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Application of an Environmental Decision Support System to a Water Quality Trading Program Affected by Surface Water Diversions

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Abstract Environmental decision support systems (EDSSs) are an emerging tool used to integrate the evaluation of highly complex and interrelated physicochemical, biological, hydrological, social, and economic aspects of environmental problems. An EDSS approach is developed to address hot-spot concerns for a water quality trading program intended to implement the total maximum daily load (TMDL) for phosphorus in the Non-Tidal Passaic River Basin of New Jersey. Twenty-two wastewater treatment plants (WWTPs) spread throughout the watershed are considered the major sources of phosphorus loading to the river system. Periodic surface water diversions to a major reservoir from the confluence of two key tributaries alter the natural hydrology of the watershed and must be considered in the development of a trading framework that ensures protection of water quality. An EDSS is applied that enables the selection of a water quality trading framework that protects the watershed from phosphorus-induced hot spots. The EDSS employs Simon's (1960) three stages of the decision-making process: intelligence, design, and choice. The identification of two potential hot spots and three diversion scenarios enables the delineation of three management areas for buying and selling of phosphorus credits among WWTPs. The result shows that the most conservative option entails consideration of two possible diversion scenarios, and trading between management areas is restricted accordingly. The method described here is believed to be the first application of an EDSS to a water quality trading program that explicitly accounts for surface water diversions.

Keywords Environmental decision support systems · Water quality trading · Water resource management · Total maximum daily load · Watershed management

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Introduction

Population growth, urbanization, industrialization, and agricultural development have impaired the health of ecosystems and particularly impacted water resources. Scientists attempting to solve these issues are faced with the complexity of environmental systems, thus increasing the uncertainty of solutions.

Guariso and others (1989) and Sarang and others (2006) have explained the major reasons for the complexity of environmental systems:

1. Dynamics: All major components of the ecosystems such as air, water, land, energy and live organisms including humans are interrelated and interconnected.
2. Spatial dimension of the environment: Physical processes in environmental systems occur in two- or three-dimensional spaces.
3. Complexity of physicochemical and biological aspects of the environment: Many environmental systems involve the interaction of physicochemical and biological processes.
4. Stochastic behavior of environmental systems: Many environmental processes involve nondeterministic

behavior, by which the next system state is partially, but not fully, determined by the previous system state. In addition, the system variables are uncertain, and their extent of involvement in the whole system is approximate.
5. Periodicity: Many environmental systems occur or change in a specific period of time that adds to the complexity of the systems.
6. Heterogeneity and scale: Heterogeneity and differences in scale make it difficult to characterize environmental systems by measurable parameters.

The large number and depth of involvement among the aforementioned factors form the range of complexity in environmental systems. The range of complexity corresponds with the degree of uncertainty and leads to risk associated with decisions. Funtowicz and Ravetz (1999) and Poch and others (2004) have classified the complexity of environmental systems into three levels.

I. The first level of complexity pertains to a simple system with a low degree of uncertainty. A simple model is adequate to describe the system. In the context of water, the change of dissolved oxygen concentration in a pristine river after discharging a known amount of biochemical oxygen demanding (BOD) load is an example of the first level of complexity.
II. The second level of complexity is less manageable than the first level, and simple models are no longer adequate. In this level, sufficient experience is required to tackle the problem, and the degree of uncertainty is greater than the first level. Therefore, expert involvement in problem solving is an important component in addition to modeling. This level of complexity in river ecosystems is evident when applying a water quality model, and a few dominant parameters must be recognized from a much larger parameter set.
III. The third level of complexity involves the interaction of social and scientific factors. To meet numerous and potentially conflicting environmental, economic, and policy goals, system management becomes extremely complex. An example of the third level of complexity is water quality and quantity management at the watershed scale, where social, economic, and legal variables must be considered in addition to scientific factors.

It is important to note that in modeling of water quantity and quality, a more complex model does not guarantee more accurate results (Doherty and Johnston 2003). Although it is generally true that system fine detail can be replicated only through a necessary degree of model complexity, added complexity also increases the number of nonunique parameter solution sets and amount of model uncertainty. The most an appropriately complex model can guarantee is that the true system behavior will lie somewhere within the uncertainty limits of the model predictions (Doherty and Johnston 2003). When available data to calibrate a model are sparse, the increased uncertainty of a complex model might render a simpler model more useful. Ultimately, it is the intended use of the model (i.e., the problem to be solved) that should guide the selection of the model and the degree of complexity required. The least complex model that reliably answers the question is ideal (Rauch and others 2002).

In recent decades, a number of mathematical models, software tools such as geographic information systems (GIS), and artificial intelligence techniques have been developed to analyze environmental problems and provide appropriate alternatives for decision makers. Most applications have achieved satisfactory results for problems of Level I complexity (Poch and others 2004). Recent efforts for solving environmental issues of Level II and III complexity have led to the development of a new integrated approach: the environmental decision support system (EDSS). Just as with water resource modeling, the authors believe that the least complex EDSS that achieves the task is ideal, which, in turn, enhances EDSS effectiveness.

Among environmental issues, management of water quantity and/or quality is a primary concern in many regions of the United States. The issues are further complicated when human activities have significantly altered the natural state of the watersheds; the phenomena of surface water diversions and point-source pollution are specifically examined in this article. Given that many watersheds throughout the nation have been affected by human activities, the first level of complexity is rarely observed.

An EDSS approach is developed in this article for a water quality trading project in New Jersey. Water quality trading is of Level III complexity in that it is multidisciplinary and involves social, economic, and scientific factors. The presence of periodic surface water diversions in the Non-Tidal Passaic River Basin further increases the level of complexity of water quality trading in that watershed.

This article presents the first application of an EDSS to water quality trading. The EDSS described here was effective in that it provided a simple solution to a complex problem. Phosphorus-induced hot spots affected by diversions is a complex obstacle to a trading program that must achieve water quality protection. The scope of this EDSS is limited to development of a trading framework that achieves the goal of water quality protection. This EDSS does not include economic and societal aspects of water quality trading.

