Journal of Hydrology (2008) **355**, 123–130

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Effects of climate and land management change on streamflow in the driftless area of Wisconsin

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Received 2 November 2007; received in revised form 4 March 2008; accepted 11 March 2008

KEYWORDS
Streamflow trends;
Climate change;
Land use/land management;
Hydrogeology;
Driftless Area

Summary Baseflow and precipitation in the Kickapoo River Watershed, located in the Driftless Area of Wisconsin, exhibit a step increase around 1970, similar to minimum and median flows in many other central and eastern USA streams. Potential effects on streamflow due to climatic and land management changes were evaluated by comparing volumetric changes in the hydrologic budget before and after 1970. Increases in precipitation do not fully account for the increase in baseflow, which appears to be offset by a volumetric decrease in stormflow. This suggests that factors that influence the partitioning of precipitation into overland runoff or infiltration have changed. A transition from relatively more intensive to relatively less intensive agricultural land use is generally associated with higher infiltration rates, and likely influences partitioning of flow. Changes in agricultural land management practices in the Driftless Area, which began in the mid-1930s, do not coincide with the abrupt increase in baseflow around 1970. Instead, the *timing* of hydrologic change appears to coincide with changes in precipitation, whereas the *magnitude* of the change in baseflow and stormflow was likely amplified by changes in agricultural land management.

Introduction

Many streams in the central and eastern USA have exhibited statistically significant increases in the minimum and median annual flows during the past century (Lins and Slack, 1999); the change has been described as a step increase near 1970 (McCabe and Wolock, 2002). An increase

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0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2008.03.010

in precipitation, particularly in fall and winter (Karl and Knight, 1998; Lettenmaier et al., 1994), has been postulated as one possible driver of this step change (McCabe and Wolock, 2002).

Other studies attributed increasing baseflows and decreasing stormflows at the individual watershed scale or regional landscape scale to improvements in agricultural land management. Potter (1991) identified decreasing flood peak magnitudes and flood volumes and increasing baseflow volumes in the East Branch of the Pecatonica River in southwestern Wisconsin during the period 1940–1986. Gebert and Krug (1996) and Schilling and Libra (2003) found similar upward baseflow trends and downward stormflow trends in agricultural areas of Wisconsin and Iowa. These studies found no evidence that climatic patterns were responsible for the streamflow trends and instead proposed that concerted efforts since the mid-1930s to improve agricultural land management practices were likely responsible. Krug (1996) used the Precipitation Runoff Model (PRMS; Leavesley et al., 1983) to evaluate increased baseflows and decreased stormflows between 1934–1940 and 1979–1981 in the Coon Creek Watershed, Wisconsin. This site was the first watershed-scale soil and water conservation demonstration project in the USA (Potter and Love, 1942; Anderson, 2002; Gaumnitz, 2002). By matching observed hydrographs for each time period, Krug (1996) estimated a 20% increase in soil hydraulic conductivity and 100% increase in water holding capacity of the soil.

Changes in climate and land management are both potential drivers for the changes in hydrology noted in the Driftless Area of Wisconsin. However, attempts to identify direct causal relations between streamflow trends and land management (Kent, 1999) or climatic variables (Lettenmaier et al., 1994) have met with limited success. In this paper, we use data from the Driftless Area of Wisconsin to show that both of these potential drivers are operating to change the hydrologic response of the system. Climatic change appears to control the timing and direction (increase or decrease) of the change, while land management changes amplify the response beyond that which can be explained by climate factors alone. This combination of climatic and land management drivers may be an important consideration for evaluating and predicting watershed-scale response to possible climate change scenarios or land management change scenarios.

Site description

The Coon Creek and Kickapoo River Watersheds are in a region of southwestern Wisconsin referred to as the Driftless Area (Fig. 1) due to a lack of glacial drift deposits from continental glaciers that covered much of the surrounding region during the Pleistocene Epoch. Long-term precipitation averages about 81 cm/yr, of which approximately 57 cm/yr is returned to the atmosphere via evapotranspiration (Table 1). The annual temperature ranges between −30 and +30 °C, and the growing season generally extends from May 2 to September 30 (NRCS, 2003).

