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Evapotranspiration response to land cover and climate change in a Midwest U.S. watershed

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Abstract

In temperate humid watersheds, evapotranspiration returns more than half of the annual precipitation to the atmosphere, thereby determining the balance available to recharge groundwaters and support stream flow and lake levels. Changes in evapotranspiration rates and therefore watershed hydrology could be driven by changes in land use or climate. Here we examine the watershed water balance over the past 50 years for a watershed in southwest Michigan covered by cropland, grassland, forest, and wetlands. Over the study period about 27% of the watershed has been abandoned from row-crop agriculture to perennial vegetation and about 20% of the watershed has reverted to deciduous forest, and the climate has warmed by 1.14°C. Despite these changes, precipitation and stream discharge, and by inference evapotranspiration, have been stable over the study period. The remarkably stable rates of evapotranspirative water loss from the watershed across a period of significant land cover change indicate that rainfed annual crops and perennial vegetation have similar evapotranspiration rates, a conclusion supported by measurements of evapotranspiration from various vegetation types based on soil water monitoring. Therefore the hydrology of this humid temperate landscape has been resilient in the face of both land cover and climate change over the past 50 years.

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1. Introduction

In temperate humid watersheds, evapotranspiration (ET) returns more than half of the annual precipitation to the atmosphere (Hanson 1991), mainly during the growing season by plant transpiration. The balance between precipitation and ET recharges groundwaters and supports stream flow and lake levels. Paired catchment studies often have shown that changes in the nature of the vegetation cover, especially deforestation or afforestation, alter ecosystem ET rates and thereby change stream flows (Bosch and Hewlett 1982, Hornbeck et al. 1993, Zhang et al. 2001, Brown et al. 2005). However, these studies are often conducted in experimental forests and generally compare stream water yields between two kinds of perennial vegetation (woody and herbaceous).

There have been fewer catchment-scale comparisons of water yield from annual vegetation such as corn and soybean vs. perennial vegetation such as forest or grasslands, yet land cover change from perennial vegetation to cropland and vice versa has occurred throughout the world as a result of agricultural expansion and contraction. In eastern North America, the original forests and grasslands were largely converted to agricultural lands by European settlers, but since the mid 1900s a substantial fraction of the converted land has reverted back to successional fields and forests as the more marginal agricultural lands were abandoned due to low profitability, poor suitability to mechanized cultivation, and concerns about soil erosion and degradation (Houghton and Hackler 2000).

Southern Michigan has experienced land cover transformations over the past two centuries that are typical of eastern North America (Ramankutty et al. 2010). Originally covered by deciduous forest with lesser areas of oak savanna and prairie (Comer et al. 1995), upland areas were nearly completely deforested and converted to agriculture by

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the late 1800s. Extensive drainage of wetlands wherever practical, particularly in the early 1900s, further expanded agricultural land use (Dahl 1990). In the mid-1900s some of this agricultural land was abandoned to successional vegetation, first in the most marginal locations where agriculture proved unsustainable due to poor soils or slopes (exacerbated by the drought and economic depression of the 1930s), then in former wetlands and other places of lower productivity. Fragmentation of land ownership and an influx of exurbanites into the rural areas also contributed to the contraction of agricultural land area, as did the federal Conservation Reserve Program (CRP), conservation easements, and other incentives to remove land from agricultural production.

Further land cover changes are likely in the future. As grain crops have become more profitable due to global demand for food and US policies that support ethanol production from corn, more land in grasslands (including CRP land) is being converted to grow corn and soybean (Lark et al. 2015). Meanwhile, successional ecosystems are becoming mature forests in many locations (Pugh 2015). Climate change and invasive plant species will increasingly drive changes in the nature and phenology of vegetation communities (Simberloff 2000). Further changes to the nature of vegetation in agricultural landscapes may occur if cellulosic biofuel crops are increasingly grown in the future (Gelfand et al. 2013).

