The use of mathematical models in teaching wastewater treatment engineering

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Abstract Mathematical modeling of wastewater treatment processes has become increasingly popular in recent years. To prepare students for their future careers, environmental engineering education should provide students with sufficient background and experiences to understand and apply mathematical models efficiently and responsibly. Approaches for introducing mathematical modeling into courses on wastewater treatment engineering are discussed depending on the learning objectives, level of the course and the time available.

Keywords Education; environmental engineering education; mathematical modelling; teaching tools; wastewater treatment

Introduction

In recent years, mathematical modeling of wastewater treatment processes has become an accepted tool in engineering practice and is extensively used by consulting companies and regulating agencies. Application of mathematical models ranges from research to treatment plant design, operation, control, and troubleshooting. Universities must provide students with sufficient background so that they can make efficient and responsible use of these mathematical models. In addition to preparing students for their future job requirements, mathematical modeling can be integrated into university curricula to enhance teaching of basic courses through computer-aided learning. A variety of different modeling approaches and software packages are available today. Most of these models and software tools, however, were developed for research applications or for practical applications in consulting companies and many of the currently available software tools are not well suited for application in teaching. Only recently have simulation tools been developed that are specifically focused on teaching (Lant and Emmett, 2001). The purpose of this paper is to describe different approaches to including mathematical modeling into courses on wastewater treatment. Categories of model application are discussed as well as ideas on how to increase teaching effectiveness.

Categories

Teaching of mathematical modeling must depend on the specific learning objective, the time available, the level of education, and the software tools to be used. These different categories and the implications for teaching are discussed below. Different people often have very different ideas about the level of detail to be included when teaching mathematical modeling of wastewater treatment engineering. Thus, it is important to clarify the following topics before introducing mathematical modeling into a course.

Motivation and learning objectives

Demonstration. In-class experiments can greatly enhance the understanding of basic

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concepts. Visual information in an experiment can enhance what has been derived before using mathematical equations. However, performing real world experiments in class can be very time consuming. Computer simulations can be used as a surrogate for performing the actual experiment. For these applications, the model is assumed to represent reality. The main objective of these simulations is to demonstrate the behavior of the studied system. Students are not actively involved in running the model and do not necessarily need to understand the specific background of the applied models or numerical solution procedures.

Simulations. If students have a fundamental understanding of processes occurring in a wastewater treatment plant, then they can use software tools that allow them to evaluate different process configurations and operating strategies. A software tool that allows the students to interactively simulate a system without requiring a detailed understanding of the model behind the system or the numerical procedures involved is called a simulator. Using such a simulator, the student can select a predefined model such as the activated sludge model No. 1, with predefined parameters in a predefined configuration (Henze *et al*., 1987). For the students, the objective of using such a simulator is to improve their understanding of processes and interactions of these processes in treatment systems, to improve system design, and to improve operation by testing different operating schemes, scenarios, and control designs.

Model building. To benefit the most from using a mathematical model, students should learn about the background of the model and the steps involved in model building (Dochain and Vanrolleghem, 2001). With such an improved understanding of the mathematical models, the user can often better anticipate possible pitfalls in model application. There are three levels of complexity in model building: (i) Configuring a plant using predefined unit processes (aeration tank, settler, splitter, biofilm reactor) and parameters, (ii) Calibrating a plant on actual data (parameter estimation, sludge and wastewater characterization), (iii) Creating a new model with a new set of equations, to deal with processes that cannot be modeled with the available models (e.g. because of toxicity effects or a specific compound that is to be modeled). Creating a new model includes the following steps:

- Problem specification
- Compilation of prior knowledge
- Setting up a verbal model
- Translation into mathematical model
- Implementing into modeling software and solving the equations
- Determination of parameter sensitivity
- Experimental design
- Parameter estimation
- Model validation
- Model application to solve the problem originally specified (. . . if the model is found to be valid in the previous step)

The objective of including model building in a curriculum is to teach the potentials and shortcomings of a specific mathematical modeling approach. The very exercise of creating a model can be beneficial, as it requires the modeler to ask critical questions about the system being modeled (Henze *et al*., 1987).

Numerical methods. Mathematical simulations describing water and wastewater treatment systems involve non-linear and parallel processes, and the numerical integration of these systems can be challenging. Today, there is advanced software available that facilitates the numerical solution of these complex systems and students in environmental engineering generally do not have to focus on developing their own numerical procedures. However, a basic understanding of numerical methods will help to predict numerical problems when using a simulator.

Type of software

Different categories of software can be used to do mathematical modeling (Carstensen *et al.*, 1998):

Spreadsheets. (e.g. EXCEL) can be used effectively for steady state calculations. For educational purposes, simple numerical procedures such as the Euler integration rule to integrate ordinary differential equations can be evaluated using a spreadsheet.

Low level programming tools. (e.g. C, Fortran, Pascal, . . .) allow the greatest flexibility creating new models. Building new modeling software using general purpose or low level programming tools is time consuming and generally restricted to students familiar with programming.

General purpose simulation tools. (e.g. Maple, Mathematica, MATLAB/Simulink, . . .) can be used to implement mathematical models. Some modules are available that help in implementing relevant processes in wastewater treatment (Olsson and Newell, 1999, http://www.iea.lth.se/support/index.html).