Environmental Decision Support Systems

Many scientists have attempted to define the term "decision support system" (DSS), but the concept is extremely broad; thus, the definitions vary depending on the author's point of view (Druzdzel and Flynn 1999). This study utilized the concept of DSS per Simon's (1960) decision-making process, which includes three basic stages: (1) intelligence (Is there any problem or any opportunity for change?), (2) design (What are the alternatives?), and (3) choice (Which alternative is best?) (Thill 1999). A recent example of an EDSS based on Simon's decision-making process is MULINO for assessing alternative measures for the reduction of nitrogen pressure from agriculture on water resources at the European level. The result of the application of MULINO at the regional scale emphasizes the potential of the tool for evaluating the effects of policy measures applied at different spatial implementation strategies. (Fassio and others 2005).

The EDSS is a specialized type of DSS and has been categorized by Rizzoli and Young (1997) based on several aspects. One aspect is the user of the EDSS:

- The environmental scientist, who develops the models and tests them based on their accuracy.
- The environmental manager (decision maker), who works with the models prepared by the environmental scientist.
- The environmental stakeholder, who needs to understand the impacts of proposed decisions on his/her interests.

The second aspect is the type of EDSS:

- *Problem-specific EDSS*. This type of EDSS can be used to tackle problems corresponding to a specific domain of knowledge. For example, if an EDSS is developed to predict nutrient conditions in a particular river system, this type of EDSS could be applied in a different river system for the same purpose if the driving force is similar and adequate experimental data are available for model validation.
- *Situation- and problem-specific EDSS*. These EDSSs are tailored to a specific location and cannot be easily modified and applied in a new location. The Illinois River Decision Support System (ILRDSS) is an example of a situation-specific EDSS to help stakeholders, including water users and water managers, to make appropriate decisions (Demissie and others 2001). This EDSS was initially developed to solve the problems of sedimentation, water level fluctuation, and navigation.

A third aspect defined by Rizzoli and Young (1997) is whether the EDSS is capable of handling spatial data management issues. Most EDSSs have a noticeable spatial dimension. This is addressed in terms of environmental modeling with spatially distributed models that demonstrate environmental phenomena in one (river models), two (air and water models), and three (land, air, and water quality models) components (Fedra 1993; Lukasheh and others 2001). However, not all EDSSs depend on the use of spatial data management including GIS, which in some cases might be unsuitable or distracting for users (Rizzoli and Young 1997).

A literature review by Cortes and others (2000) of EDSS applications found that water management issues comprise the highest-ranked focus area with 25% of all references. Examples of EDSSs applied to water resource management include WARMF (Chen and others 1999, 2004), AQUATOOL (Fassio and others 2005), and EVALUWET (Janssen and others 2005). Although problems of water resource management are a popular application of EDSSs, the authors are not aware of any EDSS previously applied to water quality trading.

Water Quality Trading

Section 303(d) of the Clean Water Act (CWA) requires states to identify impaired water bodies that cannot meet ambient-based water quality standards. Regulators are then required to determine the total maximum daily load (TMDL) of pollutants. The TMDL calculates the maximum pollutant load that a water body can assimilate and still meet water quality standards, and it then allocates allowable loads to point and nonpoint pollutant sources. A TMDL is thus akin to a "pollution budget." Loads from natural background sources and a margin of safety are accounted for in setting load allocations for point and nonpoint sources (Chen and others 1999).

In terms of TMDL implementation, water quality trading offers a management alternative to command and control regulation. Trading is a watershed-based and market-based approach to meeting and exceeding water quality goals. The Environmental Protection Agency (EPA) supports water quality trading and issued policy guidance in 2003 on trading (USEPA 2003). Trading is based on the premise that sources in a watershed can face very different costs to control the same pollutant. A trading program allots a certain number of pollution credits to sources in the watershed. The number of credits typically corresponds to the TMDL allocation and can be adjusted for fate and transport effects as the pollutant moves downstream. The sources can either discharge under their limit and sell their credits or discharge over their limit and purchase credits. The net effect will be to improve water quality in the watershed, ideally at a lower cost than making each individual pollutant source implement pollution controls to comply with the required TMDL reductions. Trading can occur among point sources and nonpoint sources. Depending on the structure of the program, sources can trade directly or indirectly with each other (USEPA 2004).

Water quality trading is a complex undertaking because key science, economics, and policy issues are involved and intertwined. For example, trading program development must consider (1) watershed hydrology, point and nonpoint source pollutant discharges, and pollutant fate and transport in the watershed, (2) socioeconomic factors such as population density, income levels, and equity concerns, (3) varied land-use patterns that have wide-ranging impacts on water quality, (4) the differing jurisdiction of the CWA over point and nonpoint sources, and (5) the assorted interests of diverse stakeholders such as nongovernmental organizations (NGOs), regulators, wastewater treatment plants (WWTPs), and municipalities.

Water Quality Trading of Phosphorus: Case Study in the Non-Tidal Passaic River Basin

Approximately one-quarter of New Jersey's population (i.e., two million people) lives in the non-tidal portion of the Passaic River Basin (Fig. 1). The 803-square mile watershed, which includes the Wanaque Reservoir (capacity of 29.6 billion gallons), is a major source of drinking water for New Jersey residents both inside and outside of the basin. The New Jersey Department of Environmental Protection (NJDEP) 2004 Integrated List of Waterbodies identified over 200 stream miles in the Non-Tidal Passaic River Basin as impaired for phosphorus (NJDEP 2004). In-stream phosphorus concentrations in these segments were greater than the 0.1-mg/L New Jersey Surface Water Quality Standard for total phosphorus. Excessive phosphorus is a concern because it can stimulate algal blooms, which then decrease levels of

