

## Managing water quality in a New York City watershed

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### ABSTRACT

Currently economic growth in a New York City watershed is limited due to phosphorus concentrations exceeding standards. The phosphorus concentration in the Cannonsville reservoir in New York State must be reduced to safeguard New York City's drinking water supply, and to enable economic growth to continue in the reservoir's watershed. In Delaware County, where the reservoir is located, the problem of finding and selecting promising measures to reduce phosphorus loads is extremely complex and involves numerous stakeholders. A two-level modeling approach based on Visual-Interactive Decision Modeling (VIDEMO) was used to analyse the problem, using game theory and optimization. The analysis resulted in practical guidelines for land use management, taking into consideration the possible strategies by other parties and stakeholders.

**Key words** | water quality management, decision making, conceptual modeling, New York City watershed, phosphorus management, policy analysis.

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### INTRODUCTION

Decision making in water management faces increasing complexity and uncertainty. Not only are the physical processes difficult to describe and to analyse, but also numerous parties are involved in decision making, each with its own values and views on water management. This growing complexity has led to the use of different analytic concepts and models to address water management problems (e.g. Thiessen *et al.* 1998; Schleich & White 1997; Becker & Easter 1997; Watkins *et al.* 2000). Models can help decision makers structure knowledge and identify information gaps. This may help them set priorities and prepare for negotiations with other stakeholders.

Rather than approaching water management problems from one specific analytic concept, using this NYC watershed problem we intend to illustrate the benefits of a problem-oriented approach that integrates various analytic concepts. If the choice for an analytic method is made before a clear understanding of the problem has been gained, the risk of trying to solve the wrong problem increases. Starting with a broad problem-oriented approach can improve the communication between analysts and decision makers, as

communication is less likely to be distorted by the use of a certain analytic method (Loucks 1992).

The problem that is addressed in this paper is that of water quality management in a watershed that provides water to New York City. The inhabitants of New York City depend on upstate watersheds for their drinking water supply. Water is collected in several reservoirs and is not filtered before distribution to the users. New York City wants to maintain this situation because filtration is very costly. This is only possible if the Federal Environmental Protection Agency (EPA) grants New York City the filtration avoidance it requested in 1992 and if the water in the reservoirs meets very high quality standards.

Currently the phosphorus concentration in the Cannonsville reservoir in Delaware County does not meet the Federal standards, thus limiting the use of the reservoir's water (Hermans 1999). Based on the prevalent watershed rules, set by New York City in co-ordination with New York State, the Cannonsville watershed has a phosphorus restricted status. This status prohibits the addition of phosphorus loads in the watershed, which in turn severely restricts economic growth.

This problem will be analysed from the perspective of the local government of Delaware County. It is a complex decision problem with respect to the behaviour of phosphorus in the physical environment, but also because of the societal issues related to water quality management. Local government agencies and businesses inside Delaware County are involved, as well as New York City's water supply agency, State and Federal environmental protection agencies and various citizen interest groups. Delaware County will have to take into account the interests and possible courses of actions of these other organisations in the formulation of its strategy.

This paper demonstrates a modeling approach that can be used by the analysts to support the decision makers in Delaware County to gain insight into the problem situation and to grasp some of the important issues. This approach, called Visual Interactive Decision Modeling (VIDEMO) (Beroggi 1999*b*) is a problem-oriented approach. Reported advantages of VIDEMO are that the problem is not constrained too early in the problem solving process, that the visual approach provides an easy communication platform between analysts and policy makers, and that it covers a wide range of analytic operations research and management science tools (Largesse *et al.* 1996; Beroggi 1999*b, c*, 2000).

This paper will continue with a short introduction of the VIDEMO approach, after which its use is illustrated by application to the case of Delaware County. The strategic level problem and the tactical level problem were analysed separately. Game theory was used for the strategic analysis, while integer programming was used at the tactical level. The results of both analyses are discussed. The paper ends with an evaluation of the modeling approaches applied to this problem.

## VISUAL INTERACTIVE DECISION MODELING

Visual Interactive Decision Modeling (VIDEMO) provides an environment where the analyst, together with stakeholders (which we will denote as the decision makers) can focus first on problem identification, then on model definition, and finally on problem resolution. The

modeling process begins by translating the decision maker's mental model into a visual model that depicts the elements of the problem and their relations. Six classes of elements are used. They are derived from a broad spectrum of analytic modeling approaches. These element classes are (Beroggi 1999*a, b*):

1. actors: decision makers or stakeholders;
2. actions: alternatives, tactics, or strategies, depending on the level of abstraction at which the problem is addressed;
3. criteria: used to evaluate the actions;
4. scenarios: uncertain events that must be considered when evaluating the actions;
5. content goals: aspiration levels for criteria, for example, to maximise profit, or to realise at least a certain target reduction of costs;
6. structural goals: state how actions must be combined to form potential solutions.

