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Applications of Neural Networks and Fuzzy Logic for Integrated Water Management: Review of Theory and Applications

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Abstract

In this paper, applications of two mostly widely used particular types of data-driven models, namely artificial neural networks (ANN) and fuzzy logic-based models, to modeling in the water resources management field are considered. Neural network and fuzzy logic have been successfully applied to a wide range of problems covering a variety of sectors. Their practical applications, especially of neural networks expanded enormously starting from mid 80s till 90s partly due to a spectacular increase in computing power. During the last decade ANN evolved from being only a research tool into a tool that is applied to many real world problems: physical system control, various engineering problems, statistics, medical and biological fields. Consequently they are applied more and more in water management field as well. This paper reviews the applications of neural network and fuzzy adaptive systems for integrated water resources management.

Keywords*: Artificial neural network, fuzzy logic, water quality management.*

1. Introduction

1.1. ANN and Fuzzy logic techniques for water management

A wide range of application of ANN and Fuzzy logic techniques has been investigated in the field of water resources management. The water resources management is a highly complex issue covering a wide spectrum of activities in the field of assessment, planning, designing, operation and maintenance. Water quality management problem is mostly based on imprecise and insufficient information. Most of the time, goals or constraints may not be defined precisely due to the fact that they are based on ill-defined and subjective requirements of human judgement or preferences. Although, the numerical models are available for water quality simulation, the uncertainties and imprecision are not well covered in those models. Furthermore, the need for calibration of water quality models makes the neural networks advantageous over these models. Range of this type of problem varies from water quality of subcatchment surface water to water quality of the urban drainage and drinking water supply systems.

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2. Artificial neural network

ANN models emulate biological neurons to solve complex problems in the manner similar to the human brain. In the early 1940's, McCulloch and Pitts (1943), studied the potential and capabilities of interconnecting several basic components based on the model of a neuron. Later, Hebb (1949) studied the adaptation laws involved in neural systems. Rosenblatt (1958) coined the term 'Perceptron' and devised an architecture, which received much attention. Minsky and Papert (1969) introduced a rigorous analysis of the Perceptron and they proved many properties and pointed out limitations of several related models. In the 1970s, the work of Grossberg (1976) came to prominence. In the period 1980's onwards, the interest in studying the mechanism and structure of the brain has been increasing. This increasing research interest has led to the development of new computational intelligence models, *i.e.*, ANN models for solving complex problems like pattern recognition and fast information processing and adaptation.

2.1. Applications of Neural networks in the water sector

2.1.1. Drinking water systems

Prediction of drinking water consumption is not an easy task, there might be many influencing factors on the subject. Only few water supply companies in the Netherlands use automated prediction models. Moreover, the accuracy of the prediction by these models is not always satisfactory, particularly during the peak consumption period on the daily basis, the error level reaches 25%. Aafjes *et. al* (1997) investigated a short term prediction of community water consumption by ANN, traditional expert system and combination of ANN and expert system. Water consumption data of Friesland for two years have been used for the study. For neural network model development, 5 variants have been studied to relate the predicted water consumption to the previous 1 to 7 days' consumption data. The hourly consumption data for previous day and hourly consumption of the same day one week before, together as input variables gave the best result. Also the day of week is given as input because the water consumption may vary on different days of week. Obviously the climate characteristics are one of the influencing factors for water consumption. Therefore, the measured data such as air pressure, global radiation, temperature and the precipitation are included as well. The accuracy of neural network based prediction of water consumption is considered as fair to good. For short-term prediction, the comparison of ANN model's result with the conventional statistical analysis based model's (ARIMA) result shows an improvement in the ANN model.

2.1.2. Drinking water quality

In water quality control, the estimation of water quality evolution from the treatment plant to the consumer's tap is an important issue. During the water transportation through the distribution network, the residual chlorine concentration guarantees microbiologically safe water quality. The residual chlorine concentration diminishes due to the reactions within the pipeline. The comparative study of conventional first order modeling approach and ANN model on the residual chlorine evolution is carried out by Rodriguez *et al* (1997). The obtained results of ANN model show high accuracy and make the combinations of the two approaches as promising in this particular field of research.

Zhang and Stanley (1997) investigated the problem of forecasting of raw water quality coming to the treatment plant using neural network model. In order to meet the changes in incoming water quality and supply high quality water to the consumers by adjusting the treatment processes in an optimal manner, it is desirable to know the quality of incoming water in advance. By previous research it was found that the colour of raw water and turbidity are the most important parameters to affect the treatment processes. To predict the colour of water, the inputs to the neural network model are turbidity, river flow rate, precipitation at a meteorological station located upstream in the basin and their derivatives. The result of ANN model is found to be promising and it may serve as a solid ground for real-time operation such as computerised coagulation dosing control.