Recently we reported ET measurements in candidate cellulosic cropping systems at a location in southwest Michigan, USA. We estimated ET using two distinct approaches: 1) by monitoring soil water content with time domain reflectometry in annual crops (maize) as well as perennial grasslands and hybrid poplar stands (Hamilton et al. 2015); and 2) by monitoring energy and water vapor fluxes using eddy covariance

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in corn, switchgrass, and prairie at a nearby site (Abraha et al. 2015). Results suggest strikingly similar growing-season ET among these diverse plant systems, raising the question of whether land cover changes would significantly affect ET in the Midwest U.S., as suggested in some modeling studies (e.g., Le et al. 2011, VanLoocke et al. 2012, Zhuang et al. 2013).

Here we further investigate this question at a watershed scale, examining a 50-year record of stream discharge and precipitation in a watershed that has experienced significant land cover change, but without the complications of urbanization, dams, and stormwater management changes that are typical of larger watersheds.

2. Methods

2.1 Study site

Augusta Creek is a 3rd-order stream in southwest Michigan (Kalamazoo and Barry counties) that drains a predominantly rural landscape (95 km^2) composed of a mosaic of forest, fallow fields, annual crops, wetlands, lakes, light residential development, and golf courses (figure 1). There are no impervious surfaces or storm drainage systems that drain into the stream above the discharge measurement point, and urban land use covers <4% of the watershed (land cover proportions over the 50-year period are presented later). The stream is groundwater-fed, gaining water along most of its length. Its tributaries emanate from wetlands or small lakes, and prairie fen wetlands line much of the stream channels.

The stream runs through deep glacial deposits and lies well above the bedrock. The most common soils in upland areas are well-drained Typic Hapludalfs developed on postglacial terrain (Thoen 1990), and there is little to no overland flow from upland areas

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to the stream due to the high permeability of these coarse-textured soils (Rheaume 1990). Irrigation of crops was rare in the area until very recently; some expansion has taken place since 2005.

