent organic matter at the 0-15, 15-30, 30-45, and 45-60 cm depths were 6.5 and 6.8, 4.3 and 2.8, 2.0 and 1.3, 1.1 and 0.8 for the former cropped and native sites, respectively. Although some studies have found greater carbon content in native prairie soils than cultivated soils (Purakayastha et al., 2008), the results reported here suggest *lower* concentration of organic matter at the undisturbed, native site. The hydrogen peroxide analysis method used here may not fully oxidize refractory carbon (Mikutta et al., 2005), which may be more abundant in the undisturbed prairie soil.

Degree of Saturation

These results suggest that differences in the degree of saturation or "wetness" (Dingman, 2002) relate to the differences and dynamics of the changing ground-surface cover at the monitoring sites, rather than differences in soil properties. TDR monitoring (Figure 2) shows typical patterns of soil moisture during the growing seasons 2002-2007, with up to a difference of 20% concurrently between the two sites. A large range in both seasonal and inter-annual wetness is apparent. For example, 2005 was comparatively wet and the former cropped site maintained a

Table 1. Results of grain-size and infiltrometer analysis.

	Native Site	Former Cropped Site
Texture (n=12)	mm	mm
80 percentile, sd	1.04, 0.29	0.85, 0.37
50 percentile, sd	0.54, 0.10	0.48, 0.05
20 percentile, sd	0.21, 0.14	0.16, 0.09
Average K (n=3)	cm hr^{-1}	cm hr^{-1}
Tension = 15 cm	2.3	1.8
Tension = 10 cm	5.3	4.2
Tension = 6 cm	12	9.0
Tension = 3 cm	88	18