3. Fuzzy logic

FL is a form of multi-valued logic derived from fuzzy set theory that deals with reasoning, which is approximate rather than precise. In contrast to yes/no or 0/1 binary logic, FL provides a set of membership values inclusively between 0 and 1 to indicate the degree of truth (fuzzy). In agricultural process modelling and control systems that are ill-defined and with uncertainties can be modelled with a Fuzzy Inference System (FIS) employing fuzzy 'If–Then' rules to quantify human knowledge and reasoning processes without employing precise quantitative analyses. The FIS should include the following functional blocks (Jang, 1993):

• Fuzzification interface that transforms the crisp inputs into degrees of match with linguistic values;
• Knowledge base that includes
◦ Rule-base containing a number of fuzzy 'If–Then' rules;
◦ Database that defines the membership functions of the fuzzy sets used in the fuzzy rules;
• Decision-making unit that performs the inference operations on the rules; and
• Defuzzification interface that transforms the fuzzy results of the inference into a crisp output.

The fuzzy systems are advanced techniques for handling imprecision in soft computing.

3.1. Applications of fuzzy logic approaches

3.1.1. Water quality analysis

As mentioned before, water quality problem has many inherent uncertainties and fuzzy logic approach is particularly suitable for uncertain problems with imprecise information. Water quality standards can be defined by smoother transitions from desirable to unsuitable quality levels. Comparative study on the use of fuzzy logic and multiple regression analysis for chemical water quality analysis and taste tests are carried out by Iwanaga *et al* (1997). The study was carried out on a data set with several varieties of high quality water in Japan. The correlation analysis was carried out to investigate whether the standards for chemical evaluation confirm the national standard. The multiple regression formula was used for judging the water quality for the other regions. And the fuzzy inference was applied to build a predictive model for judging water for all the regions in the country. The both results are compared and it was found that the performance of the fuzzy logic approach was better than the conventional predictive model.

4. Neuro-fuzzy and hybrid approaches

In the preceding theory, some of the successful applications of the fuzzy logic approach were presented. The applications show the advantages of the fuzzy logic approach where the conventional model based approaches are difficult to be implemented. Unfortunately, with the increase in the complexity of the process being modeled, the difficulty in developing dependable fuzzy rules and membership functions increases. This has led to the development of another approach which is mostly known as neuro-fuzzy or fuzzy-neuro approach. It has the benefits of both neural networks and fuzzy logic and is attracting an army of researchers in this field. The neuro-fuzzy hybrid system combines the advantages of fuzzy logic system, which deal with explicit knowledge that can be explained and understood, and neural networks, which deal with implicit knowledge, which can be acquired by learning. Basically, there are different hybrid development strategies that can be distinguished concerning the integration of the techniques. In total, there are five hybrid development strategies that have been identified (Medsker, 1995):

- stand alone (non-interactive, independent software components)
- transformational (same with the stand-alone, but the system begins with one of the technique and finishes with the other type of technique as a result of transformation)
- loose coupling (separate intelligent systems that communicate through data files, such as pre-processors, postprocessors, coprocessors and user interfaces)
- tight coupling (separate systems pass information through the memory resident data rather than the external files, basically the shared data structures that facilitate interactive problem solving via the independent agents)
- full integration (the systems share data structure and knowledge representation.

4.1. Application of neuro-fuzzy systems

4.1.1. Drinking water systems estimation of state of water distribution network

In a water distribution network, the system state is estimated on the basis of the telemetry measurements and the prediction of consumption (called as pseudo measurements). Both of the requirements can have high level of uncertainties. The above measurements are used to determine the state of the system through a mathematical modeling, of which the performance is not always guaranteed due to uncertainties in the input parameters of the model. There are two types of faults or uncertainties in such a system: measurement errors caused by equipments and topological errors caused by faults due to the leakage and wrong valve status. Measurement errors are not correlated and thus the measurements with error can be discarded. But the detection and identification of topological errors are still not studied comprehensively. The Generalised Fuzzy Min-Max Neural Networks (GFMM NN) approach for clustering and classification is applied for this purpose (Gabrys and Bargiela, 1999). This is a fully integrated hybrid structure. The neuro-fuzzy recognition system is used to identify and detect a leakage in the system. The training data set is generated by the system state estimation procedure combined with the Confidence Limit Algorithm (CLA) for the quantification of inaccuracies of system state estimation due to uncertainties in input data. Generation of the training data set of the networks is done in 3 stages: simulation of the state, estimation of accurate measurements and the CLA. Leakage of the system is simulated as a demand between two nodes and not as a pressure difference. Reservoir inflows and the other network consumption are adjusted to compensate the additional demand. The wrong operation of a valve is simulated in a way that the valves those are usually open, remain as closed. The recognition system developed is a two-level system where the first level is to distinguish the typical behaviour of the system (such as night load, peak load etc.) and the second level is to detect the anomalies. The result of this approach shows that the neuro-fuzzy system can be trained successfully for the estimated system-state as well as the residuals with their confidence limit. Both have advantages and disadvantages, however, the simulation of a system based on the estimated system state gives better results in terms of accuracy.

Conclusion

ANN and Fuzzy logic techniques are applied to a large number of problems in the water management field. They are mostly applied in the following areas:

- Water quality management such as sewer water quality, urban storm water quality, water quality in a pipe network, drinking water system etc.
- Planning such as community water demand prediction etc.

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