Journal of Hydrology 551 (2017) 188–202

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Annual baseflow variations as influenced by climate variability and agricultural land use change in the Missouri River Basin

Laurent Ahiablame [a,*], Aleksey Y. Sheshukov [b], Vahid Rahmani [b,c], Daniel Moriasi [d]

[a] Department of Agricultural and Biosystems Engineering, South Dakota State University, Brookings, SD 57007, USA
[b] Department of Biological and Agricultural Engineering, Kansas State University, Manhattan, KS 66506, USA
[c] Kansas Biological Survey, University of Kansas, Lawrence, KS 66047, USA
[d] USDA-ARS Grazinglands Research Laboratory, El Reno, OK 73036, USA

ARTICLE INFO

Article history:
Received 26 May 2016
Received in revised form 25 May 2017
Accepted 26 May 2017
Available online 31 May 2017

Keywords:
Watershed hydrology
Groundwater discharge
Cultivated cropland
Precipitation
Elasticity coefficient

ABSTRACT

The Missouri River system has a large water storage capacity, where baseflow plays an important role. Understanding historical baseflow characteristics with respect to climate and land use impacts is essential for effective planning and management of water resources in the Missouri River Basin (MORB). This study evaluated statistical trends in baseflow and precipitation for 99 MORB minimally disturbed watersheds during 1950–2014. Elasticity of baseflow to climate variability and agricultural land use change were quantified for the 99 studied watersheds. Baseflow was derived from daily streamflow records with a recursive digital filter method. The results showed that baseflow varied between 38 and 80% (0 and 331 mm/year) of total streamflow with an average of 60%, indicating that more than half of streamflow in the MORB is derived from baseflow. The trend analysis revealed that precipitation increased during the study period in 78 out of 99 watersheds, leading to 1–3.9% noticeable increase in baseflow for 68 of 99 watersheds. Although the changes in baseflow obtained in this study were a result of the combined effects of climate and land use change across the basin, upward trends in baseflow generally coincide with increased precipitation and agricultural land use trends in the basin. Agricultural land use increase mostly led to a 0–5.7% decrease in annual baseflow in the basin, except toward east of the basin where baseflow mostly increased with agricultural land use increase (0.1–2.0%). In general, a 1% increase in precipitation and a 1% increase in agricultural land use resulted in 1.5% increase and 0.2% decrease in baseflow, respectively, during the study period. These results are entirely dependent on the quality of data used; however, they provide useful insight into the relative influence of climate and land use change on baseflow conditions in the Great Plains region of the USA.

1. Introduction

Baseflow is an important component of streamflow (Santhi et al., 2008; Ahiablame et al., 2013; Rumsey et al., 2015). As such, understanding its availability and contribution to streamflow are critical for appropriate planning and management of water resources (Santhi et al., 2008). Baseflow discharge to streams has been associated with a wide range of drivers including climate, topographical relief, geology, soils, vegetation, and human activities (Zhang and Schilling, 2006; Price, 2011).

With growing concerns regarding potential adverse impacts of global climate change and land use change on water resources (IPCC, 2014a,b; Xu et al., 2013a), analysis of baseflow trends is salient within the context of changes in hydroclimatology of a region (Zhang and Schilling, 2006). Global climate observations indicate more frequent extreme events since the early 20th century typified by increases in temperature, precipitation, and atmospheric greenhouse gas concentrations with direct impacts on regional water resources (NOAA, 2016) Continued global warming has led to intensification of hydrologic regimes (e.g. Nyenje and Batelaan, 2009; Price, 2011), with regional differences and patterns (Price, 2011). Baseflow feedback to the global warming has been extreme, especially seasonal baseflow which increased with earlier snowmelt, leading to reduced late-summer baseflow (e.g. Yusoff et al., 2002; Brabets and Walvoord, 2009; Huntington et al., 2009; Xie et al., 2010). Recently, Ficklin et al. (2016) also showed that climate

* Corresponding author.
E-mail addresses: laurent.ahiablame@sdstate.edu (L. Ahiablame), ashesh@ksu.edu (A.Y. Sheshukov), vrahmani@ksu.edu (V. Rahmani), daniel.moriasi@ars.usda.gov (D. Moriasi).

http://dx.doi.org/10.1016/j.jhydrol.2017.05.055
0022-1694/

driven changes in baseflow in United States watersheds vary across the nation and seasons; except in the northeast where climate change contributed to consistent baseflow increase during fall and winter and decrease during all seasons in the southwest. In the Midwest and Great Plains regions, analysis of historical streamflow records revealed increasing trends in streamflow and baseflow due to the influence of climate (e.g. Lins and Slack, 2005; Novotny and Heinz, 2006; Kibria et al., 2016).

