EVALUATING WATERSHED POLLUTANT TRADING SCHEMES UNDER UNCERTAINTY: A COMPUTATIONAL APPROACH

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Abstract. We present and illustrate an approach to evaluate the options for watershed pollutant trading based on the development and application of a comprehensive simulation model. In particular, attention is focused on phosphorus as a nutrient/pollutant, and our illustrative case focuses on a portion of Chattahoochee watershed, between the outflow from Lake Lanier at the Buford Dam and the inflow to Lake West Point, i.e., passing southwards through metropolitan Atlanta. The model – in fact, an assembly of three sub-models – simulates the full dynamic behavior of not merely nonpoint sources of pollutants but also point-source discharges, and the consequent propagation of variations in stream flow, sediment flux, and phosphorus flux through the principal tributaries and main stem of the Chattahoochee River. In order to account for uncertainties, which are significant in current representations of transient variations in stream water quality, the entire model is embedded in a framework of Monte Carlo simulation. We use this general framework and the specific case study to show how various candidate options for pollutant trading can be evaluated on a consistent basis for their reliability in the presence of uncertainty. We consider this kind of "*in silico*" evaluation especially important at a time when there is a strong aspiration to see pollutant trading schemes implemented, but little direct evidence of their successes/failures in actual practice.

INTRODUCTION

Given that curtailing sources of pollution in a watershed can incur very different costs, even for the same pollutant, watershed pollutant trading allows facilities facing higher pollution control costs to meet their regulatory obligations by purchasing environmentally equivalent (or superior) pollution reductions from another source at a lower cost, thus achieving the same water quality improvement at lower overall cost (USEPA 2004).

Programs for pollutant trading programs should be based on adequate scientific understanding of the watershed and pollutant characteristic. Due to the complexity (and uncertainty) involved in the discharge, transport, and fate of water pollutants, mathematical models are often used for associated watershed planning and management studies. One goal of the work reported upon herein, therefore, is to assemble a set of models into a watershed simulation system so that the dynamic behavior of both point and nonpoint discharges of pollutants into river system and the instream routing processes could be simulated in a compatible manner.

One major quantitative task in designing the pollutant trading scheme is the determination of the *water quality equivalence* of pollutant reductions at different discharge points. This implies the following: given an amount of pollutant abatement, determine how much credit (to pollute elsewhere) can be sold so that the resulting stream water quality is at least as good as the current condition. Due to significant uncertainties involved in estimation of pollutant sources, their transport and fate, performance of abatement technologies, and predicted post-trading water quality, trading schemes should be assessed with a clear account of the consequences of such uncertainty, in order to ensure their reliability.

Since diffused pollution discharges throughout the watershed are believed to be the primary source of uncertainties, in most studies hitherto, with evaluation of the uncertainty in nonpoint-source behavior, a trading ratio for nonpoint-source (NPS) to point-source (PS) trades of NPS/PS>1 is often used to express the idea that the pollution credit the proposed abatement scheme can generate and sell should be less than the quantity of reduction (Sessions and Leifman, 1999; USEPA 2004). In this paper, we propose to undertake evaluations of watershed pollutant trading schemes with a more complete and explicit account and analysis of the effects of uncertainty.

On the basis of the prior understanding of the uncertain factors having an impact on watershed pollutant behavior, our watershed models are embedded within the framework of a Monte Carlo (MC) simulation. Pollutant concentrations are accordingly expressed in terms of probability distributions, reflecting the consequences of accounting for the various sources of uncertainty. Assessment of any proposed trading scheme is then based on comparing the statistical attributes of estimated river water quality before and after implementation of the proposed schemes. We take a part of the Chattahoochee watershed as a case study through which to develop our proposed procedure for assessing trading programs.

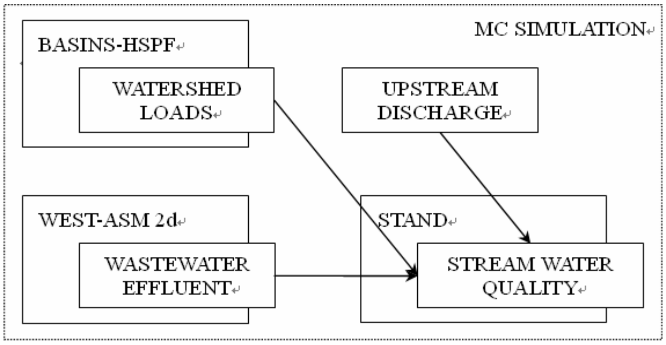

Figure 1: Components in the Watershed Water Quality Simulation System

ASSEMBLY OF WATERSHED MODEL

Simulation of watershed pollutant behavior is achieved herein through three component models, embedded in a Monte Carlo simulation framework for the analysis of uncertainty (Figure 1). BASINS-HSPF (Hydrologic Simulation Program–FORTRAN) (USEPA, 2001) estimates pollutant loads from nonpoint sources, mainly generated in runoff following storm events, from a number of sub-basins throughout the watershed. The WEST-based Activated Sludge Model No.2d (ASM 2d) (Henze et al, 1999) simulates the behavior of the point-source, treated sewage discharges from urban wastewater treatment plants. The consequences of these nonpoint and point discharges for the quality of the receiving river are then simulated by the Sediment-Transport-Associated Nutrient Dynamics (STAND) model (Zeng and Beck, 2001).