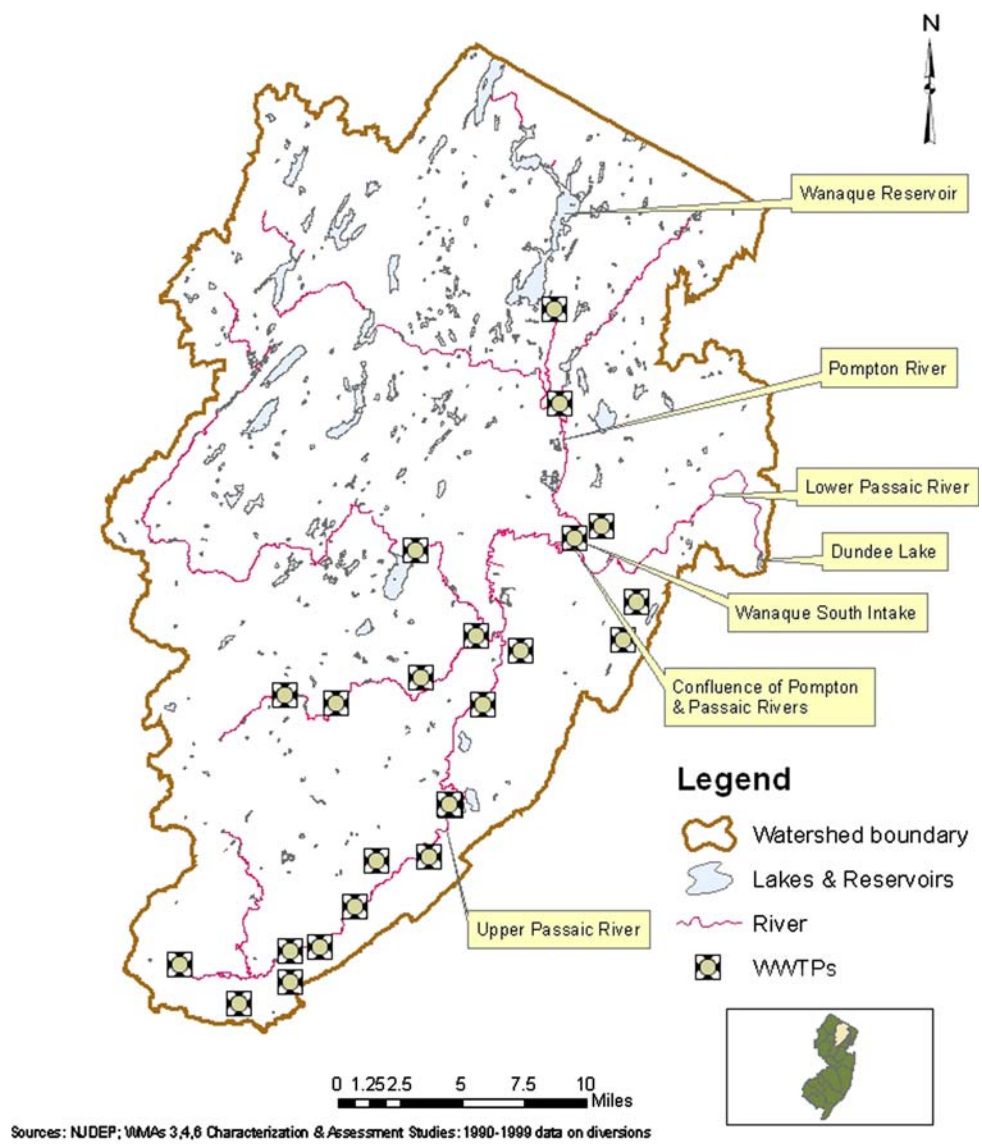

Fig. 1 Main features of the Non-Tidal Passaic River Basin

dissolved oxygen, create taste and odor problems in drinking water, and can result in fish kills. As a result, NJDEP has proposed a phosphorus TMDL (NJDEP 2007). Phosphorus loading is currently dominated by point sources, and the proposed TMDL allocations are based on a 0.4-mg/L long-term average discharge of total phosphorus from each WWTP (NJDEP 2007). Of the 22 main WWTPs in the watershed, analysis of 2005 monthly discharge monitoring reports shows that only 3 WWTPs have long-term average total phosphorus discharge below 0.4 mg/L. The traditional regulatory approach toward implementing the TMDL via the state's pollution discharge elimination permit would mandate each of the 19 WWTPs with long-term average total phosphorus discharge greater than 0.4 mg/L to upgrade their phosphorus-removal processes, which could be very expensive for the WWTPs involved.

The authors are part of a university team tasked with developing a water quality trading program to implement the phosphorus TMDL for the Non-Tidal Passaic River Basin. The situation in the Non-Tidal Passaic River Basin is well suited for water quality trading from a number of perspectives, including science, economics, and public policy. Extensive watershed studies and water quality modeling have been undertaken to characterize the fate and transport of phosphorus throughout the watershed (NJDWSC 2002a, b, c; Omni Environmental 2007a). Although most of the affected WWTPs have not provided cost estimates to achieve compliance with more stringent effluent limits, it is assumed that given the wide gap in median household incomes ($33,000 to $148,000; U.S. Census Bureau 2002) among municipalities in the watershed, combined with the differences in timing of capital investment cycles among the WWTPs, there is an expected variance on the part of WWTPs in terms of ability to afford upgrades to remove phosphorus. Moreover, the NJDEP and the WWTPs are open to trading as a viable and cooperative solution that will assuage a potentially conflict-ridden command and control approach. Thus, there is reasonable expectation that conditions are suitable for point source to point source trading of phosphorus between WWTPs.

Despite the large number of factors that favor water quality trading in the Non-Tidal Passaic River Basin, there are also several complicating factors that could impede implementation of the trading program if not adequately addressed. These complicating issues are multidisciplinary and affect a wide variety of stakeholders with diverse interests. Furthermore, the presence of surface water diversions in the basin adds a complexity not encountered by previous water quality trading projects. The well-known Long Island Sound trading program, for example, has cost-effectively improved water quality (USEPA 2004), but that program is not faced with the challenge of trading in a watershed with major surface water diversions.

