ARTICLE IN PRESS

Geoscience Frontiers xxx (2016) 1–11

Contents lists available at ScienceDirect

China University of Geosciences (Beijing)

Geoscience Frontiers

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

Research paper

A comparative analysis among computational intelligence techniques for dissolved oxygen prediction in Delaware River

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A R T I C L E I N F O

Article history:
Received 13 February 2016
Received in revised form
9 April 2016
Accepted 30 April 2016
Available online xxx

Keywords:
Dissolved oxygen
SVM
LGP
ANN
Modeling

A B S T R A C T

Most of the water quality models previously developed and used in dissolved oxygen (DO) prediction are complex. Moreover, reliable data available to develop/calibrate new DO models is scarce. Therefore, there is a need to study and develop models that can handle easily measurable parameters of a particular site, even with short length. In recent decades, computational intelligence techniques, as effective approaches for predicting complicated and significant indicator of the state of aquatic ecosystems such as DO, have created a great change in predictions. In this study, three different AI methods comprising: (1) two types of artificial neural networks (ANN) namely multi linear perceptron (MLP) and radial based function (RBF); (2) an advancement of genetic programming namely linear genetic programming (LGP); and (3) a support vector machine (SVM) technique were used for DO prediction in Delaware River located at Trenton, USA. For evaluating the performance of the proposed models, root mean square error (RMSE), Nash–Sutcliffe efficiency coefficient (NS), mean absolute relative error (MARE) and, correlation coefficient statistics (R) were used to choose the best predictive model. The comparison of estimation accuracies of various intelligence models illustrated that the SVM was able to develop the most accurate model in DO estimation in comparison to other models. Also, it was found that the LGP model performs better than the both ANNs models. For example, the determination coefficient was 0.99 for the best SVM model, while it was 0.96, 0.91 and 0.81 for the best LGP, MLP and RBF models, respectively. In general, the results indicated that an SVM model could be employed satisfactorily in DO estimation.

1. Introduction

Dissolved oxygen (DO) concentration reflects the equilibrium between oxygen-producing (e.g., photosynthesis) and oxygen-consuming (e.g., aerobic respiration, nitrification, and chemical oxidation) processes in aquatic ecosystems. It depends on many factors such as temperature, salinity, oxygen depletion, oxygen sources, and others (Kalff, 2002; YSI, 2009). DO level is the criterion of health (Rankovic et al., 2010), which is frequently used for water quality control at different aquatic systems such as reservoirs and wetlands (Singh et al., 2009; Ay and Kisi, 2012; Kisi et al., 2013).

The water quality modeling using either deterministic (Garcia et al., 2002; Hull et al., 2008; Shukla et al., 2008) or stochastic approaches (Boano et al., 2006) recently received great attention because of its important role in human and environment health. Owing to the dynamic feature of DO concentration, especially in rivers and wetlands, it is greatly advisable to generate DO models for aquatic ecosystems periodically, so that quality control measures can be optimized throughout a time horizons. To this end, implementation of different artificial intelligence (AI) techniques were suggested in the relevant literature.

Since 1990s, based on the understanding of the brain and nervous systems, artificial neural networks (ANNs) have been gradually used in hydrological predictions. An ANN learns to solve a problem by developing a memory capable of correlating a large number of input patterns with a resulting set of yields. They operate like a "black box" model, requiring no detailed information about the system (Ahmed et al., 2013). One of the most important

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Peer-review under responsibility of China University of Geosciences (Beijing).

http://dx.doi.org/10.1016/j.gsf.2016.04.007

advantages of ANNs is their ability to handle large and complex systems with many interrelated parameters (Nourani et al., 2011). An extensive review of its use in hydrological field was given by ASCE Task Committee on application of ANN in hydrology (ASCE, 2000). Different ANN algorithms were applied for water quality modeling. For example, Schmid and Koskiaho (2006) investigated the accuracy of various multi-layer perceptron (MLP) algorithms to forecast DO concentration in Finland. Singh et al. (2009) modeled DO concentration and biological oxygen demand (BOD) in the Gomti River in India using three-layer feed forward neural networks (FNN) with back propagation learning. FNN algorithm was also implemented by Rankovic et al. (2010) to predict DO in Gruza Reservoir, Serbia. Ay and Kisi (2012) compared efficiency of two different ANN algorithms in DO prediction in Foundation Creek, Colorado. Antanasijević et al. (2013) developed three different ANN architectures to improve the performance ANN modeling in DO concentration in the Danube River. More recently, back propagation neural network (BPNN) and adaptive neural-based fuzzy inference system (ANFIS) were applied by Chen and Liu (2014) to estimate the DO concentration in the Feitsui Reservoir of northern Taiwan. All of the abovementioned studies demonstrated that different ANN algorithms can be used as a satisfactory tool for DO modeling. However, explicit formulation of DO for the ecosystem of the interest remains as a problem.