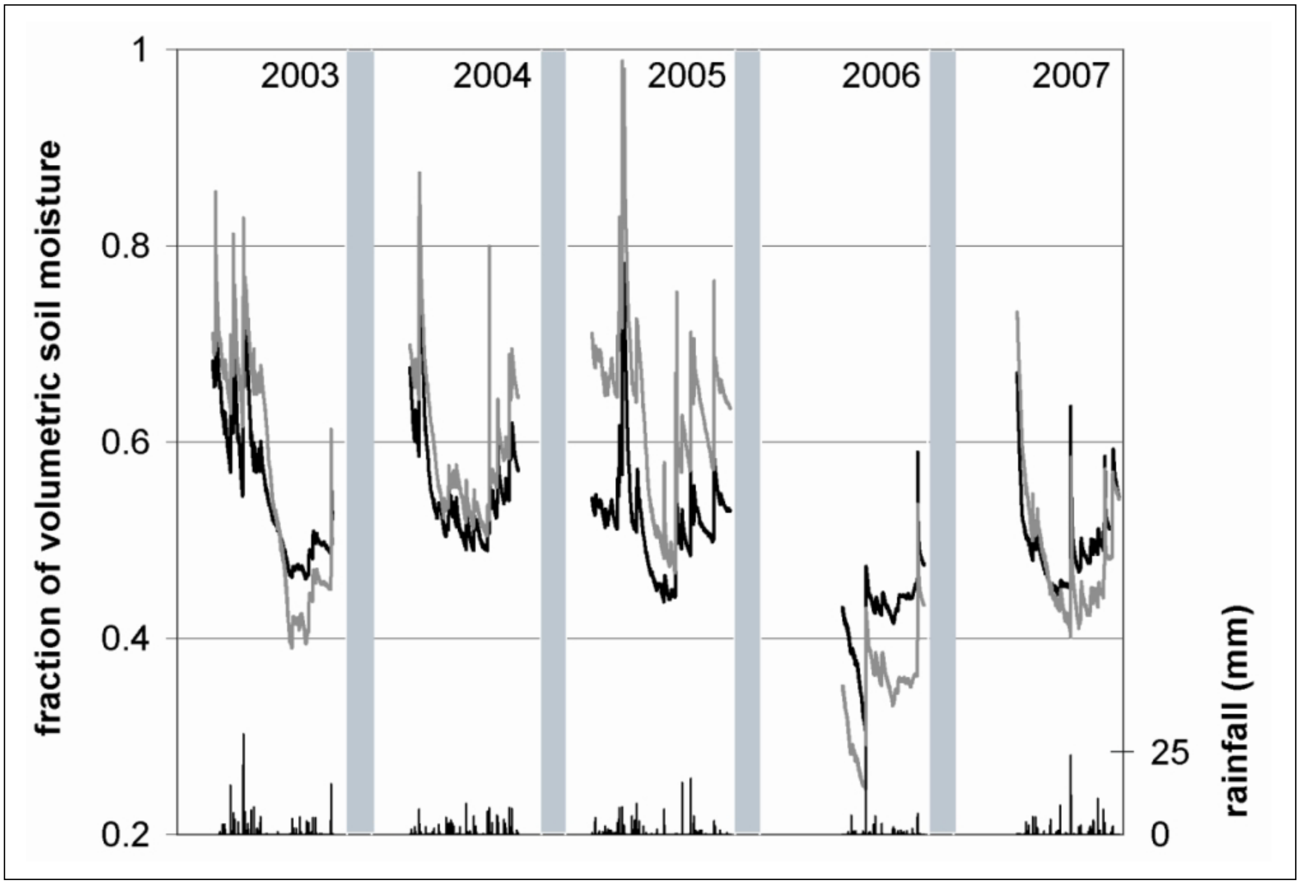

Figure 2. Fraction of the volumetric soil moisture at saturation or soil wetness for the main growing season, approximately 1 April through 31 October 2003-2007. The gray and black lines represent the former cropped and native prairie sites, respectively; the vertical gray bands show winter (1 November – 31 March) data gaps.

continuously wetter profile than the native prairie control site. In contrast, during the unusually dry summer of 2006, greater soil moisture was maintained at the native site. A clear seasonal change occurred in 2002, when the profile at former cropped site rapidly dried during a mid-season hiatus in rainfall (Figure 2). During and prior to this period, the native site showed a much smaller variation in wetness (0.70 - 0.47) compared to the former cropped site (0.85 - 0.39).

Water Table and Recharge Variability

For each rainfall during the 2002-2003 continuous monitoring period, the water table rose more beneath the former cropped site than the native prairie (Figure 3), suggesting greater recharge. Results (Table 2) show a large range of precipitation to water-table-rise ratios (0.08 to 0.34). Most of the difference is likely due not only to uncertainties associated with estimating the effective specific yield, but also to seasonal differences in evapotranspiration. For example, rainfall that occurs during periods of senescence results in a smaller precipitation to water-table-rise ratio (events 1-5, Table 2) than rain during active growth (events 6-11), when much of the infiltrating precipitation is lost to evapotranspiration. Event 3, which was very small (4 mm), followed periods of freezing weather during September and October and resulted in a large rise of the water table (50 mm), suggesting an effective specific yield of about 0.08.

The product of effective specific yield (0.08) and the relative rise of the water table gives an estimate of actual groundwater recharge that accounts for loss to vadose storage and