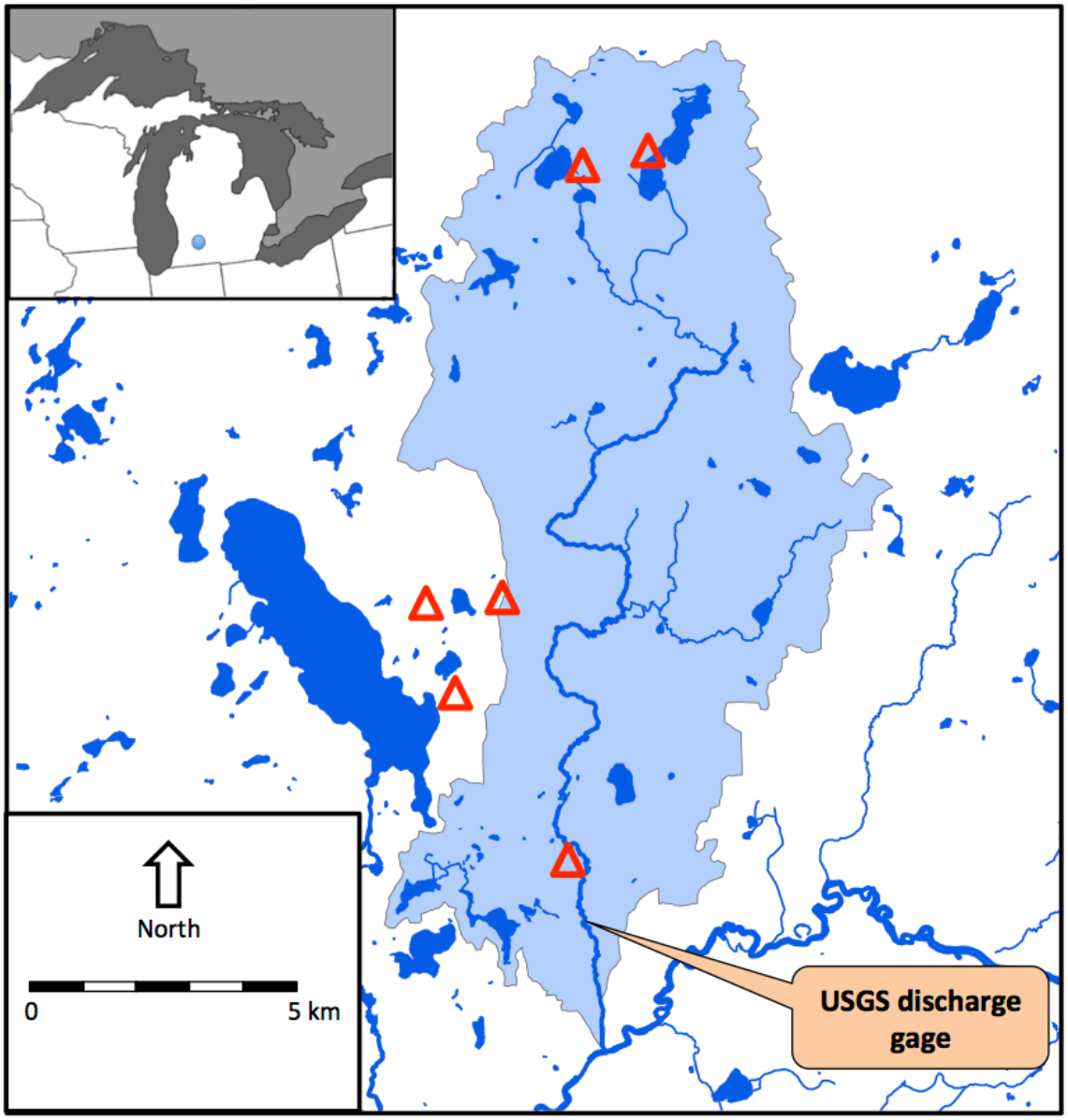

Figure 1. Location of Augusta Creek in Michigan (inset) and watershed boundaries (shaded). Precipitation measurement sites are shown by triangles.

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Augusta Creek is in the vicinity of the W.K. Kellogg Biological Station (KBS), where we conduct agricultural experiments under the aegis of the Great Lakes Bioenergy Research Center (GLBRC) and KBS Long Term Ecological Research site (www.lter.kbs.msu.edu; 42.3956° N, 85.3749° W and 288 m asl). Mean annual air temperature is 10.1 °C and annual precipitation is 1005 mm, 511 mm of which falls during the May-Sep growing season (1981–2010) (NCDC 2013).

2.2 Land cover changes

Land cover for 1960 was estimated from georectified and mosaicked aerial photographs in a geographic information system (ArcGIS). The watershed boundaries above the discharge measurement point (US Geological Survey; Hydrologic Unit Codes 04050003040060 plus 04050003040070) and wetlands and lakes (National Wetlands Inventory: http://www.fws.gov/wetlands/) were overlain on the aerial photo mosaic and land cover was examined in the upland portions of the watershed. Based on the National Wetlands Inventory, wetlands and lakes contiguous with the stream system amount to 15.9 km^2, or 16.6 % of the watershed above the discharge measurement point. Isolated wetlands and small lakes also occur throughout the upland watershed, covering 5.2% of its area. Wetland areas were assumed to be constant over the study period; there has been no wetland drainage or creation in the watershed since 1960, and within the area mapped boundaries generally include intermittently wet soils with high water tables.

Land cover for 2014 was estimated in the GIS from the Cropland Data Layer (http://nassgeodata.gmu.edu/CropScape/). For this purpose, we combined all field crops (primarily corn, soybean and small grains) into the annual crop category, and all forests

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(deciduous and coniferous) into the forest category. Conifers are not native to the upland landscape here, but have been planted throughout the watershed; their total area as of 2014 amounts to ~3% of the total forest area and 1% of the upland watershed. The grassland and pasture category includes hay as well as fallow fields (no native grassland remains). The width of rural roads was exaggerated 3–5 fold in the Cropland Data Layer, presumably due to automated classification of mixed pixels, so vegetated edges of roadways were manually reclassified as grasslands. Land cover for an intermediate date (1978), based on aerial photo interpretation, was available from the Michigan Resource Inventory System (MIRIS) (http://www.ciesin.org/IC/mdnr/mrip.html); this data set was comparable for forest but combines annual crops with some kinds of pasture, and was therefore not compared for those categories.