A significant portion of the Chattahoochee River has been chosen for this case study. It covers the river segment from Buford Dam at the outflow of Lake Lanier, southwards past the city of Atlanta, as far as the inlet to Lake West Point (Figure 2). In essence, the principal outputs of interest from the model are the concentrations of phosphorus, for a case of nutrient trading, at various cross sections along the river, provided as daily time-series for a variety of hydrological years.

Nonpoint source pollution load assessment

Processes of rainfall-runoff generation in the watershed, i.e., rainfall, interception, surface runoff, infiltration, interflow and base flow, mobilization and washoff of sediment and associated phosphorus release, are modeled by HSPF. For the model requirements, the watershed is separated into sub-basins (Figure 2), drawing upon the relevant spatial data of properties such as land use and soil type. Using 36 years of historical daily precipitation sequences as model inputs, corresponding spatial and temporal distributions of runoff and nonpoint-source pollutant loadings are generated. For example, for the year of 1995 (a moderate hydrological year) and the 13th sub-basin, Peachtree Creek (in downtown Atlanta), the nonpoint source loads are illustrated (Figure 3).

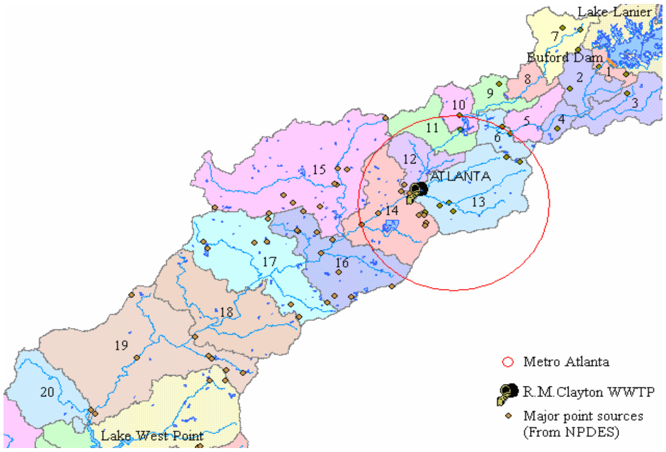

Figure 2: Pollutant Sources in Chattahoochee Watershed around Metro-Atlanta Area; Numbering and Coloring Identifies Different Sub-basins.

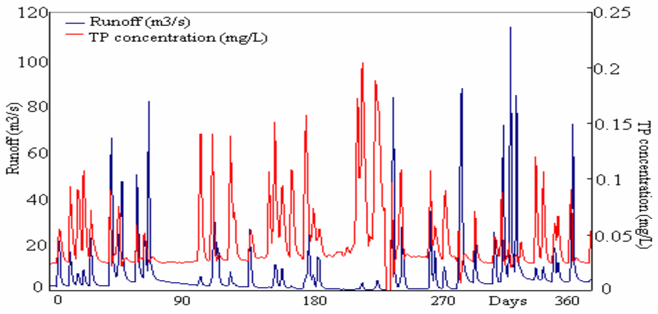

Figure 3: Peachtree Creek Watershed (Sub-basin 13) NPS Contributions (flow and phosphate concentrations) in 1995

Point source pollution load assessment

According to the NPDES (WPD 2006), over twenty main point sources are located in the studied segment of Chattahoochee (Figure 2). In the present study, however, simulation of just the single discharge from Atlanta's largest wastewater treatment plant, the R.M. Clayton facility (with a capacity of 100 million gallons per day) is included to show our simulation and uncertainty processing framework. Compared with NPSs, point sources has less uncertainties, the simulation conducted here is mainly addressing the temporal variation and different projected effluent limit. WEST (http://www.hemmis.com) is an advanced software platform for simulating *inter alia* the behavior of a wastewater treatment plant. From its "library" of options, Activated Sludge Model No.2d (ASM 2d) has been selected to provide simulation of removal of phosphorus. Given previous detailed and comprehensive studies of (simulated) wastewater treatment plant behavior (Jiang *et al*, 2005), patterns of treated sewage discharges, which are typical for Georgia, are obtained. Current operation of the R.M Clayton WWTP lacks unit treatment processes designed specifically to remove phosphorus, such that the current effluent TP concentration is bounded only at 2 mg/L. The model generates the sequences of simulated effluent discharge and total phosphorus (TP).