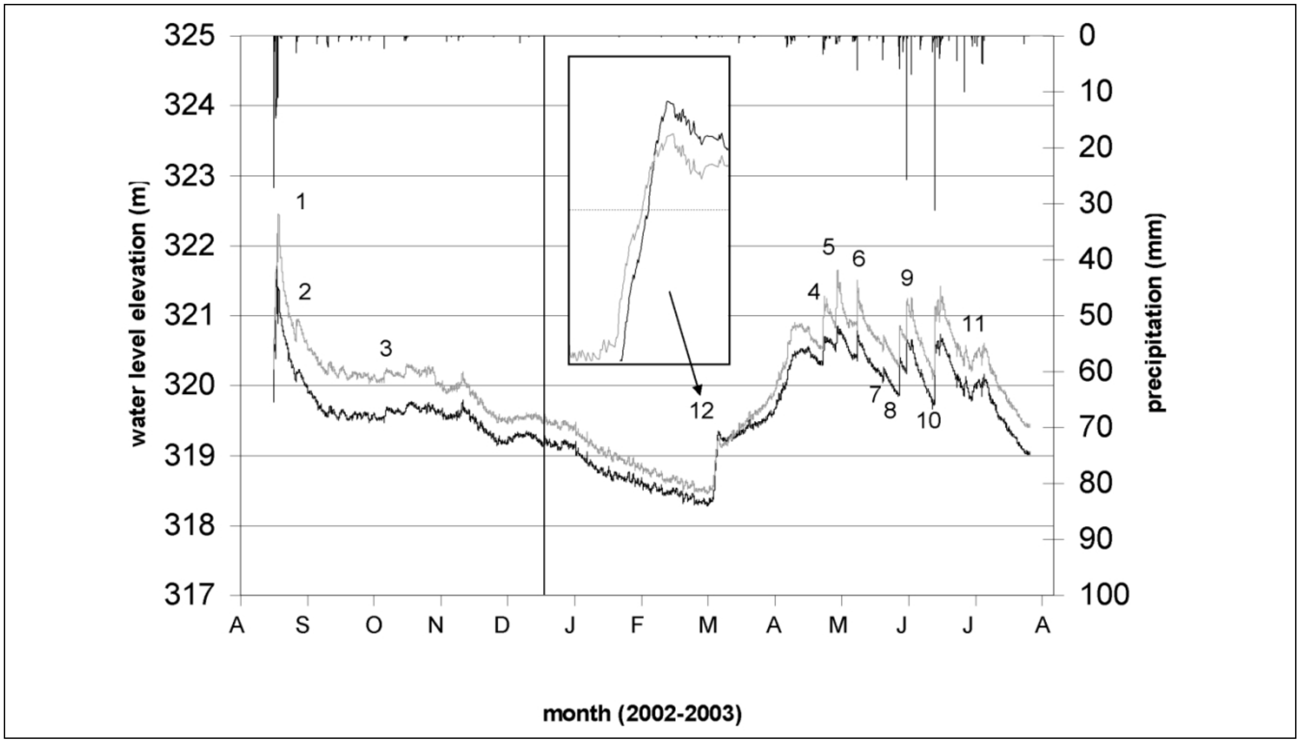

Figure 3. Precipitation and continuous water-table elevation at the former cropped site (gray) and native prairie (black) monitoring sites. Numbers 1-11 correspond to the precipitation, infiltration, and recharge events referenced in Table 2. The insert shows details of the water-level rise at event 12, which is related to spring thaw and not precipitation.

Table 2. Groundwater recharge estimated from rain events and water-table rise 2002-2003.

Event (Fig. 3)	Storm Start Date	Storm End Date	Water Level Rise (m)		Precipitation (mm)	Water Level Rise / Precipitation		Estimated Recharge (m)	
			Cropped	Native		Cropped	Native	Cropped	Native
1	30-Aug-02	2-Sep-03	0.67	0.60	74	9.0	8.1	0.053	0.048
2	8-Sep-02	10-Sep-02	0.08	0.05	8	10.1	5.8	0.006	0.004
3	18-Oct-02	21-Oct-02	0.05	0.05	4	12.0	12.8	0.004	0.004
4	3-May-03	5-May-03	0.20	0.09	15	13.2	6.1	0.016	0.008
5	9-May-03	10-May-03	0.23	0.12	21	10.9	5.9	0.019	0.010
6	18-May-03	19-May-03	0.21	0.13	21	10.2	6.3	0.017	0.010
7	30-May-03	31-May-03	0.05	0.05	9	6.4	6.0	0.004	0.004
8	6-Jun-03	7-Jun-03	0.17	0.15	15	11.2	10.0	0.014	0.012
9	10-Jun03	12-Jun-03	0.20	0.15	49	4.0	3.0	0.016	0.012
10	22-Jun-03	25-Jun-03	0.39	0.32	57	6.9	5.6	0.031	0.026
11	9-Jul-03	14-Jul-03	0.10	0.10	26	4.0	3.7	0.008	0.008
*Total					302			0.195	0.151

evapotranspiration, and interception (Table 2). In every case, the rise of the water table at the former cropped site was greater than the native prairie site. This method indicates 0.20 and 0.15 m of recharge for the former cropped and native sites, respectively, for 0.3 meters of total rainfall, which compares closely to the 0.2 m yr^{-1} recharge rate estimated for coarse soils of the glacial Lake Agassiz beach ridges (Lorenz and Delin, 2007).