2.3 Discharge and climate records

The discharge of Augusta Creek has been monitored below the lowermost tributary inflow since 1964 by the US Geological Survey (station 04105700). The long-term mean discharge at this point, which drains 95.3 km^2, is 1.28 $m^3 s^{-1}$. Daily discharge measurements for October 1964 through September 2014 were partitioned into baseflow and stormflow using the Web-based Hydrograph Analysis Tool (WHAT) described by Lim et al. (2005). Mean annual baseflow and stormflow discharges were calculated on a water-year basis beginning on 1 October of each year, and water years are labeled by the starting year (i.e., water year 1964 is 1 October 1964–30 September 1965).

Climate data were drawn from several sources and compiled on a water-year basis. Precipitation observations are from at least three stations (except 1992 which has

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two) distributed across the watershed from north to south (figure 1); outliers were excluded if not supported by more than one station. Air temperature and drought index data were obtained from the Midwest Regional Climate Center (http://mrcc.isws.illinois.edu/).

2.4 Water balance calculations

Evapotranspiration has often been estimated from watershed water balances (e.g., Hanson 1991). For Augusta Creek, the water balance for the upland portion of the watershed was determined as the difference between annual totals of precipitation falling on the uplands (i.e., the watershed excluding wetlands and lakes contiguous with the stream channels) and the stream baseflow discharge expressed as mm y^{-1} based on the upland watershed area. Isolated lakes and wetlands were included in the upland watershed area. This calculation assumes that stormflow represents direct capture of precipitation from the wetlands and lakes contiguous with the stream system, whereas baseflow represents infiltration and percolation of precipitation falling on the upland watershed. Other assumptions that are reasonable in this case include no significant interannual storage changes in the aquifer volumes, or inter-basin transfers of water. The difference between precipitation inputs on the uplands and stream baseflow outputs is therefore the "apparent ET" of the upland watershed.

2.5 ET estimation from soil water content measurements

Since 2009, soil water profiles throughout the root zone and below were monitored hourly using permanently installed, horizontally inserted time domain reflectometry

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(TDR) probes at depths of 20, 35, 50, 65, 90 and 125 cm as well as a vertically inserted probe at 0–10 cm depth. Our methods for estimating ET from soil water profiles are described by Hamilton et al. (2015), who presented data on six biofuel cropping systems harvested each fall. Here we present the mean ET rates for three of those systems that resemble vegetation found on the broader landscape: 1) continuous no-till corn; 2) a restored native prairie planted with 18 species of forbs and grasses; and 3) a hybrid poplar plantation (*Populus nigra* × *P. maximowiczii 'NM6'*). In addition, we present comparable water use measurements for four other systems in the same vicinity: 1) a fallow field abandoned from row-crop agriculture in 2008 and harvested each fall; 2) a mature deciduous forest (>50 years old) dominated by sugar maple (*Acer saccharum*), red oak (*Quercus rubra*) and hickory (*Carya* spp.) trees; and 3) an early successional forest (ca. 25 years old) dominated by shrubs including autumn olive (*Elaeagnus umbellate*) and honeysuckle (*Lonicera* sp.) as well as a few medium-sized sugar maple and black cherry (*Prunus serotina*) trees.

3. Results and Discussion

3.1 Land use and climate changes

Corn has been the dominant agricultural crop over the 50-year study period with the balance of harvested crops shifting increasingly to soybean since the 1970s, as in the greater Midwest US region (Gage et al. 2015). Data on Kalamazoo County from the annual Census of Agriculture (U.S. Department of Agriculture: http://www.agcensus.usda.gov/) indicate that in 1964 corn accounted for 69% of harvested cropland, soybean for 5.7%, and the balance was mostly oats with some barley

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and wheat. By 1987 corn was 58% and soybean 28% of harvested cropland, and by 2007 these two crops accounted for 64% and 32% of the harvested cropland.

Land cover in the upland watershed changed significantly between 1960 and 2014 (figure 2). The proportion of the upland watershed in annual crops decreased from 57 to 30%, while forest increased from 15 to 35%. The proportion of grassland remained similar, although only 20% of the 1960 upland grassland was still grassland in 2014; most of the 1960 grassland became forest (43%) or cropland (22%), while some newly abandoned cropland became grassland. The 1978 MIRIS land cover data (not shown; see Methods) indicate that 94% of the forest present in 2014 existed by 1978, so most reforestation began between 1960–78. Urban and residential development represents a small fraction of the watershed (<2.4%), not including golf courses created during the study period that covered 4.5% of the upland watershed by 2014. Similar changes in land cover occurred in adjacent watersheds.