Modern agricultural land management was introduced to the Driftless Area during the first watershed-scale soil and water conservation demonstration project in the USA (Potter and Love, 1942; Anderson, 2002; Gaumnitz, 2002),

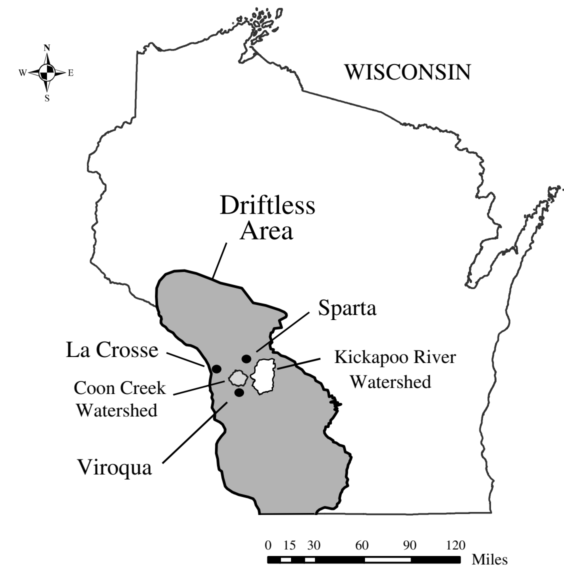

Figure 1 Site locations described in this paper.

conducted from 1934 to 1940 in the Coon Creek Watershed. Land use remained predominantly agricultural on ridges and in valleys, but management practices such as contour plowing, crop rotation and strip cropping were introduced; wooded hillslopes were largely fenced off from grazing cattle (Trimble and Lund, 1982). These early agricultural land management practices quickly spread to the rest of the Driftless Area and beyond as farmers observed noticeable improvements in soil and hydrologic conditions (Trimble and Lund, 1982). Other management practices introduced later, such as the Conservation Reserve Program, continued to improve soil properties and reduce runoff.

The Driftless Area is characterized by three general landscape units, each of which has distinct geologic characteristics that control water runoff and infiltration. Relatively flat ridges are typically underlain by a clay-rich (82 ± 9.1% — Frolking et al., 1983) residuum that formed from weathering of dolomite bedrock (Frolking, 1982; Stensvold and Stiles, 2005). Hillslope soils are typically thin and dominated by sand and rock fragments from the underlying permeable sandstones, while valley soils are generally loamy (Knox, 1972; Evans, 2003). Decreased flooding and increased baseflow have primarily been attributed to improved tillage practices in the agricultural fields (Potter, 1991; Gebert and Krug, 1996; Krug, 1996). Increased recharge, attributed to cessation of grazing on hillslopes, was recently shown to be important to watershed-scale stream response (Juckem, 2003; Juckem et al., 2005).

Properties controlling infiltration on hillslopes are influenced by land management practices. Sartz (1969) measured 20 times higher runoff from grazed forested hillslopes than from undisturbed forested hillslopes at an experimental forest located about 10 km from Coon Valley. Knighton (1970) showed that forest floor thickness was significantly less and soil compaction was greater on grazed slopes compared to ungrazed slopes. Moreover, soil structure recovered within a decade, with no permanent damage after grazing was stopped (Knighton, 1970). In addition, Roldán (undated written communication) estimated that for-

Table 1 Average annual precipitation, evapotranspiration, baseflow, stormflow and snow fall for the 30-year periods from 1941 to 1970 and 1971 to 2000

Time period	Precipitation (P)	Evapotranspiration (ET)	Net precipitation (P − ET)	Snow fall	Baseflow (BF)	Stormflow (SF)	Total flow (BF + SF)
1941–1970	78.3	56.5	21.8	106.9	14.0	7.8	21.8
1971–2000	82.8	57.6	25.2	107.4	19.2	6.0	25.2
Change	4.5 (6%)	1.1 (2%)	3.4 (16%)	0.5 (0.4%)	5.2 (37%)	−1.8 (−23%)	3.4 (16%)

