Journal of Hydrology 525 (2015) 559–571

Contents lists available at ScienceDirect

Journal of Hydrology

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

Long-term changes in nitrate conditions over the 20th century in two Midwestern Corn Belt streams

Valerie Kelly [a,*], Edward G. Stets [b], Charlie Crawford [c]

[a] U.S. Geological Survey, Retired, 2130 SW 5th Avenue, Portland, OR 97201, United States
[b] U.S. Geological Survey, 3215 Marine Street, Boulder, CO 80303, United States
[c] U.S. Geological Survey, 5957 Lakeside Blvd., Indianapolis, IN 46278, United States

ARTICLE INFO

Article history:
Received 12 June 2014
Received in revised form 2 October 2014
Accepted 30 March 2015
Available online 7 April 2015
This manuscript was handled by Andras Bardossy, Editor-in-Chief, with the assistance of Attilio Castellarin, Associate Editor

Keywords:
Nitrate
Nutrient transport
Stationarity
Corn Belt streams
Weighted regression

SUMMARY

Long-term changes in nitrate concentration and flux between the middle of the 20th century and the first decade of the 21st century were estimated for the Des Moines River and the Middle Illinois River, two Midwestern Corn Belt streams, using a novel weighted regression approach that is able to detect subtle changes in solute transport behavior over time. The results show that the largest changes in flow-normalized concentration and flux occurred between 1960 and 1980 in both streams, with smaller or negligible changes between 1980 and 2004. Contrasting patterns were observed between (1) nitrate export linked to non-point sources, explicitly runoff of synthetic fertilizer or other surface sources and (2) nitrate export presumably associated with point sources such as urban wastewater or confined livestock feeding facilities, with each of these modes of transport important under different domains of streamflow. Surface runoff was estimated to be consistently most important under high-flow conditions during the spring in both rivers. Nitrate export may also have been considerable in the Des Moines River even under some conditions during the winter when flows are generally lower, suggesting the influence of point sources during this time. Similar results were shown for the Middle Illinois River, which is subject to significant influence of wastewater from the Chicago area, where elevated nitrate concentrations were associated with at the lowest flows during the winter and fall. By modeling concentration directly, this study highlights the complex relationship between concentration and streamflow that has evolved in these two basins over the last 50 years. This approach provides insights about changing conditions that only become observable when stationarity in the relationship between concentration and streamflow is not assumed.

1. Introduction

High concentrations of nitrate in streams is a significant driver of eutrophic conditions and corresponding hypoxia in many receiving waters, including Chesapeake Bay (Boesch et al., 2001) and the Gulf of Mexico (Turner et al., 2006). While nitrogen, especially as nitrate, is generally present in low concentrations in pristine streams, excessive nitrate concentrations in streams are governed to a large extent by the impact of anthropogenic influences that have been in place for decades, especially from the use of synthetic nitrate fertilizer and the changing quality and extent of wastewater treatment (Carpenter et al., 1998; Galloway et al., 2003). Despite the long-term nature of these types of human impacts, most efforts to evaluate the effects of human activities affecting nitrate delivery to surface waters are based on data from relatively short time frames consisting of a few decades only, generally dating back to the 1970s or 1980s at the longest (Sprague et al., 2011). This paper provides a longer-term (e.g. more than 50 years) historical perspective on nitrate concentrations in two streams—the Des Moines River and the Illinois River—that are currently subject to excess nitrate conditions in an effort to provide greater understanding of how these conditions have developed over time.

For this study we focused on describing and evaluating changes in the relationship between concentration and streamflow for two streams in the Corn Belt region of the U.S. The study includes the period from just prior to 1960 to the first decade of the 21st century, which incorporates two key factors affecting nitrate delivery to these streams: the introduction of synthetic nitrogen fertilizer and corresponding development of intensive corn agriculture in the Midwest, and investments in wastewater treatment

* Corresponding author. Tel.: +1 503 251 3200.
E-mail addresses: vjkelly@usgs.gov (V. Kelly), estets@usgs.gov (E.G. Stets), cgcrawfo@usgs.gov (C. Crawford).

http://dx.doi.org/10.1016/j.jhydrol.2015.03.062
0022-1694/Published by Elsevier B.V.

technology. The analysis is essentially exploratory, though rigorous, with the assumption that a descriptive approach is suitable to examine the key patterns of nitrate export within the dynamic context of changing anthropogenic sources, potentially compounded by changing streamflow conditions during this time frame.

The analysis presented here is focused on the following questions: What changes in streamflow and nitrate conditions have occurred over the relevant period of record for these streams? Has the relationship between nitrate concentration/flux and streamflow changed? What kind of seasonal patterns occur? How do changing flow patterns interact with changing nitrate sources to generate patterns of nitrate export?