The region has experienced a 1.14°C increase in mean annual air temperature over the 50-year period (Supplementary figure 1). Annual precipitation over the period averaged 948 ± 118 mm y^{-1} with no linear temporal trend ($p = 0.93$) for the Augusta Creek watershed (figure 3(a)). No linear trend exists in mean annual values for either the Palmer Drought Severity Index or the Palmer Hydrological Drought Index ($p = 0.34$ and 0.67, respectively; data not shown).

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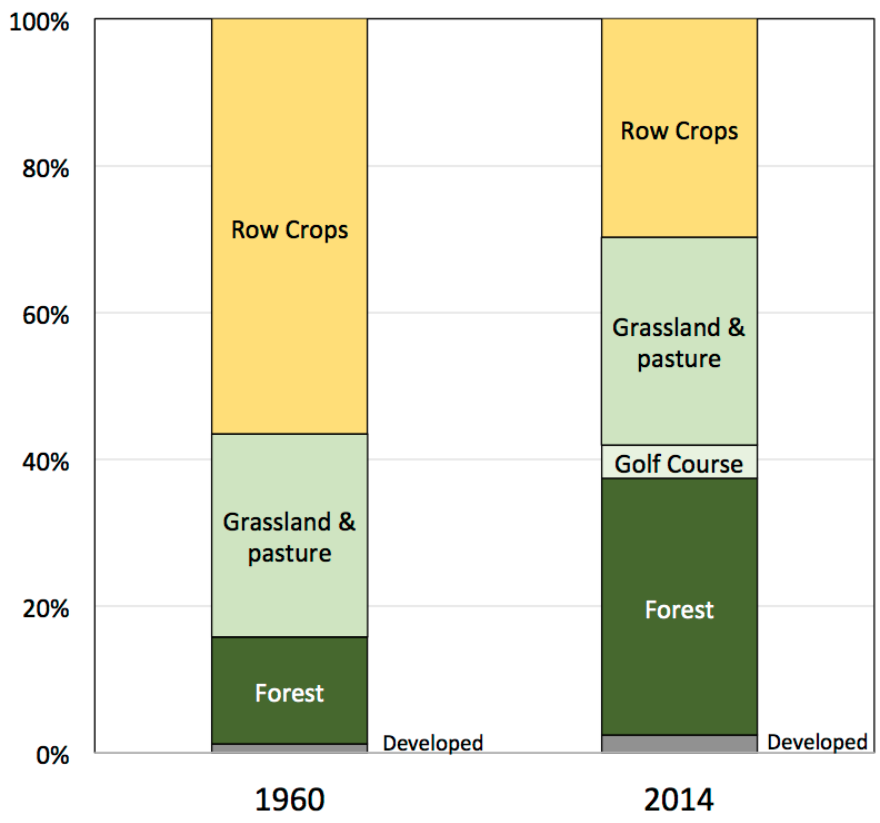

Figure 2. Land cover change in the Augusta Creek watershed. Estimates are based on analysis of aerial photos (1960) or satellite imagery (2014 Cropland Data Layer: http://nassgeodata.gmu.edu/CropScape/).

3.2 Watershed hydrology

Stream discharge partitioned into stormflow and baseflow shows how groundwater dominates the total flow of Augusta Creek; baseflow averaged 78% of the total discharge (figure 3(b)). There is no linear trend in total ($p = 0.14$), stormflow ($p = 0.91$), or baseflow ($p = 0.83$) discharge over the 50 years. In this watershed, stormflow likely reflects mainly precipitation falling on lakes and wetlands that are contiguous with

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the stream channels because soils are highly permeable and there are few impervious surfaces and little overland runoff from uplands to the streams.