All values are in centimeters over the basin.

ested acreage (primarily on hillslopes) in one township in the Coon Creek Watershed increased from 3459 ha (36.7% of the township) in 1939 to 3951 ha (42.0%) in 1967, and then increased to 4687 ha (49.8%) in 1993 (USGS National Gap Analysis Program, 1994). Similar increases occurred in the Kickapoo Watershed (Franklin, 1997), and other watersheds in the Driftless Area (Kent, 1999).

Methods

Long-term trends in baseflow are driven by trends in groundwater recharge. However, recharge rates are spatially and temporally variable and difficult to determine. A groundwater flow model of the Coon Creek Watershed was used to demonstrate that if the watershed was larger than approximately 50 km^2, spatial variability in recharge (including recharge to multiple, layered aquifers) in the Driftless Area could be approximated by an average recharge rate calculated by dividing the average annual baseflow by the upstream drainage area of a watershed (Juckem et al., 2005). Given this work, as well as stream erosion through the layered confining units in the Driftless Area, annual discrepancies between recharge and baseflow are expected to be negligible at the scale used in this study. Thus, to supplement the noncontinuous hydrologic dataset for Coon Creek, streamflow data from the continuously operated USGS gaging station on the Kickapoo River at La Farge, Wis. (upstream drainage area of 690 km^2, Fig. 1) were used to evaluate hydrologic trends. Baseflow was estimated using a baseflow-separation program (Wahl and Wahl, 1995) based on a modified version of the Institute of Hydrology method (Institute of Hydrology, 1980a, 1980b). Parameters for the program included a three-day minimum flow period that was determined by ''tuning'' the separator as instructed, and a recession constant of 0.98, as was estimated by Potter (1991) for the East Branch of the Pecatonica River in the Driftless Area of Wisconsin. These baseflow trends were compared to climatic data obtained by averaging daily values from long-term weather stations in Sparta and Viroqua, Wis.; data from La Crosse, Wis. were used for 1988, 1990, and 1994, when data were lacking for the Sparta and Viroqua stations (Fig. 1).

Using 1970 (McCabe and Wolock, 2002) as the date of potential change in precipitation and baseflow in the Kickapoo River Basin, several abrupt transition Auto Regressive Integrated Moving Average (ARIMA) intervention models (Box and Tiao, 1975) were used to determine if and how mean conditions for the 60-year period from 1941 to 2000 had changed (i.e., abrupt change or gradual trends). The best ARIMA intervention model to describe changes in mean conditions was determined by comparing the Akaike Information Criterion (AIC). The AIC penalizes larger and more complicated models of equal fit, similar to an adjusted coefficient of determination (r^2) value. The ARIMA intervention models included: (1) linear trend, (2) step with no trend, (3) step with a constant slope, (4) ramp without a step, (5) ramp with a step, (6) hinge, and (7) broken hinge. The ''step with no trend'' ARIMA model produced the best statistically significant description of the data (lowest AIC value) of all ARIMA models for annual data. This indicates that the most appropriate evaluation of change is a comparison of two simple 30-year averages (1941–1970 and 1971–2000) in the hydro-climatic data for the Kickapoo River Basin. Only ARIMA intervention models with a step produced a statistically significant description of the non-growing season data (described below).

Changes over time were evaluated using data for full water years and the non-growing season (October 1 of the prior year to May 1 of the current year) as determined by the Viroqua Wetlands Determination (WETS) station (NRCS, 2003). The non-growing season was used to minimize possible confounding effects from uncertainty in evapotranspiration rates over this period. The average Kickapoo River baseflow was divided by the drainage area to provide an estimate of groundwater recharge, which in turn was compared to average precipitation, snowfall, and total streamflow and stormflow (divided by drainage area) for the same 30-year periods. Evapotranspiration was estimated on an annual basis as precipitation minus total streamflow per unit area. Pan evaporation data were not used due to uncertainty with how these data correlate with actual evapotranspiration for the Kickapoo River Basin (Lawrimore and Peterson, 2000; Golubev et al., 2001; Hobbins et al., 2004).