DISCUSSION

Flashiness of Soil Water Content

These results show that not only does soil water content vary more for the former cropped site than the native prairie, but the data also reveal that the native site maintains more moisture during drought and has a lower degree of saturation following rainfall. This suggests a greater resiliency to drought and deluge conditions (Figure 2). An analogy can be drawn between soil-water dynamics and the flow regime of streams and rivers (Poff et al., 1997), characterized by watersheds that tend to effectively store precipitation and release it as baseflow, in contrast to "flashy" streams that respond quickly to precipitation and runoff. Baker et al. (2004) developed a method to quantify flashiness, which is applied here to characterize temporal changes in soil water content

$$R-B\,index = \frac{\sum_{i=1}^{n}\left|\mu_i - \mu_{i-1}\right|}{\sum_{i=1}^{n}\mu_i} \tag{3}$$

where μ represents the relative volumetric water content in a specified depth interval of the soil horizon and i is the hourly change in μ. Perhaps as expected, changes in soil water vary greatly: rapid during and following rainfall and slow for dry, senescent periods.

To better visualize the difference between the two sites, the index was computed hourly and then averaged for one month periods for the five-year growing seasons 2003 through 2007 (Figure 4).

It shows that the former cultivated site consistently exhibited greater flashiness in soil water, except for May and July 2004 (Figure 4). During the spring of 2004, the area surrounding the native prairie control site was burned as part of on-going preserve management, suggesting that the difference in surface cover and above-ground plant mass at the two sites, at least in part, controls soil-water storage.

Longer Term Changes in the Average Depth to the Water Table

Although water levels at the two sites track very closely and respond in a similar way, there are two significant differences. First, in contrast to the rise of the water table following rainfall, the rise in spring 2003 (event 12, Figure 3), which revealed a typical early spring pattern in this region (Gerla and Matheney, 1996), showed that the water level rose more beneath the native prairie than the former cropped area. Note that the rise is not associated with precipitation (Figure 3), but rather early-season infiltration of groundwater that moved upward into the frozen unsaturated zone during the winter, along with snowmelt. This suggests that the native grass site has greater capacity to store translocated water during the winter months. Alternatively, the native prairie may also capture snow more efficiently, although most snow at this location during spring 2003 sublimated rather than melted and infiltrated.Second, periodic measurements from 2003 - 2008 suggest that when compared to the native prairie, the water table beneath the former cropped site dropped significantly since restoration in 2001 (Figure 5), with the difference in water-level elevation between the