In-stream pollutant transformation

Stream hydraulic processes (flow routing), suspended sediment transport, exchanges of suspended sediment with bed sediment, and the behavior of phosphorus are simulated by STAND (Zeng and Beck, 2001). Relative to the channel component in BASINS-HSPF, STAND is better suited to simulating flow and sediment concentrations under transient, highly unsteady conditions. During the evaluation of pollutant sources, we address the load of total phosphorus, and in the simulation of channel process, the addressed form is phosphate (as phosphorus), consistent with EPA's water quality standard.

The nonpoint-source and point-source pollutant loads, from their respective sub-models, together with variations in the upstream discharge from Buford Dam, collectively provide the external forcing functions for STAND. The in-stream processes are characterized by a set of parameters associated with the fluvial attributes of the channel segments. Annual sequences of daily variations of stream water quality under different climate and watershed conditions are the primary outputs of interest. Again taking the year 1995 as an example, typical patterns of these outputs are shown in Figure 5 for stream discharge, while the accompanying sequences of suspended sediment and phosphate concentration are given in Figure 6 (at inlet to Lake West Point; USGS station 03328550).

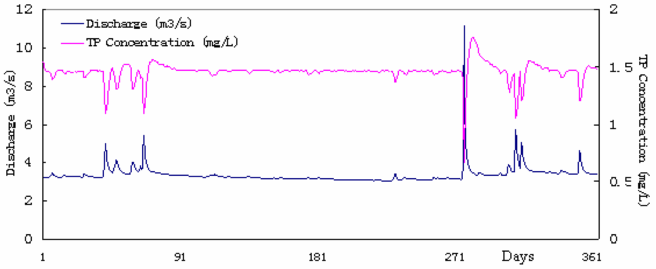

Figure 4: Discharge and TP Concentration from R.M. Clayton WWTP (1995)

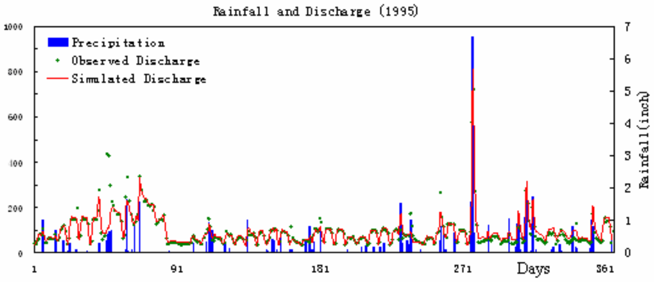

Figure 5: Observed and STAND-Simulated Stream Discharge (1995)

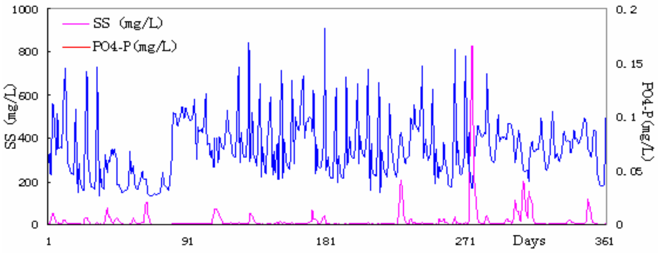

Figure 6: STAND-Simulated SS and PO4-P concentration (1995)

ANALYSIS OF UNCERTAINTY

Watershed hydrological processes and their associated fluxes and transformations of variables characterizing water quality are subject to significant uncertainties, in particular, in respect of water quality and its transient behavior in response to precipitation events. Herein, methods based essentially on Monte Carlo simulation are employed for analyzing the consequences of these uncertainties, in respect of (eventually) identifying trading schemes likely to be maximally robust against these affects of uncertainty.

Preliminary studies indicate that four uncertain factors affect sediment and nutrient behavior in this segment of Chattahoochee River (Osidele et al., 2003): (i) reservoir operations at the upstream Buford Dam, which determine the release pattern from Lake Lanier; (ii) watershed loading resulting from precipitation-induced nutrient washoff and overland transport; (iii) urban wastewater discharge and effects of wastewater treatment plant operations; and (iv) in-stream pollutant behavior. A key task for watershed pollutant trading research is to account for these uncertainties quantitatively and to manipulate them, in order to keep satisfying designated environmental objectives.