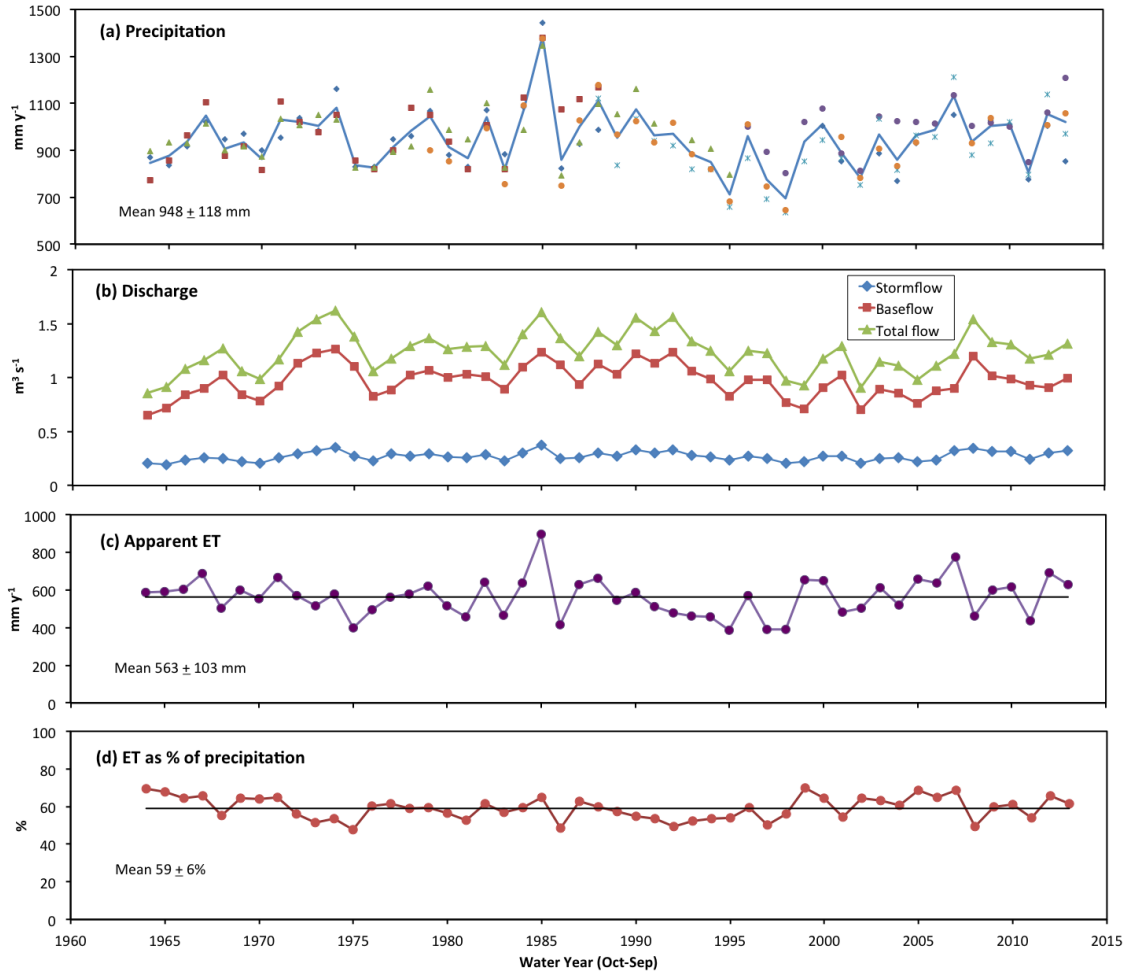

Figure 3. Precipitation, stream discharge, and apparent evapotranspiration (ET). Panels show annual (Oct-Sep) values of (a) precipitation measured at 3-6 stations (mean = blue line); (b) stream discharge partitioned into baseflow and stormflow; (c) apparent evapotranspiration (ET) estimated as the difference between precipitation and baseflow discharge; and (d) apparent ET as a percentage of annual precipitation. Horizontal lines show the means.

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Our annual water balances for Augusta Creek resemble earlier estimates calculated over three representative years (1971, 1977 and 1985) (Rheaume 1990), which indicated that 62, 65 and 59%, respectively, of the annual precipitation was returned to the atmosphere as ET, mainly during the growing season (May–Sep), although those estimates included ET from contiguous lakes and wetlands as well as uplands. That study also employed hydrograph separation to estimate that about 75% of the annual stream flow in those years was supported by groundwater discharge; our estimate of mean baseflow contribution over the 50-year period is 78%.

