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Improving management of windrow composting systems by modeling runoff water quality dynamics using recurrent neural network

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ABSTRACT

The recurrent neural network is a tool that can provide valuable insights when forecasting future likelihood of events using dynamic time series. One of the challenging research problems is to extend the black-box modeling into white-box modeling in order to gain insights into the physical processes. Sensitivity analysis has shown a great contribution in overcoming this challenge. The main objective of this study was to perform a detailed sensitivity analysis of recurrent neural network in order to identify parameters that are important for predicting water quality constituents.

We used a windrow composting pad located at UGA Bioconversion center, Athens, GA, USA as our study site. Runoff from windrow composting pad was collected in order to prevent the discharge of organic pollutants. We used time series data from nine years of precipitation, temperature, pond volume, material volume on the pad, total suspended solids (TSS), biological oxygen demand (BOD) and nitrate (NO_3) concentration levels of stored runoff in the collection pond.

Previously, we applied recurrent neural network for predicting TSS, BOD and NO_3 as well as performed auto-correlation and cross-correlation analysis (Shim and Tollner, 2014). We used first eight years of data (from January 2001 to December 2008) to build the model and last year of data (from January 2009 to December 2009) to evaluate the model. Within this paper, we showed that the detailed sensitivity analysis of recurrent neural network can allow a better understanding of water quality dynamics of collected runoff and assist in identifying strategies for better management of windrow composting systems.

1. Introduction

Application of neural networks showed extreme growth in different research areas, including water management. Nourani and Fard (2012) used artificial neural networks in order to model evaporation process. Garbrecht (2006) used ANN for rainfall-runoff modeling Toth et al. (2000) applied neural networks for flood forecasting. In the field of water quality modeling, Schmid and Koskiaho (2006) applied static ANN known as a multilayer perceptron (MLP) type of neural network for the modeling of dissolved oxygen in a wetland pond. Milot et al. (2002) studied contribution of MLP (or feedforward neural network (FFNP)) for modeling trihalomethanes occurrence in drinking water. Verma et al. (2013) implemented MLP network for predicting total suspended solids (TSS) in wastewater. Suen and Eheart (2003) evaluated performance of radial basis function (RBF) neural network (a type of statistical neural network) for modeling nitrate concentrations in a river. Singh et al. (2009) constructed FFNP for computing dissolved oxygen (DO) and biological oxygen demand (BOD) of the river water. Also, they adopted FFNP approach for predicting BOD and chemical oxygen demand (COD) levels in wastewater treatment plant effluent (Singh et al., 2010).

Recurrent neural network (RNN) is a type of artificial neural networks that captures non-linear dynamics of time series. An architectural approach of RNN with embedded memory, "Nonlinear Autoregressive model with exogenous input" (NARX) demonstrated promising qualities for modeling of nonlinear dynamic systems (Xie et al., 2009). Pisoni et al. (2009) used NARX neural networks for forecasting peak of ozone concentration in their air pollution study. Jeong et al. (2001, 2006) applied RNN model for predicting phytoplankton dynamics in a river. Moreover, Liu et al. (2013) adopted RNN for forecasting suspended sediment concentration in a river system. However, to our knowledge, very few studies applied NARX network for predicting water quality parameters of collected runoff from open windrow composting systems.

Windrow composting systems are alternatives for degrading organic pollutants while preserving opportunities for beneficial

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reuse. The main advantage of composting pad application is the avoidance of environmental impacts associated with uncontrolled organic pollutants, such as leachate and methane production (Dorahy et al., 2009). Having a composting option is important for certain industrial sectors of interest to state of Georgia. Outreach personnel in Georgia estimate that there are forty to fifty windrow composting facilities in the state. However, open windrow composting systems allow direct rainfall on its surface (Dorahy et al., 2009). Typically, windrow composting systems are located in remote areas and runoff cannot be directly treated in a wastewater treatment plant. The main challenge in managing the windrow composting systems is that water quality of pond effluent often exceeds regulatory limits. Pad runoff is highly regulated by U.S. Environmental Protection Agency (EPA) and Georgia Department of Natural Resources (GA DNR) due to pollution potential (Kalaba and Wilson, 2005; Wilson et al., 2004). TSS and BOD regulatory limits are 90 mg/L and 50 mg/L, respectively. Therefore, better management of windrow composting pad is needed in order to meet the regulations for pond effluent.

In our previous study, we showed that a multiple-output neural network demonstrated a better performance than a single-output neural network. We applied RNN for forecasting runoff water quality constituents such as Total Suspended Solids (TSS), Biological Oxygen Demand (BOD) and NO_3 (nitrate) levels from windrow composting pad (Shim and Tollner, 2014). We also performed autocorrelation and cross-correlation analysis in order to identify the time series trends and correlations between the variables. One of the challenging research problems in neural network modeling is the black-box nature of this method (Maier and Dandy, 2000). Jeong et al. (2006) conducted sensitivity analysis in order to explain phytoplankton dynamics using meteorological, hydrological, physical and chemical parameters.