Streamflow variability for a given year, as described by the standard deviation of daily discharge (σ_q), was computed for the period May 1 to November 30. Winter and early spring seasons were excluded because factors other than concurrent precipitation (e.g., air temperature, solar radiation, and frost depth) can control the timing and magnitude of snowmelt. Evaluation of the frozen ground hydrology and related complex snowmelt-runoff processes was beyond the scope of this investigation. Streamflow variability was compared to the standard deviation of daily precipitation (σ_p) from May 1 to November 30. In addition, streamflow variability (σ_q) was normalized by dividing by precipitation variability (σ_p). Comparison between the 30-year pre- and post-1970 periods was performed by counting the number of highly variable years, defined here as years for which σ_q, σ_p, or σ_q/σ_p

exceeded the 75th percentile of values calculated using the entire 60-year period from 1941 to 2000.

Land management factors were evaluated by measuring infiltration rates with a double-ring infiltrometer in three landscape settings: ridges, hillslopes, and valleys. Details of the method can be found in Bouwer (1986), Juckem (2003), and Juckem et al. (2005). Effects of land management practices were evaluated by categorizing the infiltration measurement site according to the relative intensity of the current land use. Examples of relatively intense land use included: cultivated agricultural fields, pastures, and gullies; relatively less intense land use included: fallow fields, non-grazed woodlands, and grassy agricultural waterways. Quantifying changes in land area characterized by either relatively more or less intensive land use was beyond the scope of this study. Instead, changes in infiltration were assumed to correspond with gradual increases in relatively less intensive land uses (e.g., forested acreage) and decreases in relatively more intensive uses (e.g., pasture and cropland) in the Kickapoo and Coon Creek Watersheds (Franklin, 1997; Roldán, undated written communication).

Results and discussion

A plot of annual precipitation and baseflow in the Kickapoo River Watershed (Fig. 2) suggests a step increase around 1970 similar to that described by McCabe and Wolock (2002). On an annual basis (Table 1), baseflow normalized by watershed area (or recharge) increased by 5.2 cm from the pre-1970 period to the post-1970 period, which is more than the 4.5 cm increase in precipitation. In addition, evapotranspiration increased by 1.1 cm, thereby reducing the net precipitation increase, or the water available to infiltrate and recharge the water table, to about 3.4 cm. Results showed little sensitivity to parameter values for the baseflow separation program over a reasonable range (three- to six-day minimum flow period, and a recession constant of 0.96–0.99, as identified by Potter (1991)). Specifically, this range of parameter values produced increases in baseflow between the pre- and post-1970 periods that ranged from 5.2 cm to 5.4 cm (no change to 0.2 cm increase relative to Table 1), indicating that the baseflow separation results may, if anything, slightly underestimate the increase in baseflow over time. The average non-growing season baseflow increased by 3.0 cm (from 8.4 to 11.4 cm, or 35%), while non-growing season precipitation increased by 2.1 cm (from 29.2 to 31.3 cm, or 7%) from pre-1970 to post 1970. Although the increase in baseflow is more than can be attributed to the net increase in precipitation, it appears to be related to reduced stormflow (Table 1). This indicates a change in the processes operating on the watershed scale that distribute precipitation between overland runoff and infiltration.