Apparent ET, the difference between precipitation on the upland watershed and baseflow discharge out of the watershed, averaged 563 ± 103 mm y^{-1} (figure 3(c)), with no linear trend ($p = 0.98$). Expressed as a percentage of annual precipitation, apparent ET averaged 59 ± 6% (figure 3(d)), also with no trend over the 50 years ($p = 0.88$). Therefore these data show that discharge from the Augusta Creek watershed has remained remarkably stable over the past 50 years in spite of large changes in land cover towards less area in annual crops and more in deciduous forest.

There are several possible explanations for this stability that we believe are unlikely. One is that there may not have been sufficient time for hydrologic responses to be detected. While the mean transit time for groundwater movement in this kind of watershed is likely greater than a decade (e.g., Saad 2008), groundwater discharge rates from an unconfined and connected aquifer system would respond to changing recharge at far faster time scales (McDonnell and Beven 2014). Succession from grassland to forest can be protracted, but the MIRIS forest cover data indicate that most of the reforestation occurred in the first 14 years of the study period (i.e., 1964–78). Many long-term paired

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catchment studies have shown that water yield after regrowth of harvested forest tends to approach a stable rate within 10–27 years (Hornbeck et al. 1993).

Another possibility is that the degree of land cover change over the study period (27% of the upland watershed abandoned from annual crops and 20% of it becoming reforested; figure 2) may not be sufficiently large to signal a change in water yield, even if annual crops and perennial vegetation had large differences in ET rates. Again, this is unlikely because long-term paired catchment studies have shown significant change with as little as 20% of the catchment either deforested or afforested (Brown et al. 2005).

Also possible is that there are offsetting effects exerted by different land covers in the vicinity (Albertson et al. 2001), but this does not seem likely because adjacent watersheds have similar mosaics of land cover, and the entire region has experienced similar changes in vegetation over this time period. Compensating factors that result in no net change in ET are also a possibility, such as the changes in crops grown as noted above. However the ET rate of oats that were commonly grown in the 1960s and 1970s is unlikely to differ much from the corn that replaced them (Allen et al. 1998).

Over the past 50 years the mean annual air temperature has increased by about 1.14 °C (Supplementary figure 1), and the frost-free season has become longer by about 9 days (Kunkle 2015), but like a change from annual crops to perennial vegetation, if anything these changes should increase ET. Evapotranspiration could increase with warming if available water were not limiting and the vegetation could remain active over the longer growing season. However, most annual crops and many grasses would senesce before the end of the potential growing season because their development is regulated by

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degree-days (Parmesan and Hanley 2015). Also, soil water tends to be drawn down to limiting levels by late in the growing season (Hamilton et al. 2015).

3.3 ET rates from representative vegetation types

We estimated ET in annual crops and perennial vegetation over the 2009–2014 period from high-resolution changes in soil water profiles (figure 4). Except for 2012, which was a severe drought year, mean growing season ET rates were 495 ± 48 mm y^{-1} for corn, 524 ± 79 for grasslands (fallow and prairie), and 532 ± 47 for woody vegetation (deciduous forest, shrubland, and poplar). These rates are statistically indistinguishable among vegetation types ($p>0.05$), further supporting the null hypothesis that ET rates are similar among annual crops, perennial grasslands, and forests in the Augusta Creek watershed. These ET observations span years of varying warmth (Supplementary figure 1) but show no relationship with mean growing-season temperature.

While soil water-based ET rates, excluding the 2012 drought year, are lower than the apparent watershed-based ET rates of 600 ± 59 mm y^{-1} in those years (2009, 2010, 2011, 2013, and 2014 in figure 3(c)), the soil water-based ET estimates reflect only the growing seasons. Year-round eddy covariance measurements of water fluxes in corn and grasslands at KBS indicate that about 30% of ET occurs outside the growing season (Abraha et al. 2015). Adding 30% to the soil water-based ET rates brings rates for corn, grasslands, and woody vegetation to 643, 681, and 692 mm y^{-1}, respectively, all higher but within 15% of the apparent watershed-based ET measurements over those years.