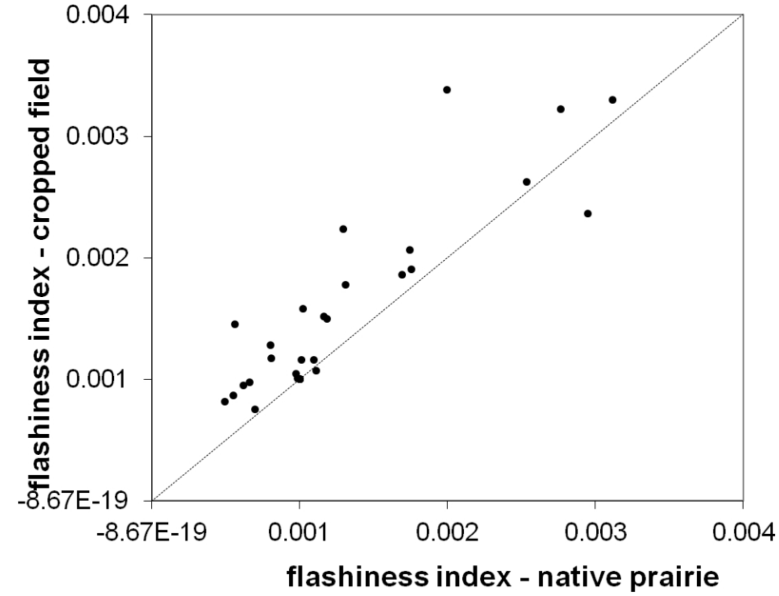

Figure 4. R-B flashiness index (Baker et al., 2004) computed for soil moisture content during the 2003-2007 growing seasons. The upper panel shows contemporaneous monthly flashiness index for the two sites (dashed line indicating equal values). Diamonds and squares in the lower panel represent the monthly average index for the former cropped and native prairie sites, respectively.

native and former cropped locations decreasing from about 0.25 m in 2003 to 0.1 m during 2008, or 3 cm yr^{-1}. This change is likely due to increasing retention of moisture in the upper soil horizons, increased transpiration because of the developing perennial grass cover, and no seasonal fallow conditions after 2001.

Application of the Mann-Kendall test shows a downward trend in the water table at the former cropped site and essentially no trend in water level 135 m away at the native prairie site (Table 2). When the difference in water level between the two locations is compared (Figure 5), the trend is striking both statistically and visually. These results strongly suggest that the land-cover change within the former cropped area led to a 0.2 m drop in the water table, which indicates a reduction in groundwater recharge as a result of the prairie reconstruction.

Implications for Hydrology and Ecology at a Larger Scale

With its obvious limitations, the results of this point/plot monitoring indicate the need for more spatially extensive studies. Plot and field-scale hydrological processes integrated together control surface water and groundwater at watershed scale. Monitoring results reported here indicate retention of moisture deeper in the prairie soil horizon during unusually dry conditions. Perhaps this originally maintained baseflow in small prairie streams during drought. Therefore, the disruption of prairie streams by agricultural development may have affected ecology and biodiversity to a greater extent than currently recognized (Dodds et al., 2004; Fritz and Dodds, 2005). More significantly, results indicate that prairie reconstruction targeted in areas that contribute to the average time-of-concentration for a flood peak may decrease floods downstream. Much additional landscape-scale monitoring and modeling, however, is needed to confirm these inferences.

CONCLUSIONS

Continuous monitoring at a paired site — a former cultivated field taken out of crop production and planted with perennial native grasses, and a nearby, undisturbed native prairie that served as a control, showed differences in the soil-moisture characteristics, water storage, and groundwater