A change in the dynamics of the annual spring snowmelt is one potential mechanism that could alter the partitioning of annual precipitation into either runoff or recharge. Evaluation of this complex process was beyond the scope of this investigation; however, the importance of such a change would be limited by the amount of water held in the snow pack. Measurement difficulties and lack of historical records notwithstanding, annual snowfall can be used as a surrogate for water contained in the snow pack. Assuming that the ratio of equivalent water content to snowfall is typically about 1:10 (Wanielista et al., 1997), the 0.5 cm increase in average annual snowfall (Table 1) represents about a 0.05 cm increase in available melt water – a value appreciably smaller than the 1.8 cm difference between the change in net annual precipitation and baseflow. Indeed, when put in terms of standardized departures (difference of a value and its mean, divided by its standard deviation) from the average for the entire 60-year period, the 5-year moving average in baseflow shows a response that is appreciably larger than the 5-year moving average in precipitation after 1970 (Fig. 3).

Summer streamflow variability (σ_q), or ''flashiness'', in the Kickapoo River (Fig. 4a) decreased from pre-1970 to post-1970, as indicated by a decrease from nine years in which σ_q exceeded the 75th percentile between 1941 and 1970 to six years for the 30-year period from 1971 to 2000. Notable exceptions to this generalization have occurred in the post-1970 record, however. One is seen in 1978 (Fig. 4a) that was a result of a stationary local summer convective cell centered on the Kickapoo River headwaters, which, in turn, caused flooding in the Kickapoo River but not elsewhere in the Driftless Area (Hughes et al., 1981). Although not included in the analysis presented here, even larger flows occurred in the Kickapoo River during August 2007 in response to the largest August precipitation ever

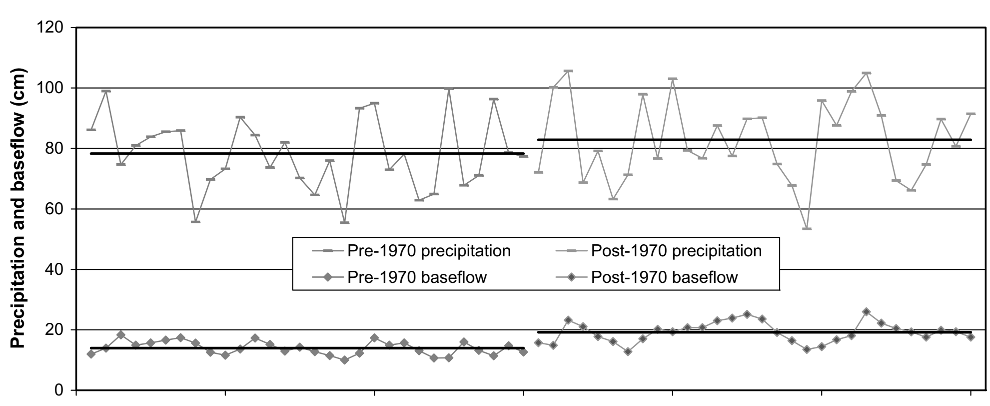

Figure 2 Annual precipitation and baseflow in the Kickapoo River Watershed, with average values shown by the horizontal lines.