While baseflow response to climate change has been a topic of interest (e.g. Choi, 2008; Smakhtin, 2001; Price, 2011), baseflow trends have concurrently been associated with land use change (e.g. Price, 2011; Juckem et al., 2008; Ma et al., 2009). Very often, climate impact amplifies the effect of land use and vice versa (Poff, 1996; Price, 2011; Choi, 2008), especially in regions where both climate and land use intensity are pronounced. For example, Juckem et al. (2008) linked changes in baseflow timing to climate and changes in baseflow magnitude to land use change in the Kickapoo River watershed, Wisconsin. In Tanzania, varying patterns of streamflow and baseflow trends, reported over a 50-year (1960–2009) study period in the Usangu watershed, were attributed to climate and anthropogenic influences which include deforestation, irrigation, and groundwater abstraction (Shu and Villholth, 2012). Based on the climate and land use change analysis in east of MORB, covering four states in the Midwest (Ohio, Indiana, Illinois, and Iowa), Xu et al. (2013a) reported that baseflow increase in 58% of the studied watersheds was predominantly caused by land surface changes. Although it is a challenge to clearly differentiate the respective influence of climate and land use change on streamflow processes in many settings, years of research showed that land use change and human-induced influences are equally notable contributors to changes in baseflow. In Iowa watersheds, increased baseflow in nearly all 11 watersheds studied was linked to improved land management and conservation practices, greater artificial drainage, increasing row crop production, and channel incision (Schilling and Libra, 2003). Zhang and Schilling (2006) showed that increasing baseflow in the Mississippi River Basin is the result of land use change and associated agricultural activities, leading to increased streamflow in this basin. In contrast, Wen and Chen (2006) reported decreases in baseflow for 20 out of 24 streams across Nebraska mainly because of changes in land use and groundwater withdrawal for irrigation. Similarly, Brikowski (2008) documented decreased baseflow for western Kansas following land use change and irrigation demands. Zomlot et al. (2015) observed a large spatial variation in recharge and baseflow in northern part of Belgium, largely driven by vegetation cover and groundwater depth.

The MORB is a major basin with considerable sources of water for agriculture, municipal, rural, and industrial use in the United States (Kammerer, 1987; Norton et al., 2014; Mehta et al., 2016). Like other parts of the world, the MORB region is experiencing risks of climate change and impacts of land use change (Mehta et al., 2013, 2016; Xu et al., 2013a; Norton et al., 2014), that affect its hydrological processes. For example, statistical significant trends in annual streamflow, likely due to the influence of climate and land use, were reported for 101 out of 227 streamflow gauges in the MORB between 1960 and 2011 (Norton et al., 2014). As an important component of streamflow, climate and land use exert substantial influence on baseflow processes (Price, 2011). Research showed that baseflow represents more than 50% of total streamflow in the United States Midwest and Great Plains regions (e.g. Santhi et al., 2008; Ahiablame et al., 2013; Rumsey et al., 2015). To continue to meet critical water demands, as mentioned above, there is a need to provide relevant science-based information to increase understanding of the role of regional controls on MORB baseflow. Knowledge of past trends as well as factors that directly influence baseflow processes in the MORB adds to the existing information system to support development of resilient adaptation and mitigation strategies for climate and land use changes. The goal of this study was to document the influence of climate and land use changes on baseflow in the MORB over the past few decades. The specific objectives were to (1) document regional patterns of baseflow trends in the MORB; and (2) quantify the relative influence of climate variability and land use change on baseflow by utilizing established statistical methods.

2. Study area

The MORB is a 1,350,000 km^2 (521,238 square miles) watershed that covers, wholly or partly, Montana, North Dakota, South Dakota, Minnesota, Wyoming, Nebraska, Iowa, Colorado, Kansas, and Missouri in the United States (approximately 1,320,000 km^2), and south of Alberta and Saskatchewan in Canada (approximately 30,000 km^2) (Fig. 1). The watershed has many landscape feature classes, ecoregions, and climates from the Northern, Middle, and Southern Rocky Mountains to the west, the Missouri Plateau to the north, and the High Plains to the east and south (Fenneman and Johnson, 1946; Norton et al., 2014). The MORB drains about one-sixth of the North American continent into the Missouri River (MOR). With 4,087.7 km (2540 miles), the MOR is the longest river in the United States (Kammerer, 1987; Norton et al., 2014). The states within the MORB rely heavily on the watershed for economic and ecological stability through support for agriculture, livestock, recreation, tourism, wildlife habitat, irrigation, drinking water, industry, and electrical power generation (Burch et al., 2007; Wyoming State Wildlife Action Plan, 2010).

The predominant land uses within the MORB consists of pasture/grassland (47%) and crop production agriculture (25%), while the rest of the land consists of shrub (10%), forest (9%), residential/urban (3%), wetlands (2%), and others (4%; water, snow, barren, and no data) (Fig. 1; Homer et al., 2015). Corn, soybean, and wheat are the predominant crops.

The climate of the MORB can be classified as cold deserts and western Cordillera in the mountainous west, semiarid prairies in the central part of the watershed, and temperate prairies to the east (USEPA, 2006; Norton et al., 2014). During the coldest month of the year (i.e. January) and warmest month of the year (i.e. July), average daily air temperature in the MORB varies from −8 °C to 37 °C, and −16 °C to 30 °C, respectively in Billings (MT) and Bismarck (ND) in the north, and from −9 °C to 32 °C, and −6 °C to 32 °C, respectively in Omaha (NE) and Kansas City (MO) in the south. Average annual rainfall varies from west to east with the least amount of precipitation in the west (<255 mm) and the greatest amount of precipitation in the east (>1140 mm) (Norton et al., 2014; Table 1). Total annual snow depth varies widely across the watershed with 1400 mm in Billings, MT, 1300 mm in Bismarck, ND, 670 mm in Omaha, NE, and 340 mm in Kansas City, MO.

3. Data and methods

3.1. Data

Ninety-nine streamflow gauge stations within the MORB were collected from the U.S. Geological Survey National Water Information System database (USGS-NWIS, 2015) based on the following criteria (Fig. 1): (1) the streamflow gauge stations must contain continuous data for at least 50 years (monthly or daily data), (2) have reduced or be completely free from water diversion, reservoir storage, and other anthropogenic regulations, and (3) have irrigated land occupying less than 10% of the draining watersheds. Of the 99 stations that satisfied these criteria, 53 stations were part of the USGS's Hydro-Climatic Data Network (HCDN; Slack and Landwehr, 1992),