Genetic Programming (GP) is another AI-based technique commonly used for hydrological predictions at nonlinear systems. The GP technique is a relatively new technique compared to ANN. The most powerful feature of GP is that the user can easily obtain an explicit program/formula of the relation between the inputs and output, which makes GP more interesting for hydrologists and practitioners (Guven and Kisi, 2013). Since the general review of GP application in water engineering is out of the scope of our study, the interested researchers can refer Ghorbani et al. (2010), Guven and Azamathulla (2012), and Traore and Guven (2013). This study specifically focuses on a new branch of GP, called Linear Genetic Programming (LGP).

Since the last decade, LGP has been pronounced as a new robust method to solve wide range of modeling problems in water engineering and has been limitedly used in estimation hydrological parameters (e.g., Guven, 2009; Guven et al., 2009; Kisi and Guven, 2010; Danandeh Mehr et al., 2013, 2014a,b and c). Guven (2009) applied LGP, a variant of GP, and two versions of neural networks for prediction of daily flow of Schuylkill River in the USA and showed that the performance of LGP was moderately better than that of ANN. Danandeh Mehr et al. (2013) applied LGP in comparison with a neuro-wavelet technique in time series modeling of stream flow on Coruh River in Turkey. Londhe and Charhate (2010) used ANN, GP and Model Trees (MT) to forecast river flow one day in advance at two stations in Narmada catchment of India. The results showed the ANNs and MT techniques performed almost equally well, but GP performed better than its counterparts. Marti et al. (2013) applied ANN and Gene Expression Programming (GEP) based models to estimate outlet DO in micro-irrigation sand filters. Also, Kisi et al. (2013) investigated the ability of GEP, ANFIS and ANN techniques in modeling DO concentration and showed that the GEP model performed better than the ANN and ANFIS models in modeling DO concentration.

Recently another mathematical tool, the Support Vector Machine (SVM), has been used in hydrology. The SVM is based on structural risk minimization (SRM) principle and is an approximation implementation of the method of SRM with a good generalization capability (Vapnik, 1998). Although SVM has been applied for a relatively short time, this learning machine has been proven to be a robust and competent algorithm for both classification and regression in many disciplines. Recently, the use of the SVM in water resources engineering has attracted much attention. Dibike et al. (2001) demonstrated its use in rainfall–runoff modeling. Liong and Sivapragasam (2002) applied SVM to flood stage forecasting in Dhaka, Bangladesh and concluded that the accuracy of SVM exceeded that of ANN in one-lead-day to seven-lead-day forecasting.

Sivapragasam and Muttil (2005) extended the rating curves developed at three gauging stations in Washington by SVM. Khan and Coulibaly (2006) applied SVM to predict future water levels in Lake Erie. Yu et al. (2006) successfully explored the usefulness of SVM based modeling technique for predicting of real-time flood stage forecasting on Lan-Yang River in Taiwan 1–6 h ahead. Cimen (2008) used SVM to predict daily suspended sediments in rivers. Wu et al. (2008) used a distributed support vector regression for river stage prediction. Wang et al. (2009) developed and compared several AI techniques include ANN, neural-based fuzzy inference system (ANFIS), GP and SVM for monthly flow forecasting using long-term observations in China. Their results indicated that the best performance can be obtained by ANFIS, GP and SVM, in terms of different evaluation criteria. To the best knowledge of the authors, there is not any published study indicating the input–output mapping capability of LGP and SVM techniques in modeling of DO concentration for rivers.

Therefore, the present study is focused on construction of different computational intelligence models, such as two different ANN models, namely, the MLP and RBF, and LGP and SVR to predict the DO concentration at a particular river water using a hydrochemical data set. The obtained results are finally compared to each other. For this purpose, based on a gauging station records, we put forward six black-box ANN structures as reference models for DO concentration prediction on Delaware River located at Trenton, NJ (USGS Station No: 01463500), USA. Then LGP and SVM were applied to model the reference scenarios. These methods offer advantages over conventional modeling, including the ability to handle large amounts of noisy data from dynamic and nonlinear systems, especially, when the underlying physical relationships are not fully understood. Ultimately, both accuracy and applicability of ANN, LGP, and SVM techniques were discussed via the comparison of their performances. It is relevant to note that the models investigated in this study are normally applied within deterministic frameworks in professional practices, which encouraged the practice of comparing the actual with predicted values. Therefore, the paper presents a comparative study on new generation computational intelligence approaches in DO modeling.

2. Methodology

2.1. Multilayer perceptron

The MLP neural network, which is a feed forward neural network with one or more layers between input and output layer, is the second most flexible mathematical structure patterned after the biological nervous system. It is a massive parallel system composed of many processing elements connected by links of variable weights (Lippman, 1987). The feed-forward MLP among many ANN paradigms is by far the most popular, which usually uses the technique of error back propagation to train the network configuration. Feed forward means that data flows in one direction from input to output layer (forward). This type of network is trained with the back propagation learning algorithm. The MLPs are widely used for pattern classification, recognition, prediction and approximation. Multilayer perceptron can solve problems which are not linearly separable. Also, the activation function consists of a sigmoid function in the hidden layer and a linear function in the output layer. It has been reported that MLP with this configuration