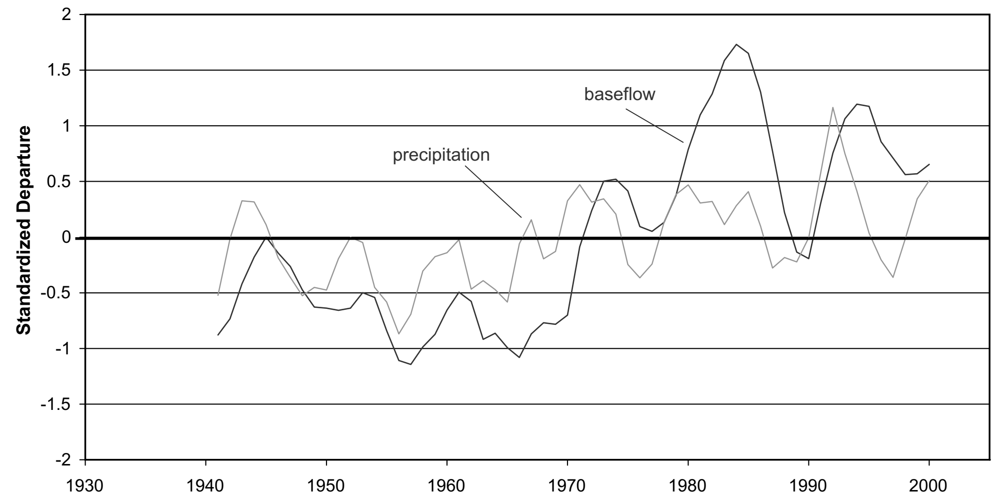

Figure 3 Five-year moving average of standardized departures of annual precipitation and baseflow in the Kickapoo River at LaFarge, WI.

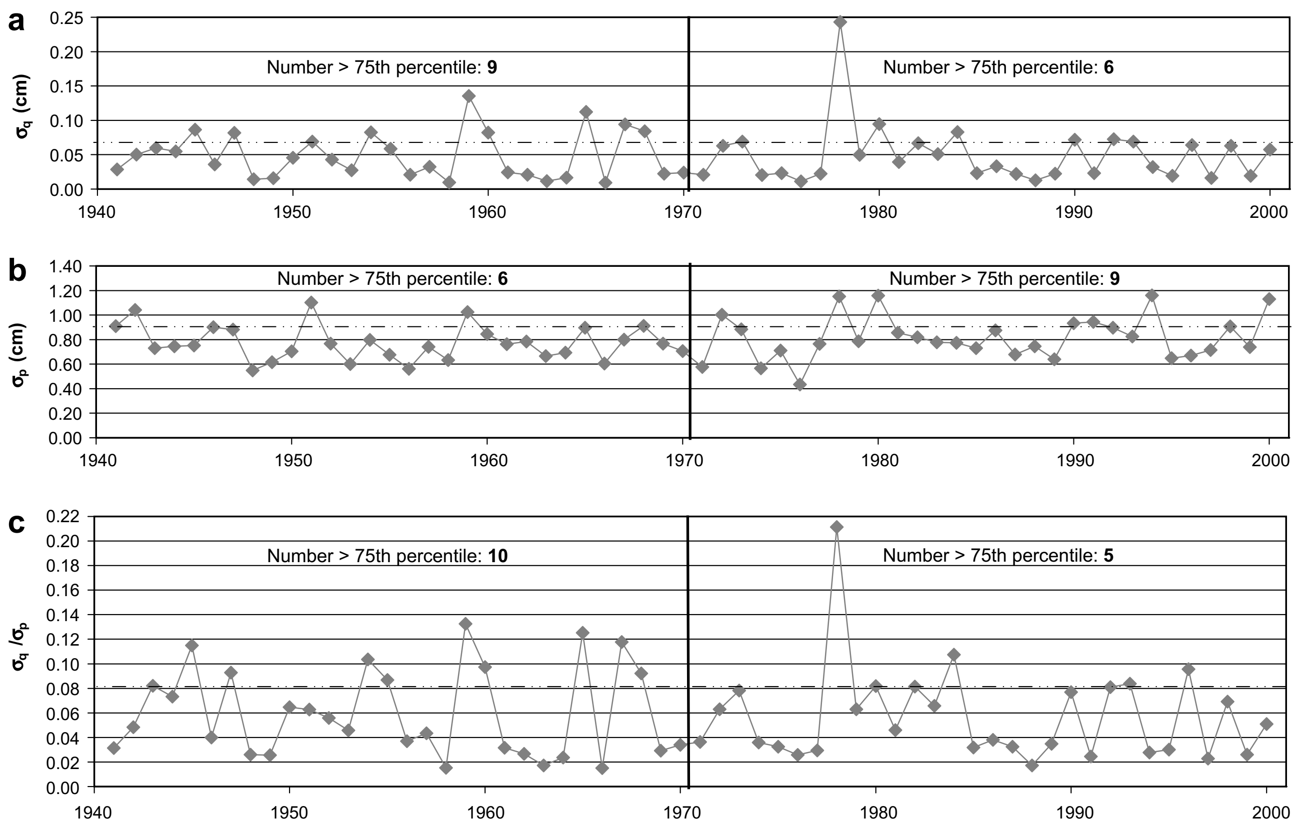

Figure 4 Standard deviation for non-snowmelt events (May 1 to November 30) of (a) streamflow (σ_q) in the Kickapoo River (b) average precipitation (σ_p), and (c) σ_q/σ_p. Horizontal dashed line identifies the 75th percentile of all values from 1941 to 2000.

measured — again underscoring the importance of the climate driver.