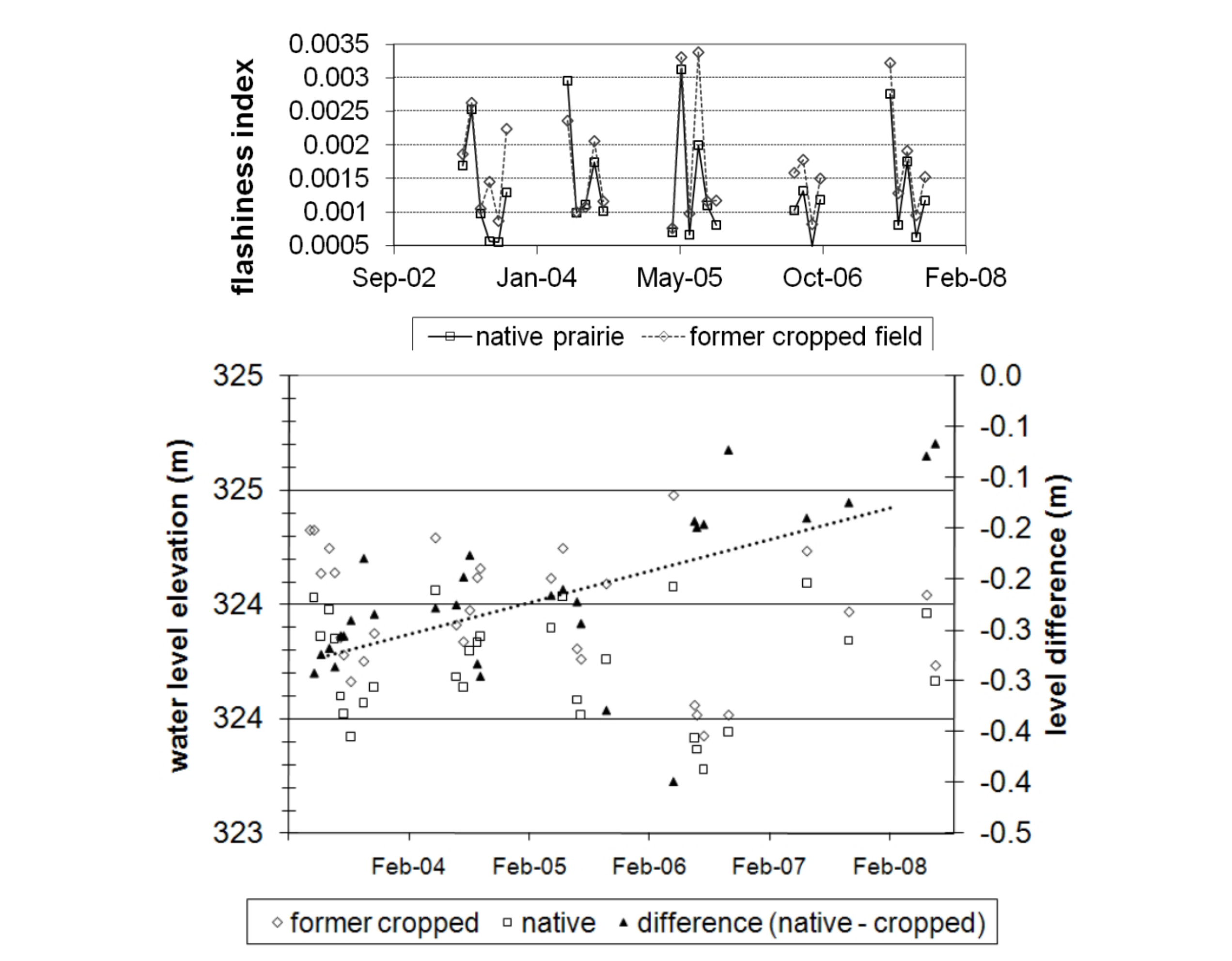

Figure 5. Discrete water-table elevations measured at former cropped (diamonds) and native prairie (squares) sites during 2003-2008. The dashed line shows the best-fit for the changing difference in the water-table elevation (solid triangles), indicating that the water table at the former cropped site dropped relative to the more static level beneath the native prairie.

recharge over five years. Although the two sites have similar physical characteristics, the hydrological conditions during monitoring contrasted significantly. The prairie site revealed a greater resilience to extremes in growing season precipitation, allowing less moisture to move through the upper 0.6 m of the soil column during wet periods and maintaining a small, but greater amount of moisture during dry times. Apparently, the native cover captured more moisture at shallow depth, which was then slowly lost to transpiration during drought and senescence.

At the former cultivated site, slower interflow, greater variably saturated storage, and increased surface retention led to reduced groundwater recharge following restoration to perennial grass. The water table at this site dropped approximately 0.3 m after five years, approaching the same average depth as the prairie site, which revealed long-term static conditions during the same period.

The 5-year contrast in flashiness and the difference in water-table depth observed at point scale can perhaps explain the processes important in the flow patterns of prairie streams affected by changes in cropping and restoration. Further research at a larger watershed scale may show that selective reconstruction of grassland from cropland could enhance baseflow in prairie streams and mitigate downstream floods.

ACKNOWLEDGMENTS

The author thanks Phillip Wilson for analyzing soil texture, organic matter content, and infiltrometry data. Dr. William Schuh, Water Appropriations Division Manager, North Dakota State Water Commission and Dr. Eric Brevik, Associate Professor, Dickinson State University provided valuable comments and detailed reviews, which were used to improve the manuscript. In addition, several anonymous reviewers contributed valuable suggestions on ways to enhance earlier versions of the manuscript.

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