General purpose tools for environmental engineering. (e.g. AQUASIM, ASIM, GPS-X, SIMBA, WEST, . . .) have an open model structure and provide the users with a large degree of freedom when implementing their own model. Basic types of reactors (e.g. CSTR, PFR, biofilm reactor) and submodels (Activated Sludge Models 1, 2, 3, Anaerobic Digestion Model 1, River Water Quality Model 1, . . . are often predefined for the user.

Closed model structure programs. (e.g. BIOWIN, EFOR, JASS, STOAT, . . .) provide the user with predefined building blocks that can be used to implement a specific wastewater treatment plant. Apart from specifying values of the given set of model parameters, the user has no degree of freedom. A restricted version of JASS (Java based Activated Sludge process Simulator) can be operated free of charge through the internet (http://www.syscon.uu.se/~psa/).

Level of complexity

Wastewater treatment is governed by the complex interaction of biological, chemical and physical processes. Modeling usually aims at including only the most relevant process in the mathematical description. Choosing the optimum level of complexity will depend on the modeling objective. Models in teaching are often more complex, as they are focused on understanding process interactions, while models for design and operation often have a reduced model complexity, focusing on the overall system performance. It is interesting to note that in activated sludge systems the models used for understanding are very similar to the models used by the practitioner – both are mainly focused on substrate conversion. For biofilms, however, there is a large variety of different modeling approaches available (Morgenroth *et al.*, 2000). When describing biofilms, models for understanding often focus on the micro scale processes within the biofilm structure. Models used by practitioners are usually much simpler and are focused on quantifying substrate flux into the biofilm as a basis for evaluating overall system performance. When teaching mathematical modeling of biofilm processes, students need to become aware of the diversity of modeling approaches, including models for understanding and practical models, and they need to be able to select the appropriate level of complexity for a given situation.

Level of course

Teaching of mathematical modeling will depend on the previous background and learning objective of the students. For students in environmental engineering at a bachelor's level, the main objective of including mathematical modeling in the curriculum can be to provide a first introduction to models and simulation tools and to use these models to enhance teaching of the core subjects through computer aided teaching. At a master's level, the focus can be on model building procedures based on existing models including calibration and optimal experimental design. At the Ph.D. level, the development of new models (equations) may be the focus. Introducing mathematical modeling into continuing education courses can be difficult, as participants often have very diverse backgrounds and also very diverse expectations about what they should learn in such a course.

Time available

If a full course can be devoted to mathematical modeling of wastewater treatment processes, then different modeling approaches and software applications can be included within that course. However, mathematical modeling can also be used to enhance courses focused on process engineering and design. In these courses, only a limited number of lectures can be devoted to mathematical modeling and, thus, model application should be limited to very simple cases

Ideas and suggestions

Early rewards

Mathematical modeling can be very time consuming and students should see the benefit for their investment early in a course. Model application should be kept simple, so that students can focus on working with model results rather than struggling with model implementation. Early on students should benefit from using numerical simulations by solving cases that cannot be easily solved using hand calculations (e.g. dynamic loading and operating conditions, complex plant configurations, and complex process interactions).

Active learning

Students should develop an intuition for advantages and problems associated with model application. Small projects during the course are an efficient way for students to gain familiarity with model building and application of the modeling software. Often, asking the right questions is the most difficult part of mathematical modeling and students should practice identifying these questions and then using the model to answer them. Thus, a project should not be specified in too much detail and leave room for the students to ask the right questions themselves.

Clearly define motivations and learning objectives

Students and teachers must clearly define the expected level of understanding when using mathematical models. If a teacher provides the student with simulation software to solve mathematical models, then it must be made clear whether the student should simply apply the already implemented models or whether they are expected to fully understand the underlying model structure and numerical solution procedures. To avoid such confusion, it is important to agree on specific learning objectives.

Combine different levels and approaches

When teaching mathematical modeling, it can be very useful to integrate different levels of modeling. For example, one can start the course by having the students experiment with a simulator and later on have the students go through the detailed process of model building. Or one can introduce mathematical modeling by having the students develop their own numerical integration routine (e.g. using a spreadsheet) and later on have students use general-purpose tools for their simulations. Mixing these different levels can provide motivation and additional background.

Simple modeling tools

To be able to use modeling software in the classroom efficiently, it is important that it is easy for the student to learn the basic functions of the program (Gujer and Larsen, 1995). Otherwise, the students spend excessive amounts of time learning how to work with the program rather than using the model to answer their questions.

Link with existing knowledge

To be able to evaluate modeling results, students should make use of their prior knowledge. Before running a simulation, it is always useful to think about the expected outcome. Analytical solutions of a corresponding simplified system and mass balance calculations can provide a good background to evaluating modeling results.

Conclusions

Mathematical modeling of wastewater treatment processes should become an integral part of environmental engineering education. On one hand, students should be provided with sufficient background to successfully apply mathematical modeling tools in their future careers. On the other hand, computer aided teaching can be used to enhance understanding of the complex interactions between physical, chemical, and biological processes in environmental engineering. Teaching mathematical modeling can mean different approaches ranging from (i) using a simulator that has been predefined to (ii) model-building using specialized simulation software to (iii) low level programming of numerical integration procedures. The level of modeling and the specific learning objectives should be carefully selected based on the time available in the course and the background of the students. Project-based learning is often useful for the students to explore and understand the opportunities and risks associated with mathematical modeling.

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