Application of an EDSS might promote a more systematic and objective approach to resolving critical issues in the development of a water quality trading program. Among a few specific issues that affect the development of a water quality trading program in the Non-Tidal Passaic River Basin, the problem of hot-spot avoidance is discussed in the next subsection and an EDSS strategy and solution is outlined. In the emerging and complex field of water quality trading, the application of EDSS to the problem of hot-spot avoidance has not been mentioned in the literature. It is hoped that the following EDSS development might provide guidance to other water quality trading programs seeking to explore EDSS as a means to resolve similar issues.

Water Quality Trading Issue: Hot-Spot Avoidance

An EDSS approach is developed for the problem of avoiding potential hot spots stemming from water quality trading in the Non-Tidal Passaic River Basin. This approach applies the three stages of Simon's widely used decision making process (Simon 1960).

Intelligence Stage: Problem Definition

"Hot spots" describes localized areas with unacceptably degraded water quality due to high concentrations of a pollutant. The US EPA (2004) notes that one concern regarding water quality trading is the potential that trades will create hot spots immediately downstream of pollutant sources that purchase credits. Trading programs must be designed to avoid the creation of hot spots.

Water quality trading in the Non-Tidal Passaic River Basin must be designed so that no hot spots are created as a result of phosphorus trades. The intelligence stage must define the concept of "phosphorus-induced hot spots" and identify where and under what conditions they can occur in the Non-Tidal Passaic River Basin.

Phosphorus-induced hot spots are locations in the watershed where excessive loading of phosphorus can increase the risk of algal blooms. A number of primary variables contribute to algal blooms, including total phosphorus, total nitrogen, temperature, and light. Additionally, there are other secondary variables that affect algal blooms (viz., flow, shade cover, and turbidity). An extensive water quality study of the system (Omni Environmental 2007a) indicated that excessive phosphorus concentrations in certain areas are more likely to stimulate algal blooms, as indicated by elevated levels of chlorophyll-*a* and increased diurnal fluctuations of dissolved oxygen. In contrast, equally high concentrations of phosphorus in other areas might not stimulate algal growth due to other limiting factors such as light availability or high stream velocity; these areas are not considered potential phosphorus-induced hot spots. Consequently, different locations in the watershed show varying sensitivity to water quality impacts from phosphorus loading (see Fig. 2). Therefore, certain locations are more vulnerable to hot-spot effects than other locations in the watershed. Specifically, two locations were identified as potential phosphorus-induced hot spots based on interpretation of the Omni Environmental (2007a) study. These locations correspond directly to the TMDL end points: the Wanaque Reservoir and Dundee Lake.

The presence of surface water diversions affects the conditions under which phosphorus-induced hot spots can occur. As noted earlier, the watershed is a source of drinking water for about one-quarter of New Jersey's population. The Wanaque Reservoir system is the state's largest reservoir system and has a long-term safe yield of 173 million gallons per day (MGD). It can receive up to 400 MGD from surface water diversions. Surface water is pumped to the Wanaque Reservoir from discrete points located downstream at a rate according to consumer demand, water availability, and regulatory restriction. This fundamentally alters the hydrology of the watershed, and diversions to the Wanaque Reservoir transform basic relationships of upstream and downstream between certain locations in the watershed. For example, when the Wanaque Reservoir does not require diverted inflow, the Passaic River is not a natural tributary or source of water to the reservoir. However, when the Wanaque Reservoir does require high volumes of diverted inflow as occurred in a 2002 drought, the Upper Passaic River waters can be diverted to the reservoir and the river effectively becomes "upstream" of the reservoir (Najarian Associates 2005). The watershed hydrology thus fluctuates with the extent of surface water diversions, resulting in dynamic relationships of upstream and downstream that