1.1. Description of study area

Stations were selected from the Century of Trends project of the U.S. Geological Survey (USGS) that compiled historical water-quality data, including nitrate, from a range of streams subject to a diverse set of anthropogenic influences (Stets et al., 2012). Two Midwestern Corn Belt tributaries to the Mississippi River were selected for this analysis: the Des Moines River (referenced to the USGS stream gage at Keosaqua, Iowa) and the Illinois River (the Middle Reach referenced to the USGS stream gage at Peoria, Illinois; hereafter termed the Middle Illinois River). Both the Des Moines River and the Illinois River drain highly agricultural watersheds while the Illinois River is also significantly affected by urban sources since its watershed encompasses the metropolitan area of Chicago (Stets et al., 2012). Nitrate export from both of these rivers is of concern because these basins represent some of the principal source areas for nitrate delivered to the Mississippi River (which is implicated in generating hypoxic conditions in the Gulf of Mexico) despite their relatively small proportion of the total drainage area for the Mississippi River (Goolsby et al., 1999).

The watershed for the Des Moines River encompasses nearly 37,500 km^2, and the area for the Middle Illinois River is comparable in size (about 41,000 km^2, Stets et al., 2012). Streamflow is higher in the Illinois River, averaging approximately 450 cubic meters per second (m^3/s) in the Middle Illinois River during the period of record for this analysis, or about twice that of the Des Moines River, which averaged approximately 210 m^3/s for the comparable period. A factor in the higher water flows in the Illinois River has been the re-engineering in the early 20th century of the Chicago and Calumet Rivers, which carried sewage wastes from the Chicago area, to flow into the Illinois River instead of Lake Michigan to protect the city's drinking water supply (Stets et al., 2012). Additional water has been diverted from Lake Michigan via the Chicago Sanitary and Shipping Canal, beginning in 1900, to further dilute sewage wastes and protect downstream water users.

Human influences reflected in land use and land cover show important similarities and differences between these river basins. Both the Des Moines and Middle Illinois River basins have been predominantly developed as cropland over the entire course of the 20th century (Fig. 1A). At the beginning of the century, more than 70 percent of both basins were in cropland and notwithstanding a decline in the 1930s, this pattern was largely sustained throughout the century (data sources described in Stets et al., 2012). While corn has been grown in these basins throughout the 20th century, its importance has increased significantly since about 1950 (Fig. 1B). This growing dominance of corn production was associated with a change in fertilizer use, which was exclusively from animal sources prior to the development of synthetic nitrogen (N) fertilizer in 1947. As more land was converted to cropland during the late 19th century, the input of nitrogen from animal sources increased as well (Fig. 1C). After the turn of the century, N inputs from animal sources remained fairly consistent, showing a slight decline during the next few decades that was followed by another increase to about the same levels by the 1960s. Much of this was associated with the growing prevalence of confined animal facilities (CAFOs), especially related to hog production in the Des Moines River Basin (Stormont, 2004), although animal sources of N generally declined through the remainder of the century, especially in the Middle Illinois River basin. After 1950, N application from synthetic fertilizer sources increased significantly from essentially zero in both river basins, reaching 4 g/km^2 by 1970 and approximating 6 g/km^2 through most of the 1980s and 1990s (Fig. 1D). With the additional consideration of N contributed from animal sources, the combined areal N input increased to approximately 8 g/km^2 in the Des Moines River in 1997–2001, and approximately 7 g/km^2 in the Middle Illinois for the same period (Stets et al., 2012).

Urban development has exerted a large influence on the Middle Illinois River while little corresponding urban development has occurred in the Des Moines River. Population density increased steadily throughout the 20th century in the Illinois River Basin (exceeding 200 people/km^2 or more than 8 million people in 2000) while remaining consistently lower by an order of magnitude (20 people/km^2 or about 750,000 people) in the Des Moines River Basin (Fig. 1E). In particular, the Chicago metropolitan area has played an important role in determining water quality in the Illinois River, especially since sewage wastes from the metropolitan area were directed to flow into the river instead of Lake Michigan at the turn of the 20th century (Stets et al., 2012).

2. Methods

No perfect analytical method exists to evaluate the available data, which are characterized by data gaps and changing sampling and analytical methods over the course of multiple decades. This analysis utilized a weighted regression of concentration on time, discharge, and season (WRTDS) approach to better extract information from the data without assuming stationary conditions, thereby identifying the general direction of observed changes over time in these long-term datasets (Hirsch et al., 2010). This method constructs a highly flexible statistical model of concentration as a function of time, discharge and season using robust smoothing techniques. Fluxes were then determined from the multiplication of discharge and the estimated concentration derived from the WRTDS model rather than as a function of a regression model, as is more commonly done (Cohn et al., 1992).

The analysis proceeded in several steps, including (1) compilation of data for nitrate concentration and streamflow for the longest coincident time frame that was available; (2) evaluation of streamflow conditions in terms of selected annual flow percentiles to assess seasonal patterns and general changes over time; (3) estimation of nitrate concentrations using a weighted regression approach; and (4) use of estimated concentrations to calculate estimated nitrate loads.

Estimated timeseries of concentrations were examined as a function of streamflow in detail for three years that encompass the full range of WRTDS model results as well as key factors related to the development of excess NO_3 in these streams. While these three years do not capture or fully represent nitrate conditions across the entire period of record, they do provide important insight into conditions at key moments: 1960 (near the beginning of nitrate fertilizer application; 1980 (near the peak of fertilizer application); and 2004 (near the end of the period of study). Patterns of nitrate export (or cumulative load distribution) as a function of streamflow were examined for each of these years to provide some context for potentially changing interactions between export and flow.