For the nonpoint-source watershed loadings and their attaching uncertainties, 36 annual sequences of daily rainfall patterns (generated from 1970-1995 historic data) and three land-use scenarios (derived from the current trends of urban development in the Atlanta region), are parameterized as indexes for the Monte Carlo simulation. For the point source, given that construction of phosphorus removal facilities are under consideration at the R. M. Clayton WWTP, the imposed, i.e., regulated effluent TP concentration limit is also parameterized so as to account for a variety of scenario uncertainties. Uncertainty in the release from Buford Dam – category (i) of the above four sources of uncertainty -- is parameterized through an index of different annual patterns of daily mean reservoir discharges. Finally, parameters reflecting in-channel fluvial processes are considered to be uncertain as well.

Taking the inlet to Lake West Point as our reference spatial location for the overall simulations, the cumulative probability distribution functions for the annual sets of daily maximum and daily mean phosphate concentrations – resulting from the propagation of uncertainties from all four of the above sources – are shown in Figure 7.

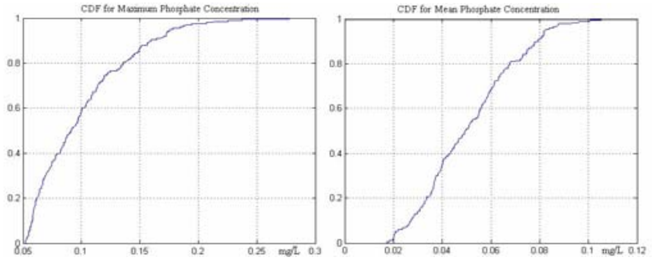

Figure 7: Cumulative Distribution Functions of Simulated Daily Maximum and Mean Phosphate Concentrations in Annual Sets

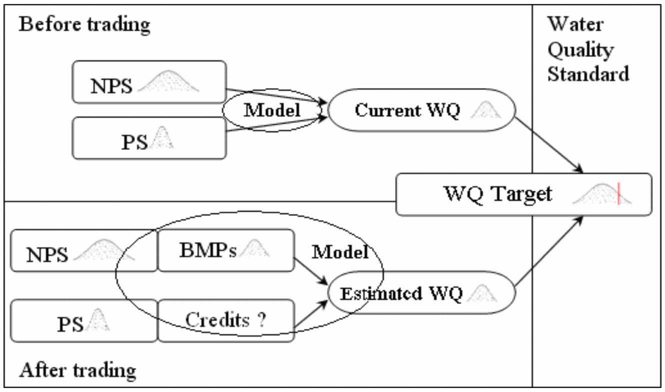

Figure 8: Suggested paradigm for pollutant trading scheme evaluation.

TOWARDS EVALUATING CANDIDATE POLLUTANT TRADING SCHEMES

The procedures of simulation and the attaching capacity for analysis of uncertainty that underpin the summary results of Figure 7 provide the platform on which we have been constructing our evaluation of candidate pollutant trading schemes. The criterion we are proposing in our evaluation is that the post-trading water quality conditions are not worse than those obtaining in the without-trading condition. Target values for water quality must accordingly be identified for the criteria determining attainment of water quality standards, specifically those linked to the designated uses for the water body of interest. For instance, if we choose 0.1 and 0.05 mg/L as the standards for phosphate (as phosphorus) concentration, the current water quality target can be expressed as an attainment probability as:

$$\begin{cases} p(\max(PO_4) < 0.1) > 60\% \\ p(mean(PO_4) < 0.05) > 50\% \end{cases}.$$

The performance of a candidate pollutant trading scheme can then be simulated using the models and procedures set out above, such that if the simulated post-trading water quality conditions can meet or surpass the pre-trading water quality target, we say this scheme is valid, or tradable in principle. As shown in Figure 8, a framework is created for assessing a trading scheme in the presence of all the sources of uncertainty involved. At the next stage, when economic costs are evaluated, building upon marginal cost estimates for phosphorus removal in point-source of wastewater treatment facilities, and the installation of Best Management Practices for curbing nonpoint sources, the most promising (and feasible) trading scheme may be recommended for implementation.

CONCLUSIONS

In this research, we have assembled a rather comprehensive model system for watershed researches, wherein the dynamic behavior of the point sources, together with that of nonpoint sources, can be properly accounted for.

In this paper, the simulation system brought the pollutant trading studies into the context of implicit analysis of uncertainty related to the watershed pollutant behavior, for generation of a reliable trading scheme. This helps to set pollutant trading programs on a more quantitative basis.

The model and uncertainty analysis framework have been set up to mimic closely the context of metropolitan Atlanta within the Chattahoochee watershed, such that we can generate all manner of patterns of stream water quality as a function of the various candidate alternatives for pollutant trading schemes and assess these in the presence of the substantial sources of uncertainty surrounding watershed behavior, facility performance, and cost estimation. On this basis we have begun developing a systematic framework for screening out preferred trading mechanisms with detailed feasibility analyses.

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