Science of the Total Environment 646 (2019) 625–633

Contents lists available at ScienceDirect

Science of the Total Environment

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

Investigating regime shifts and the factors controlling Total Inorganic Nitrogen concentrations in treated wastewater using non-homogeneous Hidden Markov and multinomial logistic regression models

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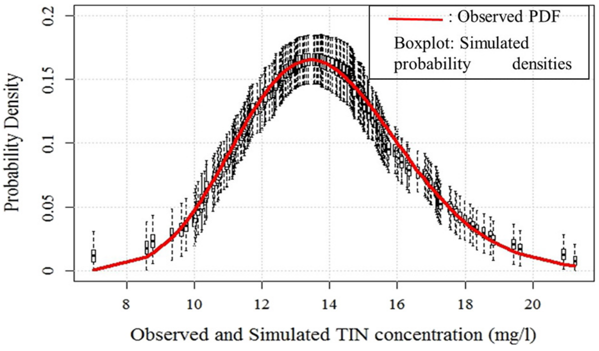
HIGHLIGHTS

- Novel statistical approach to model Total Inorganic Nitrogen (TIN) in treated wastewater
- Model characterizes temporal regimes of TIN with 84% accuracy.
- Climate & seasonality among factors affect temporal regimes of TIN.
- Model simulations successfully capture sample statistics.
- Model simulations also estimate process reliability & compliance.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 21 February 2018
Received in revised form 15 July 2018
Accepted 15 July 2018
Available online xxxx

Editor: Zhen (Jason) He

Keywords:
Total Inorganic Nitrogen
Ammonia-nitrogen
Hidden Markov Models
Multinomial regression
Wastewater
Nutrient regulations

ABSTRACT

Total Inorganic Nitrogen (TIN) in treated wastewaters: the sum of effluent ammonia-, nitrate- and nitrite-nitrogen, is a common regulatory measure of nitrogen removal. In many parts of the United States, regulatory agencies have reduced discharge limits for TIN, recognizing the environmental and health impacts of these species. However, many permit limits are based on annual average or median values, and because temporal variability in effluent TIN is common, may not achieve water quality goals. We created a performance-based modeling approach using Hidden Markov Models and multinomial logistic regression using weekly effluent water quality data from an operating wastewater treatment facility in the US, over the period of January 1, 2010–March 31, 2014. In the two-step modeling approach, Hidden Markov Models capture temporal regime shifts in effluent TIN and multinomial logistic regression identifies prominent factors associated with the regime shifts. Simulations from the proposed Hidden Markov Model and multinomial logistic regression indicate that climate factors (temperature and precipitation), seasonality, effluent total ammonia nitrogen (TAN), and prior weeks' levels of effluent TIN are predictive of effluent TIN concentrations. The hybrid HMM-regression model correctly predicted the states of compliance (state 1) and non-compliance (state 2) with TIN limits with 84% accuracy. Further analysis using model simulations suggest that although annual average or median limits for TIN are met, this plant had a >30% probability of exceeding the annual limit on a weekly time scale, and therefore may not be reliably effective in protecting receiving water quality.

1. Introduction

In the United States, discharge of nitrogen constituents in treated wastewater is typically regulated on the basis of local water quality

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https://doi.org/10.1016/j.scitotenv.2018.07.194
0048-9697/

conditions for protection of aquatic life and domestic water supplies. Historically, limits for total ammonia nitrogen (TAN) reflect risks of toxicity to aquatic life, contributions to eutrophication and dissolved oxygen consumption, and may be readily achieved during conventional aerated secondary treatment. Between 1998 and 2017 the number of States in the US and the District of Columbia enacting statewide criteria for nitrogen and/or phosphorus has more than doubled, from 11 to 24 (USEPA, 2018). Regulation of wastewater discharges remains the most used method of meeting nutrient criteria in surface water so achieving water quality standards will no doubt involve lower discharge limits for nitrogen and phosphorus. In 2010, an article by members of the Chinese Research Academy of Environmental Sciences attributed 90% of pollutant discharge to untreated wastewater and advised special efforts at environmental control of eutrophication (Wu et al., 2010). More recently, broader regulation of all nitrogen species is being considered, recognizing the diverse impacts of nitrate and other oxidized nitrogen species on drinking water quality, as well as the aquatic environment. Total Inorganic Nitrogen (TIN) is typically measured as the sum of TAN, nitrite- and nitrate-N, and nitrate usually is the principal component in plants achieving nitrification (Henze, 1991; Sattayatewa et al., 2009). Pocernich and Litke (1997) examined the relationship between effluent TAN and nitrate + nitrite-nitrogen for treatment plants discharging into the South Platte River in Colorado using linear regression for data from 40 plants with highly variable levels of effluent ammonia (1 to 18 mg/l) and nitrate + nitrite (0.02–19.8 mg/l) and found a negative relation between the two variables ($R^2 = 0.78$). However, the relatively small dataset ($n = 12$) produced large prediction errors (estimated 95% confidence interval was ±6 mg/l nitrite + nitrate-N).

Removal of nitrate via biological denitrification requires maintenance of an anoxic region in the activated sludge process sequence, and often the addition of an organic carbon source. Thus, achieving low levels of TIN in treated wastewater requires special equipment for mixing and recirculation, more complex operation, and additional costs (Colorado Department of Public Health and Environment (CDPHE), 2012; Oleszkiewicz and Barnard, 2006; Symbiont, 2011).