In contrast to the streamflow variability, average summer precipitation after 1970 was more variable, with nine years exceeding the upper quartile compared with six years prior to 1970 (Fig. 4b). Thus, the precipitation driver was more variable post-1970, but the stream response was less variable. Normalizing the two time series by dividing the streamflow variability by the precipitation variability, the decrease in streamflow variability is more pronounced, with twice as many days (10) in the upper quartile of variability prior to 1970 as the number of days (5) subsequent to 1970 (Fig. 4c). These results agree with the decrease in average annual stormflow shown in Table 1, and suggest the presence of an additional factor that mitigated the effects of increased precipitation variability.

Land management practices can influence how precipitation is partitioned into runoff or recharge. At the site-scale, higher infiltration rates were noted under less intensive land use, and this appears to be generally true across the three landscape units (Fig. 5). For example, at one hillslope site, infiltration rates were more than twice as high for a forested plot as compared with a pastured plot less than 15 m away and at nearly the same elevation. The results suggest the potential for changes in land management practices, specifically a transition to generally less intensive agricultural practices and cessation of grazing on hillslopes, to preferentially increase total infiltration and decrease runoff for a given precipitation event. As suggested by Potter (1991), Gebert and Krug (1996), and Krug (1996), among others, improved agricultural land management practices are likely an important factor responsible for decreased stormflows and increased baseflows.

Measured infiltration rates were much greater on sandy hillslopes than on loamy valley soils and the clay-rich soils on ridges (Fig. 5). This pattern demonstrates the potential of geologic properties to influence the amount of infiltration that can locally recharge the water table. It is less clear, however, how important these local changes in recharge are when scaled up to the watershed scale. What is clear is that land-use intensity affected the ability of the land to infiltrate precipitation regardless of landscape position (Fig. 5), and that the sum of these processes appears to be important on the watershed scale.

Implications for the Driftless Area and the Central and Eastern USA

Connections between climatic drivers and hydrologic trends have been suggested by others (Lettenmaier et al., 1994; Lins and Slack, 1999; McCabe and Wolock, 2002) and appear to be responsible for the timing of the step change in precipitation and baseflow observed in the Kickapoo River.

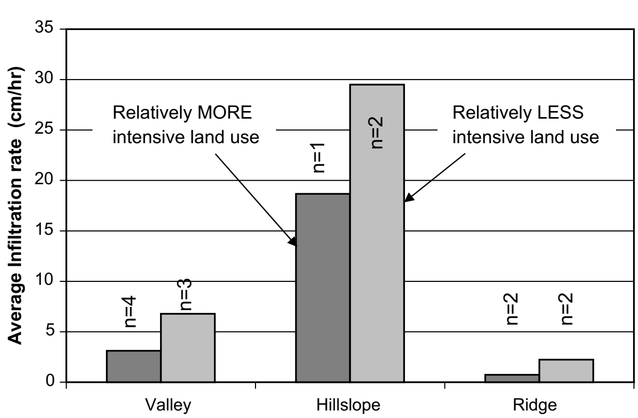

Figure 5 Infiltration rates measured in the Coon Creek Watershed using a double-ring infiltrometer; n is the number of sites measured. Relatively more intensive land use included cultivated agricultural fields, pastures and gullies; relatively less intensive land use included fallow fields, non-grazed woodlands, and waterways.