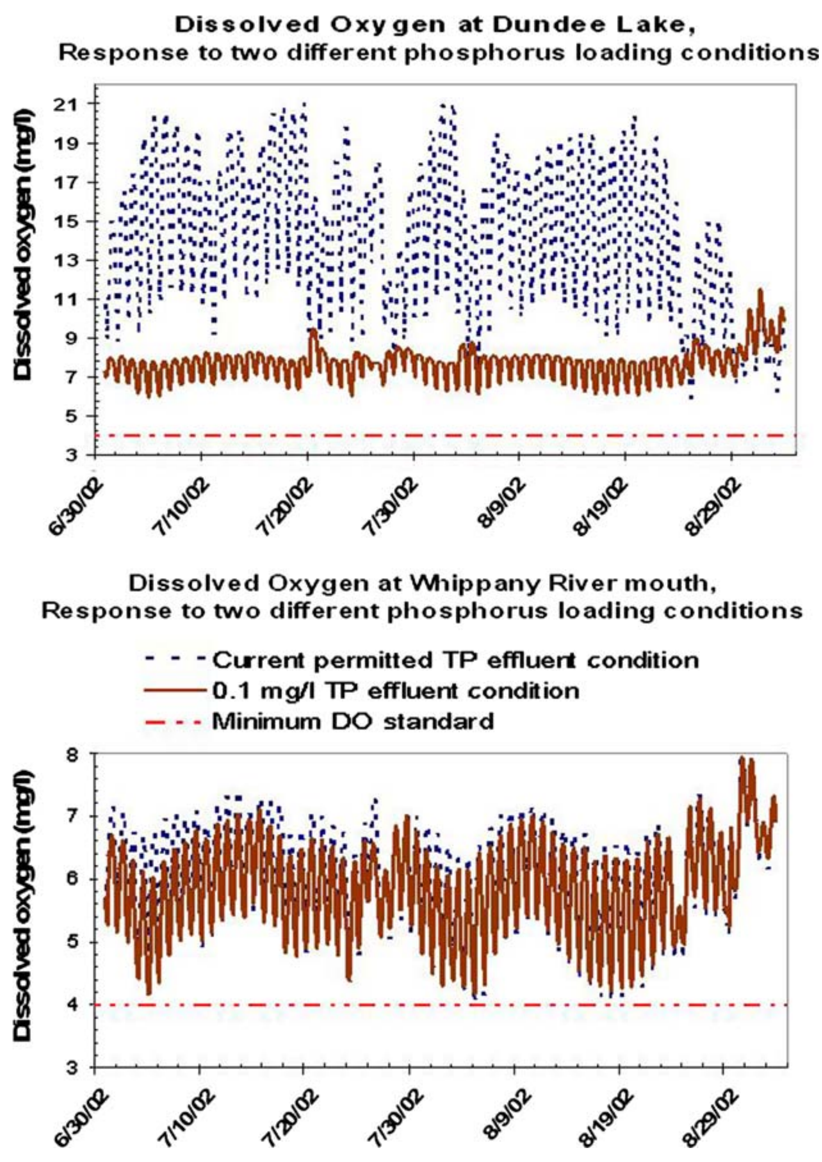

Fig. 2 Determination of "hot spots" as illustrated by different sensitivity to phosphorus loading at two locations in the watershed. The graphs (adapted from Omni Environmental 2007a) plot the simulated dissolved oxygen response at two locations under extreme high and low phosphorus loadings. The location on the top shows sensitivity and is therefore considered a potential phosphorus-induced hot spot. The applied model was calibrated and validated to 4 years of data spanning a wide range of conditions

must be accounted for in designing a trading program that avoids the creation of hot spots.

As a result, the Wanaque Reservoir is only vulnerable to phosphorus-induced hot spots from water quality trading under the condition that surface water diversions are occurring; if surface water diversions are not occurring, the Wanaque Reservoir is not vulnerable to phosphorus-induced hot spots from water quality trading. In contrast, because Dundee Lake is the natural watershed outlet and thus receives upstream phosphorus loads under all flow conditions, regardless of the occurrence of surface water diversions (Omni Environmental 2007a), it is always vulnerable to phosphorus-induced hot spots from water quality trading. This distinction between the two locations is critical to the development of a water quality trading framework that avoids the creation of hot spots and is vital to completing the next two stages in the chosen EDSS approach.

Design Stage

In this stage, a framework is designed to address the physical boundaries that govern trading among WWTPs and ensure the avoidance of phosphorus-induced hot spots.

The US EPA (2004) has recommended approaches to ensure hot-spot avoidance in a water quality trading program, such as to restrict trades so that the seller is always upstream of the buyer or to restrict the number of credits that may be used in an area susceptible to hot spots.

In light of the findings from the previous stage, the trading program development team (comprising experts in water quality modeling, wastewater treatment, environmental law and policy, and environmental economics) has proposed a trading framework that is expected to protect the Non-Tidal Passaic River Basin from phosphorus-induced hot spots associated with trading. The proposed framework establishes three "management areas" within the watershed. A management area is delineated so that its outlet represents the *only* hot-spot concern in that management area. Because there are no hot-spot concerns in addition to the management area outlets, bidirectional trades (i.e., seller can be upstream or downstream of the buyer) are allowed *within* the same management area. Trades are subject to a trading ratio in order to equalize the load traded and account for differences in attenuation of load from each WWTP relative to the management area outlet.

In comparison with a more rigid framework that stipulates that the seller must always be upstream of the buyer, the Passaic trading framework increases opportunities for trading and potential market size. Water quality is protected on the basis that high phosphorus at some, not all, locations is a hot-spot concern (viz. the Wanaque Reservoir and Dundee Lake) as determined from water quality studies conducted throughout the watershed (Omni Environmental 2007a). Dundee Lake and the pump intake for surface water diversions to the Wanaque Reservoir (i.e., Wanaque South intake) are the two management area outlets; both outlet locations can receive phosphorus loads from upstream wastewater treatment plants. Because the pump intake is located at the confluence of the Passaic and Pompton rivers and surface water diversions are designed to draw from either the Pompton River by itself *or* jointly from the Pompton and Passaic rivers, the pump intake is the outlet for two separate management areas. In total, three management areas are delineated: the Pompton management area, the Upper Passaic management area, and the Lower Passaic management area (Fig. 3).

Choice Stage

The previous stage focused on *intra*management area trading. This stage evaluates *inter*management area trading and the necessary restrictions to avoid phosphorus-induced hot spots.

Due to fluctuations in precipitation and demand for drinking water from the Wanaque Reservoir, three potential surface water diversion scenarios can occur with respect to the Wanaque South intake. These scenarios, termed "no diversion," "diversion," and "extreme diversion," are explained in detail next. Each scenario creates a different relationship between the three management areas and potential phosphorus-induced hot spots, and as a result, restrictions on intermanagement area trading differ with each scenario.

In the "no diversion" scenario, the Wanaque South intake is not activated; thus, the Wanaque Reservoir does not receive any phosphorus loads from the 22 WWTPs in the trading project. This leaves Dundee Lake as the only potential phosphorus-induced hot spot. In this case, discharge from the three management areas affects only Dundee Lake and bidirectional trading can occur throughout the entire watershed; each management area

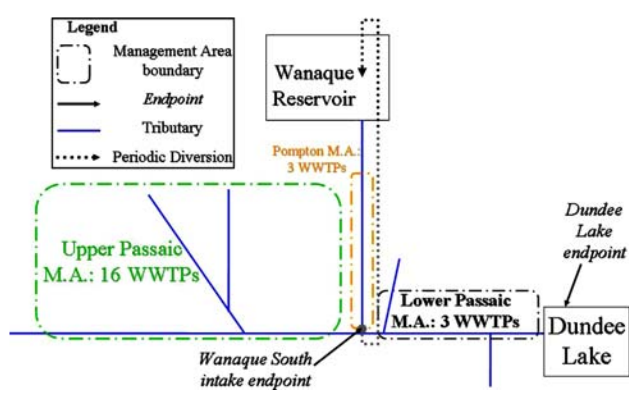

Fig. 3 Passaic trading framework

can buy or sell with the other two management areas, effectively eliminating the need to delineate management areas. The trading framework for the "no diversion" scenario is shown in Fig. 4.

