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A river water quality model integrated with a web-based geographic information system

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Abstract

Scientists often use mathematical models to assess river water quality. However, the application of the models in environmental management and risk assessment is quite limited because of the difficulty of preparing input data and interpreting model output. This paper presents a study that links ArcIMS, a Web-based Geographic Information System (GIS) software to ROUT, a national and regional scale river model which evolved from the US Environmental Protection Agency's Water Use Improvement and Impairment Model, to create a WWW-GIS-based river simulation model called GIS-ROUT. GIS-ROUT is used to predict chemical concentrations in perennially flowing rivers throughout the continental United States that receive discharges from more than 10,000 publicly owned wastewater treatment plants (WWTPs). The WWTP chemical loadings are calculated from per capita per day disposal of product ingredients and the population served by each plant. Each WWTP, containing data on treatment type and influent and effluent flows, is spatially associated with a specific receiving river segment. Based on user defined treatment-type removal rates for a particular chemical, an effluent concentration for each WWTP is calculated and used as input to the river model. Over 360,000 km of rivers are modeled, incorporating dilution and first order loss of the chemical in each river segment. The integration of spatial data, GIS, the WWW, and modeling in GIS-ROUT makes it possible to organize and analyze data spatially, and view results on interactive maps as well as tables and distribution charts. The integration allows scientists and managers in different locations to coordinate and share their estimations for environmental exposure and risk assessments.

Keywords: Risk assessment; United States; Wastewater treatment plants; ArcIMS

1. Introduction

Water quality refers to the physical, biological and chemical status of water bodies. Human influence (e.g. urbanization, agriculture, wastewater discharge) often changes surface water quality. One avenue for such influence is from the discharge of municipal wastewater treatment plant (WWTP) effluents into surface waters. In 1996, over 16,000 WWTPs served approximately 72% of the United States' population (USEPA, 1997). The water quality downstream of these WWTPs is related to the adequacy of wastewater treatment. Furthermore, since fresh surface waters are the sources for many drinking water intakes, it is also important that exposure and risk of chemicals discharged from WWTPs be evaluated.

A significant effort for scientists and managers responsible for consumer product manufacture, use and disposal is to conduct environmental and human exposure and risk assessments. Environmental risk is characterized by comparing the predicted exposure concentrations (PEC) with the predicted no effect concentrations (PNEC). Typically in practice, only one PEC value is calculated for the entire country, using a tabular approach based on the distribution of national dilution factors (Rapaport, 1988; McAvoy et al., 1993). There are two major drawbacks to this approach. First, it does not consider regional variation. It is unrealistic to assume the concentrations of a particular chemical are uniformly distributed everywhere in a country the size of the United States. Second, it does not take into consideration upstream contributions in calculating PEC. Exposure

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concentrations of chemicals downstream of WWTPs are a consequence of local discharge as well as upstream contributions. Hence, what can help raise environmental risk assessment to another level is a model that can predict concentrations of consumer product chemicals in surface waters by taking into account spatial variations of consumer usage, WWTP removal rates and chemical losses in the river.

Due to recent technological advancements, especially the increased availability and relative affordability of Geographic Information Systems (GIS), many GIS-based surface water models have been created for resource and environmental management (Cowen et al., 1995; Smith and Vidmar, 1994; Warwick and Haness, 1994; Ross and Tara, 1993; Greene and Cruise, 1995; Bennett, 1997; Djokic and Maidment, 1993; Shamsi, 1996; Goodchild et al., 1993; Poiani and Bedford, 1995; USEPA, 2001). Researchers have recognized the necessity of integrating environmental models with best available technology to overcome the barriers that hinder the use of many models (Coroza et al., 1997; Sui and Maggio, 1999).

To meet this need, a joint university–industry research team was formed to develop a system that integrates an existing river simulation model, ROUT, with a Geographical Information System (GIS) and the World-Wide-Web (WWW). This Web-GIS-based river water quality model (GIS-ROUT) provides a flexible tool for risk assessors to determine the potential concentrations of consumer product ingredients in surface waters and their contributions to surface water quality. The objective of this paper is to illustrate the efficacy of a fully integrated river model as a user-friendly decision-support tool. While ROUT predicts the environmental fate of consumer product-derived constituents found in municipal wastewater and receiving rivers, the addition of GIS to ROUT allows for spatial analysis of the modeling results, such as querying by location, summarizing by area, and examining upstream–downstream relationships. The WWW technology provides a gateway for users in different parts of the world to remotely access the GIS-ROUT model to address 'What if…' or scenario-based questions related to environmental and human exposure and assessment.

2. The ROUT model

The ROUT model was conceived during the 1984 Environmental Protection Agency (EPA) Needs Survey. That survey was charged with the task of performing a national assessment of the water quality impacts of the Construction Grants Program. The model that was developed and used for this purpose, under the direction of EPA, was the Water Use Improvement and Impairment Model (WUI2), which was a steady state water quality model. The Needs Survey collected data from more than 32,000 sewage collection and treatment facilities nationwide. These data combined with information from other databases on receiving water bodies and industrial point sources formed the input for WUI2. The experience of modeling at this national scale led to the conceptualization of ROUT, which incorporated population-based consumer product loadings in addition to conventional pollutants (Hennes and Rapaport, 1989; Cowan et al., 1993; Dyer and Caprara, 1997). The first-generation ROUT was written in FORTRAN and was located on the USEPA mainframe computer with limited access to a few model users.

Fig. 1 illustrates the ROUT modeling process. The model consists of two components—the database and river reach simulation. The database stores data extracted from several US EPA databases. The Reach File 1 (RF1), a hydrological vector database of about 1 million kilometers of perennially flowing surface waters in the continental United States Rivers, forms the river network for the model. To account for where major chemical or significant flow changes occur, the RF1 vectors were broken into segments at river confluences and WWTP discharge points. Other large USEPA data sets that were included were GAGE, containing mean and low (7Q10) river flow data (USEPA, 1995); the 1996 USEPA Clean Water Needs Survey (NEEDS File, USEPA, 1997); and the Safe Drinking Water Information System File (SDWIS), describing locations and characteristics for drinking water intakes (USEPA, 1998). All data were linked to the RF1 network via a unique river segment number.

The ROUT model algorithm simulates one-dimensional river flow at steady state. The model first calculates river flow by river segment. To estimate in-stream concentrations, the model begins at a headwater segment and procedes downstream, one segment at a time, until the terminal segment of a river is reached. Using various data files for a segment, ROUT applies the mass balance concept to compute the head-of-segment concentrations, i.e. concentration at the beginning of a segment, by accounting for WWTP input and upstream contributions. End-of-reach concentrations are determined considering three basic processes that control the fate of a chemical in a river—advection, hydrodynamic dispersion and a first order reaction. The loss function is a bulk parameter that accounts for all types of losses of chemicals in rivers, such as sorption, sedimentation and biodegradation. The end-of-segment concentrations are used as upstream contributions for the next downstream segment. A detailed description of the ROUT model algorithm can be found in Wang et al. (2000).

The second-generation ROUT was programmed in C++ for the Windows platform. All data were stored in an Access database. This represented a significant improvement to the original ROUT model. Another improvement had the continental states divided into six major drainage basins, which allowed the user to select a national or regional model run. The model output was saved in a new Access database where the user accessed results via tables.