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Trend of dissolved inorganic nitrogen at stations downstream from the Three-Gorges Dam of Yangtze River

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ABSTRACT

The TRAMO/SEATS program, combined with the Hodrick–Prescott (HP) filter, was used to detect trends and potential change points in time series of dissolved inorganic nitrogen (DIN) at three stations along the Yangtze River. The trend components were extracted, and two change points were successfully detected. The components revealed that DIN has been increasing at all the stations since the 1990s, although variations exist. Changes visible before 2002 illustrate the differences in agriculture development among regions upstream from the stations. The Three-Gorges Dam (TGD), which began to impound in 2003, led to years of different trends. The DIN concentration, which had been trending upward prior to that date, began a slightly downward trend because of NH_4^+ depletion. Readings at the Yichang station revealed this trend most strongly; those at the Hankou station less so. The Datong station was far enough away from the TGD so that no obvious effects were seen.

1. Introduction

The concentrations (or loads) of various water quality components may have long been monitored at stations in specially designated areas; however, determining whether a trend has occurred in one of these concentrations becomes complicated when various exogenous effects are taken into account. Both natural processes, such as precipitation and seasonality (Qian et al., 2007) and anthropogenic activities, such as altering water flows through the construction of dams and the addition of wastewater effluent, can change trends in water components. Tests for trends in riverine water quality have been of great interest to environmental scientists over the last 10–15 years.

Two major types of trend analysis method exist in the statistical literature: one is based on standard statistical tests, and the other utilizes a time series analysis (Awadallah et al., 2011). Historically, a variety of statistical methods for analyzing discharge effects and seasonality have been developed and applied to evaluate trends in water quality. These include nonparametric methods such as Tobit, Sen's T, Spearman's Rho, Mann-Kendall and the Seasonal Kendall tests (Qian et al., 2007), as well as parametric methods, such as the Regression Method and covariance analysis (Helsel and Hirsch, 2002; Hirsch et al., 1991; Kvaalen et al., 2002). Time series methods, initially developed as tools for the study of signal extraction in economic activities, are able to achieve seasonal adjustments with X-11, X-12 or the TRAMO/SEATS ("Time series Regression with ARIMA noise, Missing values, and Outliers"/"Signal Extraction in ARIMA Time Series") program. This pattern analysis model allows temporal modes to be broken down into seasonal patterns and overall trends. It has been successfully used in the environmental sciences; for instance, a seasonal adjustment for the total dissolved salt concentration series was applied to two main drains in the Eastern Nile Delta (Awadallah et al., 2011). Schoch et al. (2009) evaluated the effects of the Salyersville Reservoir on nitrate concentrations in the Des Moines River using an empirical time-series model. In yet another example, the seasonal patterns extracted using ARIMA analysis were used to show the periodicity of the phytoplankton bloom (Bergamino et al., 2007).

Neither statistical tests nor time series analysis are perfect, however. The main disadvantages of the statistical tests are as follows: 1) To assess a temporal trend on an annual basis, only the means or medians of the monthly values for each year are used as an aggregated measure for the whole year, as in the Man–Kendall test. 2) When removing the effect of exogenous variables, the probability distribution of the exogenous variables is assumed to be unchanged over the period of record. However, if the probability distribution has changed over the period of record, a trend may appear in the residuals but that does not necessarily indicate an

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actual trend. Correspondingly, two types of trends can be identified in trend estimation when using statistical methods. One is a monistic trend, which results in a constant net change over the whole period. The other is a step trend (two sample trend), which can only be used in cases when the record is first divided into "before" and "after" periods at the time of a known event. (for more details please see Helsel and Hirsch, 2002; Hirsch et al., 1991). The main shortcoming of time series analysis is that no statistical test can be used to illustrate the statistical decision (trend or no trend) compared with standard statistical tests (Balchin, 1995).

Considering the possible problems with traditional statistical techniques or time series methods alone, Scott et al. (2011) evaluated long-term trends (1997–2009) in the total P (TP) concentration in the Illinois River in Oklahoma and Arkansas, as well as some of its major tributaries, using flow-adjusted TP concentrations and regression tree analysis. The researchers, using Regression Tress Analysis, sought to identify specific calendar dates for which change points in P trends may have occurred and evaluated trends based on LOESS methods.

Significant disturbances from anthropogenic practices, such as the utilization of mineral fertilizers and discharges of wastes into the Yangtze River Basin (YRB) (Ding et al., 2010; Liu et al., 2003; Müller et al., 2008; Wang et al., 2011) have also caused a dramatic change in the compositions of materials in the Yangtze River. Since 2003, the operation of the Three Gorges Dam (TGD) has resulted in even more drastic alterations, such as changes in the sediments and flow conditions (Chen et al., 2003; Zhang et al., 2012) of the entire ecosystem. The Yangtze River, as a lifeline and ecosystem, has reportedly experienced dramatical degradation in recent decades (Huang et al., 2006; Müller et al., 2008). Export of nitrogen from the YRB of China is receiving increased attention due to concerns regarding excessive nutrient enrichment and eutrophication in streams and development of hypoxic conditions in the Estuary of Yangtze River. Yan et al. (2003) and Duan et al. (2007) have documented the development of N loads since 1958 and have shown that NO_3^- concentrations and fluxes increased about tenfold from 1968 to 1997. Zhang et al. (1999) and Liu et al. (2003) published surveys of concentration levels of nutrients in the whole YRB and found that nutrient levels were relatively low in the upper reaches of the river (>2500 km upstream), peaked at around 2500 km and the decreased to constant levels when reaching the estuary.