In the "diversion" scenario, the Wanaque South intake pumping demand is met fully by flow in the Pompton River. It diverts surface water to the Wanaque Reservoir from the Pompton River only, not from the Upper Passaic River. Therefore, discharge from WWTPs in the Pompton management area is diverted upstream and impacts the Wanaque Reservoir, and discharge from the Upper and Lower Passaic management areas impact Dundee Lake. (A portion of the Pompton management area discharge reaches Dundee Lake as well.) In contrast with the "no diversion" scenario, the "diversion" scenario has two potential phosphorus-induced hot spots. In order to protect the Wanaque South intake end point, the Pompton management area cannot buy phosphorus credits from the other two management areas. Because discharge from the Upper and Lower Passaic management areas affects only Dundee Lake, these two management areas can trade bidirectionally with each other. The trading framework for the "diversion" scenario is shown in Fig. 5.

Seller \ Buyer	Upper Passaic MA	Pompton MA	Lower Passaic MA
Upper Passaic MA	Yes	Yes	Yes
Pompton MA	Yes	Yes	Yes
Lower Passaic MA	Yes	Yes	Yes

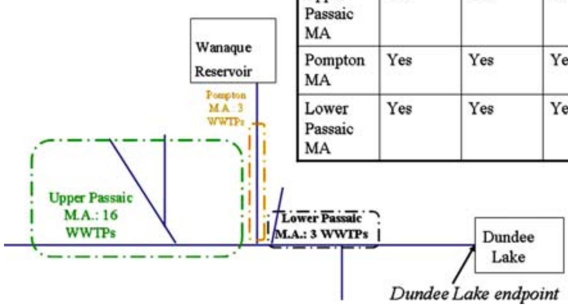

Fig. 4 Passaic trading framework: "no diversion" scenario

In the "extreme diversion" scenario, the Wanaque South intake pumping demand is not met by the Pompton River flow, and surface water is diverted to the Wanaque Reservoir from both the Pompton and Upper Passaic Rivers. Therefore, discharge from WWTPs in the Pompton and Upper Passaic management areas is diverted upstream and impacts the Wanaque Reservoir, and discharge from the Lower Passaic management area impacts Dundee Lake. (A portion of the Pompton and Upper Passaic management area discharge reaches Dundee Lake as well.) Similar to the "diversion" scenario, the "extreme diversion" scenario has two potential phosphorus-induced hot spots. However, in this case, in order to protect the Wanaque South intake end point, the Pompton and Upper Passaic management areas cannot buy phosphorus credits from the Lower Passaic management area. Because the Wanaque South intake is only affected by discharge from the Pompton and Upper Passaic management areas, these two management areas can trade bidirectionally with each other. The trading framework for the "extreme diversion" scenario is shown in Fig. 6.

The Wanaque South intake is not designed to divert surface water from other reaches such as the Lower Passaic River; therefore, the authors only considered existing infrastructure when describing the "diversion" and "extreme diversion" scenarios. This choice is justified by the prohibitive costs and absence of plans to modify the existing diversion infrastructure. In addition, the quantity of diverted water is peripheral to the macroscale issue of trading framework design. Rather, it is the source reach for diversions—Pompton River *or* Pompton and Upper Passaic rivers—that impacts the restrictions on trading between management areas. (However, at the microscale, when the development team proceeded to calculate trading ratios that account for relative attenuation effects of phosphorus between dischargers, a wide range of diverted quantities were included in the analysis. That analysis is the subject of a future article.)

Seller \ Buyer	Upper Passaic MA	Pompton MA	Lower Passaic MA
Upper Passaic MA	Yes	No	Yes
Pompton MA	Yes	Yes	Yes
Lower Passaic MA	Yes	No	Yes

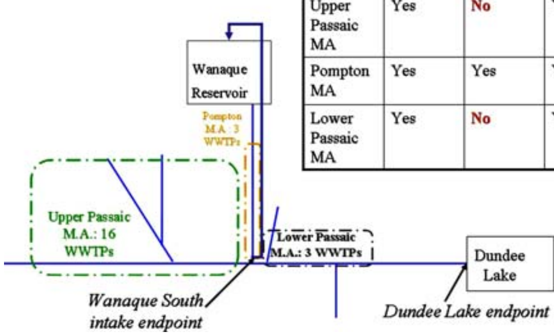

Fig. 5 Passaic trading framework: "diversion" scenario

Seller \ Buyer	Upper Passaic MA	Pompton MA	Lower Passaic MA
Upper Passaic MA	Yes	Yes	Yes
Pompton MA	Yes	Yes	Yes
Lower Passaic MA	No	No	Yes

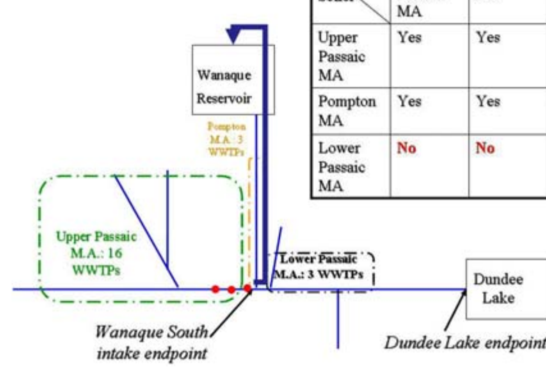

Fig. 6 Passaic trading framework: "extreme diversion" scenario

Selection of a final trading framework completes the third stage of the EDSS process applied herein. In making the selection, it is important to note that the activation of the Wanaque South intake is highly variable both within a single year and between years. In terms of the three scenarios outlined earlier, a shift from one scenario to another can occur multiple times in a year. It would be ineffective to expect the WWTPs involved to constantly jump from one trading framework to another with each change in scenario. That would likely increase transaction costs, as WWTPs would be forced to keep up to date with frequently changing trading restrictions. An alternative approach that would reduce transaction costs, protect water quality under all diversion conditions, and reduce uncertainty and risk to water quality is to merge the three trading frameworks into one framework on the basis of selecting the most stringent option in each possible intermanagement area trade. This will have the adverse effect of reducing the potential number of trades, but that is necessary in order to have a straightforward trading framework that achieves the more important goal of water quality protection under all diversion conditions.