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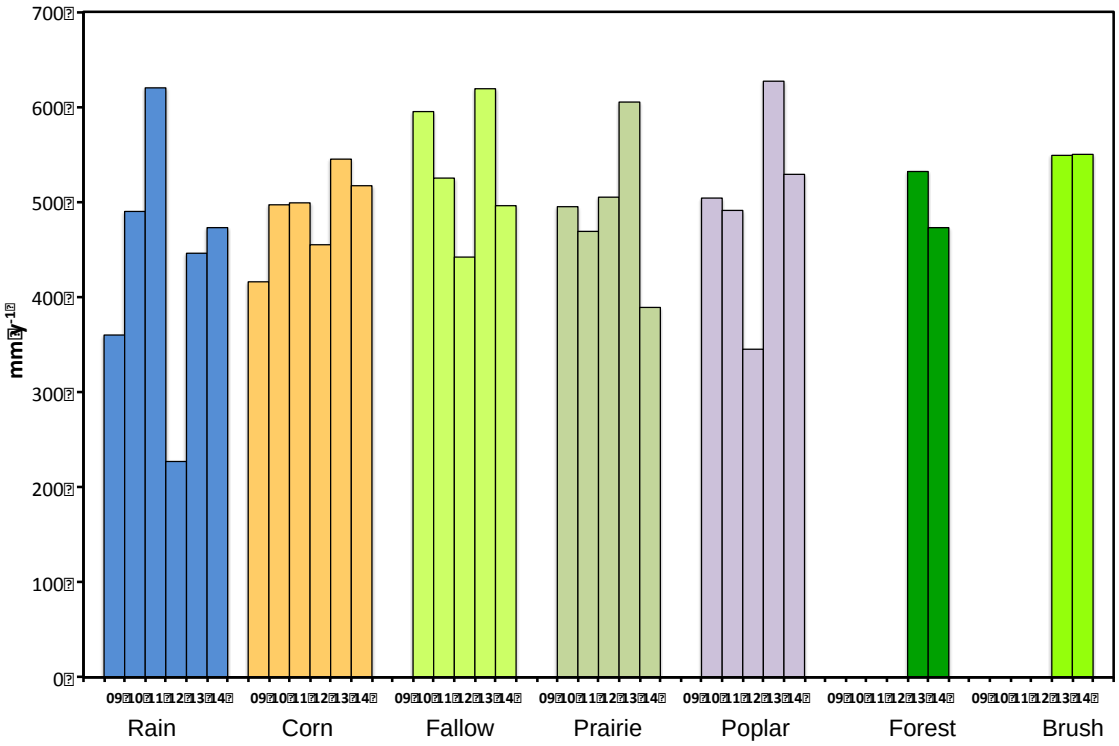

Figure 4. Rainfall (blue) and evapotranspiration over the growing season (2009-14) from annual corn and herbaceous and perennial vegetation, estimated from continuous observations of plant water uptake in soil profiles.

3.4 Conclusions

We conclude that evapotranspirative water loss has been remarkably stable across a period of decreasing cropland, increasing perennial vegetation cover, and warming temperatures, leaving a relatively consistent proportion of precipitation for groundwater recharge and streamflow. The ET estimates based on watershed water balance compare well with direct measurements in the same watershed since 2009 based on soil water monitoring by time-domain reflectometry (grasslands, annual crops, bioenergy crops and

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forest). These observations suggest that water use by rainfed annual crops and perennial vegetation must be similar in this setting, and that at least in the short term, watershed water balances are not likely to be very sensitive to future changes in land cover and climate as long as the land is vegetated, and crops are not irrigated.

Our results support the theoretical argument in Ritchie and Basso (2008) and Basso and Ritchie (2012) that when vegetation canopies exceed a leaf area index (LAI) of 3 and have sufficient water supply, ET is controlled by the atmospheric demand, which in turn depends on the energy available, making the nature of the vegetation of little consequence. At LAI <3 the partitioning between soil evaporation and plant transpiration is highly dependent on the soil surface wetness (Basso et al. 2012). The annual crops, grasslands, and forest stands where we have measured soil water have LAI values that range mostly from 3–6 during the growing season (data not shown). Yet regardless of the kind of vegetation, soil water availability usually becomes limiting by the latter part of the growing season, and thus the total ET from annual crops and perennial vegetation tends to be similar amounts in spite of their different phenologies and growing season lengths.

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