In general, US regulatory limits for nitrogen in treated wastewater are based on local water quality criteria. Very few states, including Colorado, have imposed statewide permit limits for the more easily measurable constituents of TIN, expressed as the sum of TAN, nitrate and nitrite (Colorado Department of Public Health and Environment, 2012). In 2008, the Natural Resources Defense Council (NRDC) and others petitioned the USEPA to write a national regulation for nitrogen in treated wastewater based on secondary treatment capability (Hubertz et al., 2008). In 2012, the Administrator of the EPA officially declined to issue such limits (Shapiro, 2012). Other countries have taken a more universal approach to limiting nutrients discharged from wastewater. The Netherlands has a requirement that wastewater treatment facilities must remove at least 75% of influent nitrogen and phosphorus, achieving a range of effluent total nitrogen from 6 to 8 mg/l (Hendriks and Langeveld, 2017). In 1991, the Council of European Communities adopted limits for total nitrogen of 15 mg/l for plants serving 10,000 to 100,000 population equivalents (p.e.) and 10 mg/l for plants serving >100,000 p.e. as an average of 12 or 24 samples per year depending on p.e. served by the facility. An alternate limit of 20 mg/l total nitrogen for daily samples was suggested for the larger facilities (Council of European Communities, 1991). In 2003, China has set national limits for treated wastewater total nitrogen at three levels: an older 1-B level was 20 mg/l; the current 1-A level is 15 mg/l for control of eutrophication, and a future limit of 5 mg/l is an "expectation." (Qiu et al., 2010). In countries with a smaller number of treatment facilities per population, nutrient discharge standards tend to be less stringent. In Brazil, for example, the national limit for TAN is 20 mg/l, with no limits for nitrate (von Sperling, 2016). The State of Colorado Regulation #85 limit of 15 mg/l TIN is comparable to a number of international standards for wastewater (Colorado Department of Public Health and Environment, 2012). However, because the international limits typically include organic nitrogen with limits for total nitrogen (TN), they are more conservative than the Colorado limit for TIN.

In the US, monitoring and regulation have a temporal characteristic (USEPA, 2010). Even average or median annual discharge limits are based on temporal data collected at varying frequencies from daily to monthly (USEPA, 2010). Particularly water quality based effluent limits for constituents that can be toxic to aquatic life have acute limits based on daily maxima. Effects on eutrophication and maintenance of aquatic life are often seasonal implying the need for temporal analysis of treatment performance based on variations in temperature, streamflow, and stages of aquatic life (Rossman, 1989). Finally, compliance and enforcement have temporal characteristics, which are important to wastewater utilities (Andreen, 2007; Suchetana et al., 2017; USEPA Office of Inspector General, 2001). For example, enforcement actions, including fines for permit violations are based on the number of incidents over a prescribed period. Also, it can be expected that a sequence of high levels of discharged nitrogen within a short period will have quite different water quality impacts than the same number of events spaced over a longer period (Weirich et al., 2015a). Finally, a treatment plant's ability to recover from a sequence of discharge exceedances may be quite different from a singular discharge violation (Weirich et al., 2015a).

Because of the increased focus on the control of effluent TIN in the US, a lack of understanding of its temporal variability and a significant gap in existing literature regarding the same, we were motivated to investigate the feasibility of a performance-based model to model and predict the temporal variability in effluent TIN concentration. We used data from an operating wastewater treatment facility in Colorado, United States over the period of January 1, 2010–March 31, 2014. This facility has treated an average flow of 47,320 m^3/day (12.5 million gallons per day (MGD)) over the sample period and has a design capacity of 94,635 m^3/day (25 MGD), serving a population of approximately 114,000. The data included daily average influent flow rates and measures of effluent concentrations of total ammonia-N (TAN), nitrate-N, and nitrite-N from daily grab samples. Previous research has shown a strong temporal persistence in wastewater plant treatment behavior on a monthly average basis (Suchetana et al., 2017, 2016; Weirich et al., 2015a). Because some daily measures of nitrogen species, notably nitrite, were missing, we used weekly average values, and therefore Total Inorganic Nitrogen (TIN) concentration is measured as the sum of 7-day averages of effluent TAN, nitrate and nitrite concentrations. Fig. 1 shows the time series plot of standardized average weekly effluent TIN, where standardization refers to the process of subtracting the sample mean from each observation, and dividing the difference by the sample standard deviation. Standardization of variables enables us to study their variations or fluctuations about the sample mean. From Fig. 1, we observed that the standardized effluent TIN time series exhibited regime-like behavior about the mean or average concentration (represented by the value 0 in Fig. 1); i.e., consecutive weeks when

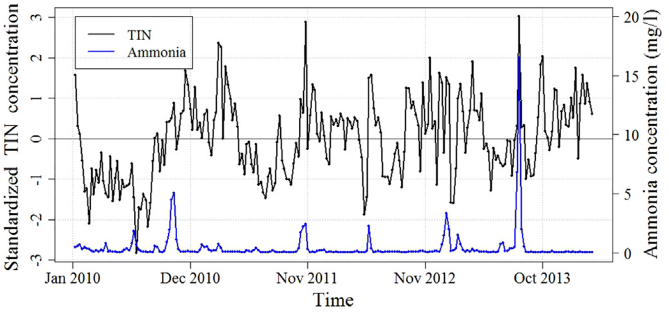

Fig. 1. Standardized average weekly effluent TIN concentrations, as obtained from an operating wastewater treatment facility in Colorado, US over the period of January 1, 2010–March 31, 2014. The blue line indicates the corresponding average weekly effluent ammonia concentrations (ammonia concentration scale on right side of figure). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)