The trading framework shown in Fig. 7 propagates any trades that are not allowed from each of the three scenarios. The result shows that the most conservative option entails consideration of two possible diversion scenarios, and trading between management areas is restricted accordingly. Thus, of the six possible intermanagement area trades, three are allowed and three are not allowed. The Lower Passaic management area can buy from but not sell to the other management areas. Conversely, the Pompton management area can sell to but not buy from the other management areas. Consequently, the Upper Passaic management area can buy from the Pompton management area and sell to the Lower Passaic management area. As noted earlier, all trades are subject to a trading ratio in order to equalize the load traded and account for differences in attenuation of load from each WWTP relative to the appropriate management area outlet.

The final Passaic trading framework (Fig. 7) was developed via an EDSS process that drew on the findings and conclusions of the calibrated/validated TMDL water quality model and supporting data (Omni Environmental 2007a). The EDSS and trading framework described here is consistent with the TMDL supporting studies (NJDEP 2007; Omni Environmental 2007a). Moreover, the EDSS was vital in analyzing the effects of complex surface water diversions on the development of a water quality trading framework that protects water quality, reduces uncertainty and risk, and reduces transaction costs. Its effectiveness is best demonstrated in that it yielded a simple solution to a complex problem.

Seller \ Buyer	Upper Passaic MA	Pompton MA	Lower Passaic MA
Upper Passaic MA	Yes	No	Yes
Pompton MA	Yes	Yes	Yes
Lower Passaic MA	No	No	Yes

Fig. 7 Final Passaic trading framework: protects water quality under all diversion conditions

A series of trade scenarios were simulated (Omni Environmental 2007b) to investigate if the proposed management area framework would protect water quality and ensure hot-spot avoidance at the TMDL end points. Intra-management and intermanagement area trade scenarios that would most stress the system and simulate critical conditions were developed to test the proposed framework (Table 1).

In all trading scenario simulations, the total phosphorus diverted at the Wanaque South intake was equal to or less than the baseline no-trade scenario (Table 2). All trading scenario simulations also demonstrated summer average chlorophyll-*a* concentrations in Dundee Lake that were less than or equal to the baseline no-trade scenario (Table 3). These simulation results verify that the trading framework is robust and can be expected to protect water quality.

Classification of Applied EDSS

Consideration of the previously discussed classification criteria of Funtowicz and Ravetz (1999), Poch and others (2004), and Rizzoli and Young (1997) allows for

Table 1 Description of trading scenarios for water quality simulation

Scenario	General description
1–4	Intra-Upper Passaic MA trade
5, 7, 9–11	Intra-Upper Passaic MA trades, and inter-MA trades between Upper Passaic selling to Lower Passaic and Pompton selling to Upper Passaic
6	Intra-Lower Passaic MA trades
8	Intra-Upper Passaic MA trades, and inter-MA trades between Pompton selling to Lower Passaic
12	Inter-MA trade between Pompton selling to Lower Passaic
13	Inter-MA trade between Upper Passaic selling to Lower Passaic

Table 2 Ratio of trade scenario to baseline for phosphorus load diverted at Wanaque South intake

Scenario	Ratio of TP load diverted (trade scenario:baseline)
1	1.00
2	a
3	1.00
4	1.00
5	0.77
6	1.00
7	0.73
8	0.79
9	0.77
10	0.78
11	0.71
12	0.83
13	0.96

Note: A ratio $\leq$1.00 indicates that the trade simulation had equal or better water quality than the no-trade baseline simulation

[a] No diversions were simulated for this scenario

Source: Adapted from Omni Environmental (2007b)

Table 3 Ratio of trade scenario to baseline for summer average chlorophyll-*a* at Dundee Lake

Scenario	Ratio of summer average chlorophyll-*a* (trade scenario:baseline)
1	0.99
2	1.00
3	0.98
4	0.97
5	0.99
6	0.97
7	0.94
8	0.98
9	0.96
10	0.96
11	0.98
12	0.99
13	0.99

Note: A ratio $\leq$1.00 indicates that the trade simulation had equal or better water quality than the no-trade baseline simulation

Source: Adapted from Omni Environmental (2007b)

classification of the problem and the EDSS solution developed in this article.

Based on the intricacy of where and under what conditions phosphorus-induced hot spots can occur in the watershed, the problem encountered is of Level III complexity.

Because the hot-spots issue in the Non-Tidal Passaic River Basin is characterized by natural phenomena linking phosphorus with algal growth, combined with human alteration of the watershed (WWTPs and surface water diversions), the EDSS type would be classified as situation- and problem-specific.

Spatial distribution of the surface water pump station and WWTPs throughout the watershed merits consideration. Spatial data management, especially GIS, thus plays an essential role for identification and analysis of critical data and information, such as extent of load attenuation from each WWTP.

The potential users of the EDSS include all the project stakeholders: the NJDEP, the US EPA, WWTPs, water purveyors, environmental NGOs, municipalities, and citizens. Environmental scientists and managers affiliated with the above stakeholders are expected to use the EDSS directly in order to explore the impacts of various trading scenarios.

Conclusions

Decision support systems have been evolving since the 1950s to help make systematic, balanced, and optimized decisions that can solve wide-ranging problems. EDSSs have been developing since the 1970s in response to the need to solve increasingly complex environmental problems. Water resource management has been the primary focus area of EDSS efforts to date. Water quality trading is an emerging management alternative to achieve TMDL implementation. The complex multidisciplinary nature of water quality trading makes it highly suitable for the application of EDSS.

An EDSS approach was developed for a water quality trading program intended to implement the TMDL for phosphorus in the Non-Tidal Passaic River Basin of New Jersey. The presence of periodic surface water diversions in the watershed introduces great complexity to the problem of trading and hot-spot avoidance. The applied EDSS, based on Simon's three stages of the decision-making process, enabled selection of a water quality trading framework that protects the watershed from phosphorus-induced hot spots under all three surface water diversion scenarios. Three options were condensed to a single framework that clearly addresses both intramanagement and intermanagement area trades. The EDSS delivered a simple solution to a complex problem that benefits the water quality trading program with reduced transaction costs, reduced uncertainty and risk, and ensured water quality protection.