However, the precipitation increase alone does not account for the full magnitude of baseflow increase, nor does it account for the decrease in streamflow variability. Conversely, changes in land management, which were introduced in the Coon Creek Watershed in the mid-1930s (Anderson, 2002; Gaumnitz, 2002), are thought to be at least partly responsible for hydrologic trends in the Driftless Area of Wisconsin (Potter, 1991; Krug, 1996), neighboring parts of the state (Gebert and Krug, 1996), and in Iowa (Schilling and Libra, 2003). High infiltration rates measured in the Coon Creek Watershed also suggest increased groundwater recharge potential as a result of the conversion to less intensive land uses. However, if land management change were the only driver of hydrologic change, changes in hydrology would be expected to occur shortly after the expansion of less intensive land use practices that started in the mid-1930s. Instead, the most evident hydrologic change appears to be a step change around 1970 (Figs. 2 and 3). Thus, it appears that the observed changes are a result of the land-use and climate drivers combined. Climate trends likely control the timing and direction of changes in baseflow and stormflow in the Kickapoo River, whereas changes in land management influence the relative magnitude of the changes.

This combination of climatic and land management drivers may also be important in other watersheds in the central and eastern USA where a similar step increase in baseflow was observed (McCabe and Wolock, 2002); however, the relative importance of the drivers appears to be different. Lettenmaier et al. (1994) presented trends in monthly air temperature, precipitation, and streamflow in the USA from 1948 to 1988. Trend magnitudes were shown as contoured maps for the six months in which the largest number of stations had statistically significant trends. The magnitude of streamflow increase near the Driftless Area in southwestern Wisconsin over this 40-year period was greater than 40% for all winter and spring months from December to May, and exceeded 60% for the months from January to March (Fig. 10 of Lettenmaier et al., 1994). Much of the remainder of the central and eastern USA where increasing streamflow trends were identified exhibited smaller changes. The relatively large increase in streamflow in the Driftless Area could be the result of a vulnerable landscape (e.g., erodible soil, extensive agriculture, and/or large topographic relief) that was initially poorly managed, followed by implementation of wide-scale improvements in land management including elimination of grazing on hillslopes underlain by permeable soils and bedrock. Watersheds in other regions of the central and eastern USA may not have been as vulnerable to poor land-use practices, and thus temporal streamflow increases were less affected by improvements in agricultural land management. This could account for the comparatively muted hydrologic response to climatic drivers outside of the Driftless Area. Indeed, in contrast to increases in streamflow noted consistently in agricultural areas of Wisconsin, no change in streamflow was noted in areas of north central Wisconsin where there is little agriculture (Gebert and Krug, 1996; Magnuson et al., 2003). This work suggests that estimates of future hydrologic conditions can be improved with a better understanding of the combined effects of climate and land management changes.

Conclusions

Neither climatic changes nor land management changes alone could fully explain both the timing and magnitude of baseflow increase in the Kickapoo River Watershed. Instead, the timing of the step increase around 1970 coincides with similar baseflow step increases in other watersheds in the central and eastern USA, and indicates a regional climatic driver such as a concurrent step increase in precipitation. The magnitude of the step increase, however, was larger than what would be expected by the increase in precipitation alone. Moreover, decreased stormflow volumes and increased infiltration rates associated with widespread agricultural conservation practices suggest that the baseflow increase was amplified by changes in soil properties that control partitioning between overland runoff and infiltration. Similar agricultural land management changes may have influenced the magnitude of step increases in baseflow in other areas of the central and eastern USA, but the effect likely was smaller in less vulnerable watersheds containing less agricultural area.

Acknowledgments

This work was supported by a grant (R/UW-GSI-003) from the University of Wisconsin Water Resources Institute/ Groundwater Coordinating Council, the Wisconsin Department of Natural Resources – Source Water Assessment Program, and the US Geological Survey's Cooperative Water Program and Ground-Water Resources Program. Comments by Kenneth Potter (University of Wisconsin – Madison), James Krohelski (US Geological Survey), and two anonymous reviewers improved the manuscript.

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