One objective in the present study is to provide a methodological example for detecting change points in water quality with seasonality and provide a basis for segmentation in long-term trend analysis at stations of the Yangtze River. The TRAMO/SEATS method was used to remove seasonality and discharge effects and to decompose the time series. Then, the HP filter was applied to discern a trend component out of a decomposed seasonal-adjusted series. Furthermore, in the study, we intend to analyze the factors affecting the dissolved inorganic nitrogen (DIN) concentration and the impacts of the TGD on stations downstream.

2. Materials and methods

2.1. Site description and data collection

The Yangtze River, which flows from west to east before emptying into the East China Sea, has served as a link between the natural world and the people living in the basin. The expansive Yangtze River Basin, which has a catchment area of 1.80×10^6 km^2, can be divided into the upper, middle and lower Yangtze reaches.

Three representative hydrological stations (Fig. 1) were chosen for this study: the Yichang, Hankou and Datong stations. They were selected to represent the upper, middle and lower Yangtze River, respectively (Chen et al., 2001). Ammonium, nitrate, and nitrite at a station were measured once a month across the cross-section, then averaged. The measurements were carried out along the Yangtze River by the Yangtze Water Resources Committee.

The concentrations of DIN, which is the sum of N concentrations in the forms of NH_4^+, NO_2^-, and NO_3^-, were analyzed. For a month when nitrite was not present, the DIN became simply the sum of $NO_2^- + NO_3^-$. Because almost all of the $NO_2^- + NO_3^-$ is in the form of NO_3^-, there is little difference between $NH_4^+ + NO_2^- + NO_3^-$ and $NH_4^+ + NO_3^-$ (Aulenbach, 2006). All concentration data from the 20-year period (1990–2009) were collected from the Changjiang Water Resources Commission (data in the year of 1990 and 1993 were missing from the Hankou station).

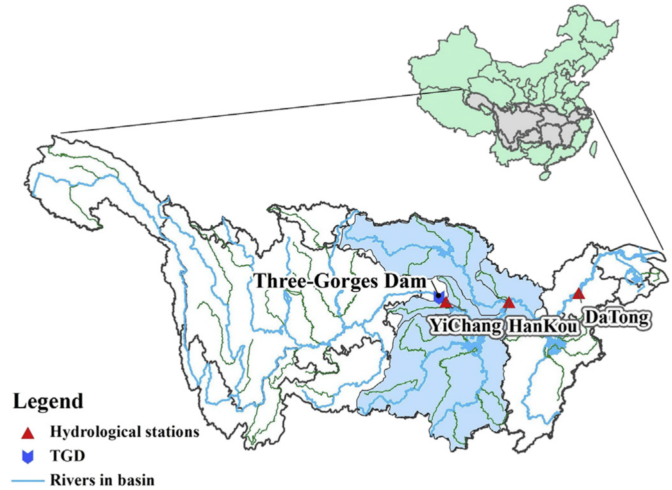

Fig. 1. Locations of the selected hydrological stations in the Yangtze River Basin.

2.2. Trend analysis methods

TRAMO is a widely used program for estimating and forecasting regression models with non-stationary (ARIMA) errors and for any sequence with missing values. SEATS is a program for estimating unobserved components in a time series. It follows the ARIMA-model-based method. The trend, seasonal, irregular, and cyclical components were estimated and forecast with signal extraction techniques applied to ARIMA models. When used for seasonal adjustments, TRAMO pre-adjusts the series that would otherwise be adjusted by SEATS (Gòmez and Maravall, 1996).

The TRAMO program automatically detects and corrects data anomalies. It then automatically selects a model and performs estimations. Both TRAMO and SEATS work best without any user intervention. For more details regarding TRAMO/SEATS techniques, the readers can consult the practical guide developed by Gòmez and Maravall (1996). We focused our attention on SEATS, which revealed most of the distinctive characteristics of the time series. The three regular components (trend-cycle, seasonal, and transitory) that SEATS resolves into a univariate time series model are regarded as the products of the ARIMA processes that are driven by statistically independent white-noise processes.

In this study, the program was used as a trial for water quality data that contained seasonal factors. Afterward, the HP filter (Cogley and Nason, 1995; Kaiser and Maravall, 1999; Pedersen, 2001), a two-sided symmetric moving average filter, was applied to a trend component that was distinct from the trend-cycle series which contained both cyclic and trend components. Once separated, the trend component was used to analyze the long-term trend of the DIN concentration at the three stations. In the HP filter, cycles are defined as a specific bands of frequency. The specific cycle is used to determine the optimal value of the smoothing parameter. The smoothing parameter in this article was chosen to be 14,400 for monthly data as was suggested by Hodrick and Prescott (1997).

Both TRAMO/SEATS and the HP filter processes were performed using Eviews 6.0 software. The total process is described below:

$$\begin{aligned}\text{Original series} &= \text{seasonally adjusted series} \\ &\quad + \text{seasonal component (by TRAMO/SEATS)}\end{aligned} \tag{1}$$

$$\begin{aligned}\text{Seasonally adjusted series} &= \text{trend} - \text{cycle component} \\ &\quad + \text{transitory component (by TRAMO/SEATS)}\end{aligned} \tag{2}$$

$$\text{Trend} - \text{cycle component} = \text{trend component} + \text{cycle component (by HP filter)} \tag{3}$$