Future areas for EDSS research in water quality trading include evaluation of specific trading scenarios in terms of economic costs and benefits, as well as selection of an optimal permitting approach for regulators to administer trading programs and minimize transaction costs.

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References

Cortes U, Sanchez-Marre M, Ceccaroni L, Roda IR, Poch M (2000) Artificial intelligence and environmental decision support systems. Artificial Intelligence 13:77–91

Chen CW, Herr J, Weintraub L (2004) Decision support system for stakeholder involvement. Journal of Environmental Engineering 130(6):714–721

Chen CW, Herr J, Ziemelis L, Goldstein RA, Olmsted L (1999) Decision Support System for Total Maximum Daily Load. Journal of Environmental Engineering 125(7):653–659

Demissie M, Tidrick M (2001) The Illinois River Decision Support System (ILRDSS). American Water Resource Association Proceedings for Decision Support Systems for Water Resources Management. Snowbird, UT, pp 7–12

Doherty J, Johnston JM (2003) Methodologies for calibration and predictive analysis of a watershed model. Journal of the American Water Resources Association 39(2):251–265

Druzdzel MJ, Flynn RR (1999) Decision support systems. In: Encyclopedia of library and information science. A. Kent/Marcel Dekker, New York

Fassio A, Giupponi C, Hiederer R, Simota C (2005) A decision support tool for simulating the effects of alternative policies affecting water resources: an application at the European scale. Journal of Hydrology 304:462–476

Fedra K (1993) GIS and environmental modeling. In: Goodchild MF, Parks BO, Steyaert LT (eds) Environmental modeling with GIS. Oxford University Press, New York

Funtowicz SO, Ravetz JR (1999) Post-normal science: an insight now maturing. Futures 31(7):641–646

Guariso G, Werthner H (1989) Environmental decision support systems. Ellis Horwood/Wiley, New York

Janssen R, Goosen H, Verhoeven ML, Verhoeven JTA, Omtzigt AQA, Maltby E (2005) Decision support for integrated wetland management. Environmental Modeling & Software 20:215–229

Lukasheh AF, Droste RL, Wraith MA (2001) Review of expert system (ES), geographic information system (GIS), decision support system (DSS), and their applications in landfill design and management. Waste Management & Research 19:177–185

Najarian Associates, Inc. (2005) Project Report: Development of a TMDL for the Wanaque Reservoir and cumulative WLAs/LAs for the Passaic River Watershed. Submitted to NJDEP Division of Watershed Management, Trenton, NJ. Available from http://www.state.nj.us/dep/watershedmgt/DOCS/Final%20Report%207-1-05.pdf (accessed 15 September 2006)

NJDEP (New Jersey Department of Environmental Protection) (2004) Integrated water quality monitoring and assessment report (305(b) and 303(d)). Water Assessment Team, Trenton, NJ

NJDEP (New Jersey Department of Environmental Protection) (2007) Total maximum daily load report for the Non-Tidal Passaic River Basin addressing phosphorus impairments—PROPOSED. Division of Watershed Management, Trenton, NJ

NJDWSC (North Jersey District Water Supply Commission) (2002a) Watershed characterization and assessment, a technical report for the Passaic River Basin Watershed Management Project. Watershed Management Area 3: Pompton, Pequannock, Wanaque, and Ramapo River Watersheds. Available from http://njedl.rutgers.edu/ftp/html/2909/index.html

NJDWSC (North Jersey District Water Supply Commission) (2002b) Watershed characterization and assessment, a technical report for the Passaic River Basin Watershed Management Project. Watershed Management Area 4: Lower Passaic and Saddle River Watersheds. Available from http://njedl.rutgers.edu/ftp/html/2910/index.html

NJDWSC (North Jersey District Water Supply Commission) (2002c) Watershed characterization and assessment, a technical report for the Passaic River Basin Watershed Management Project. Watershed Management Area 6: Upper Passaic, Whippany, and Rockaway River Watersheds. Available from http://njedl.rutgers.edu/ftp/html/2911/index.html

Omni Environmental Corporation (2007a) The Non-Tidal Passaic River Basin nutrient TMDL study Phase II watershed model and TMDL calculations: Final report. Omni Environmental Corporation, Princeton, NJ

Omni Environmental Corporation (2007b) Evaluation of phosphorus trading scenarios for the Non-Tidal Passaic River Basin nutrient TMDL. Omni Environmental Corporation, Princenton, NJ

Poch M, Comas J, Rodriguez-Roda I, Sanchez-Marre M, Cortes U (2004) Designing and building real environmental decision support systems. Environmental Modelling & Software 19:857–873

Rauch W, Bertrand-Krajewski J-L, Krebs P et al (2002) Deterministic modelling of integrated urban drainage systems. Water Science and Technology 45(3):81–94

Rizzoli AE, Young WJ (1997) Delivering environmental decision support systems: software tools and techniques. Environmental Modelling & Software 12(2–3):237–249

Sarang A, Baradarannia MR, Lence BJ, Shamsai A (2006) System dynamics application for analyzing adaptive urban water management policies in Tehran. Adaptive Management of Water Resources AWRA Summer Specialty Conference, Missoula, MT

Simon HA (1960) The new science of management decision. Harper & Row, New York

Thill JC (1999) Spatial multicriteria decision making and analysis: a geographic information science approach. Ashgate Publishing, Aldershot, UK

U.S. Census Bureau (2002) Census 2000 data for the State of New Jersey. Available from http://www.census.gov/census2000/states/nj.html (accessed 15 December 2005)

USEPA (United States Environmental Protection Agency) (2004) Water quality trading assessment handbook. Technical Report EPA 841-B-04-001. Office of Water, Washington DC

USEPA (United States Environmental Protection Agency) (2003) Final water quality trading policy. Available from http://www.epa.gov/owow/watershed/trading/finalpolicy2003.pdf (accessed December 2006)