In this paper, we used our previously developed model (Shim and Tollner, 2014) and performed sensitivity analysis using Garson's Algorithm (Garson, 1991), Olden's Method (Olden and Jackson, 2002; Olden et al., 2004), Lek's Profile Method (Lek et al., 1996) and R^2-based metric (Giam and Olden, 2015). Additionally, we extended Lek's Profile Method by adopting Sensitivity for Simultaneous Movement of Parameters (SSMP) method from Kim et al. (2007). SSMP method allowed us extend and better interpret the neural network model as well as describe the relationship between multiple inputs and output variables. As a result, the detailed sensitivity analysis allowed us to gain better insights into the system dynamics behavior and provide recommendations for effective windrow composting pad management.

The main objectives of this study were:

a) to extend the application of multiple-input-multiple-output NARX RNN;
b) to perform detailed sensitivity analysis of RNN in order to identify parameters that are important for predicting water quality constituents;
c) to better understand the dynamics of the system by ranking the input parameters and quantifying their influence on water quality prediction;
d) to suggest strategies for effective management of windrow composting systems.

2. Materials and methods

2.1. Windrow composting site characteristics

We used the windrow composting pad located at UGA Bioconversion center, Athens, GA, USA as our study site (Fig. 1). The compost material typically shows properties of being hydrophilic as approximately 15–20% of rainwater reaching a compost pile is released as surface runoff. The pad with a particle size concentration of 33% sand and 67% gravel sits on top of a tightly compacted Cecil sandy clay loam. The catchment pond has the maximum infiltration rate of less than 3.175 mm/day due to an installed clayed lining (Tollner and Das, 2004). Land application system (LAS) is a method for discharging effluent of a collection pond in order to prevent the discharge of organic pollutants. More detailed information of composting pad characteristics can be found in previous studies of Duncan et al. (2013a,b).

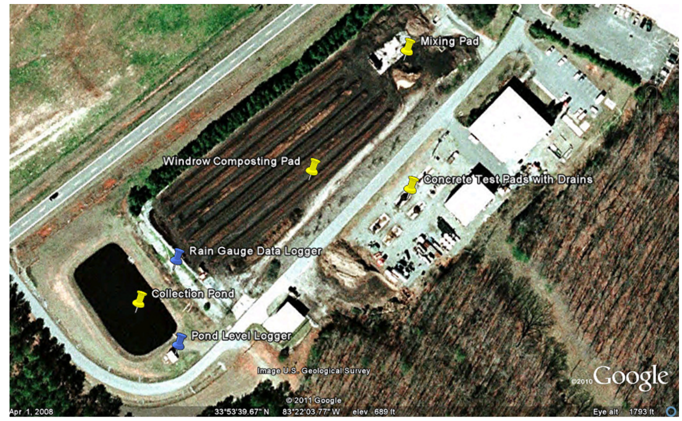

Fig. 1. Google Earth (© 2010) overhead view of the windrow composting pad at the UGA Bioconversion Center (Duncan et al., 2013a).

2.2. Observation data and descriptive statistics

We used time series data from nine years (2001–2009) of precipitation, air temperature, pond volume, material volume on the pad, total suspended solids (TSS), biological oxygen demand (BOD) and nitrate (NO_3) concentration levels of stored runoff in the collection pond. The Georgia Environmental Protection Division mandates collection, sample handling and analysis. Daily data of precipitation and temperature represent observations from Georgia Automated Environmental Monitoring Network (GA AEMN) site weather station. Weather data follows Quality Control of National Oceanic and Atmospheric administration (NOAA). Daily data of pond volume were obtained from gauge readings of pond stage. A surveyor employed by the Grounds Department at UGA collected monthly data of material volume on the pad using photogrammetric techniques. For water quality parameters data, monthly water samples of 1 L were collected in Nalgene containers at the site and sent to the UGA Feed and Environmental Water laboratory for analysis. The samples were analyzed according to Standard Methods for the Examination of Water and Wastewater as well as Methods for Chemical Analysis of Water and Wastes. Water samples were analyzed for TSS and BOD every month and for NO_3 each quarter. Detailed description of data collection and water quality analysis can be found in the previous study of Shim and Tollner (2014).

Supplementary data in Appendix A (Figs. A1–A7) represent time series data of precipitation, air temperature, pond volume, material volume on the compost pad, TSS, BOD and NO_3 at monthly resolution. Additionally, each figure contains yearly and monthly box-plots along with a histogram. For Figs. A1–A7, daily precipitation was monthly cumulated, daily air temperature and daily pond volume were monthly averaged. Additionally, quarterly nitrate data were interpolated to obtain uniform monthly data set.

Fig. A1 demonstrates that high precipitation levels usually occur during winter months whereas extreme storm events tend to appear during summer. As it is expected, air temperature has a seasonal pattern with the highest temperature usually observed in