Next, appropriate analytic modeling and solution algorithms are selected to formalise and to solve the structural model. Finally possible resolution strategies are defined and used in an attempt to satisfy all content and structural goals simultaneously. The VIDEMO approach will be applied first at the strategic and then at the tactical level of the water quality problem in Delaware County.

## STRATEGIC ANALYSIS

The problem that Delaware County faces is essentially the tactical problem of how to reduce the phosphorus loads in the Cannonsville watershed. However, before addressing this tactical level problem, it is important to frame it in its strategic context. This helps to explain its background and provides the information for a critical assessment: why phosphorus loads need to be reduced, what other parties outside the County are involved in this problem, what might happen if Delaware County does not succeed in reducing phosphorus loads, and does Delaware County have any other options? To address these questions, the problem was thus first placed into its broader context, by analysing it on the strategic level.

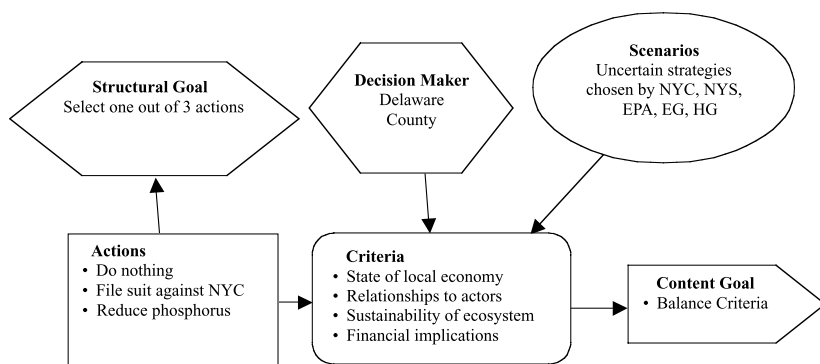


Figure 1 | Structural model at strategic policy level.

### Structural model at strategic level

The structural model of Delaware County's water quality management problem consists of the elements and relationships depicted in Figure 1. The six main actors involved at the strategic level are Delaware County (DC), New York City (NYC), New York State (NYS), the U.S. Environmental Protection Agency (EPA), environmental pressure groups (EG), and health interest groups (HG).

The model was constructed from Delaware County's (DC) perspective, where the decisions of the other actors are uncertain events (scenarios). This implies that DC perceives the actors to be in competition with one another, rather than assuming that the actors seek a collaborative solution. In the former case, concepts from game theory are appropriate analytic methods, while in the latter case, methods from group decision making would be appropriate analytic methods.

DC's main objective is to provide good living conditions for its inhabitants, while its greatest concern is economic development, as the county's traditional rural economy has encountered difficulties in adjusting to recent (inter)national developments (DC 1997). The phosphorus-restricted status of the Cannonsville watershed poses an important constraint to economic development, and therefore DC wants to evaluate possible strategies to deal with this issue. Three possible strategies are included in the structural model:

1. DC could choose to do nothing, but this would probably maintain the phosphorus-restricted status.
2. DC could attempt to lift the restrictions by filing a lawsuit against the watershed rules that were set by NYC. There is no guarantee of success, however.
3. DC could try to reduce the level of phosphorus loads through the implementation of phosphorus management measures.

The criteria used to evaluate the strategies were derived from DC's main objectives outlined above. The state of the local economy was identified as a criterion related to economic development. Because this development is currently hampered by environmental problems, and related also to the good living conditions, the criterion sustainability of the ecosystem was identified. Possible financial implications were added because of direct practical concerns; any strategy should be within the financial scope of the local government. The relationships with the other actors were added to acknowledge the importance of other actors for realising DC's objectives. The structural goal was to select one of the three strategies. The content goal was to balance these criteria in favour of DC's own interests in evaluating the strategies and scenarios.

### Formal model based on a game theoretic approach

The structural model described above was characterised by the important role of the uncertainty in the strategies

chosen by the other actors. Such a structure points to game theory as a suitable modeling approach to describe and analyse the problem. The formal model was drawn using elements of the metagame approach described by Howard (1989) to enable a focus on the uncertain strategies of other actors. The basis of the approach was the analysis of options that different actors had, the possible ways in which these options could be combined to form scenarios, and the preferences of actors regarding certain options or scenarios (Howard 1989).

The six main actors, their decision options and indications of how they would like other actors to decide are summarised in Table 1.

New York City (NYC) is mainly interested in obtaining safe drinking water at low cost. When analysing the options independently, NYC will prefer to do nothing and maintain the current situation of not having to filter its water. At the other end of the continuum is option 4: 'build a filtration plant'. NYC definitely wants to avoid this option since it would require an investment of more than  $5 \times 10^9$  US\$ (Okun *et al.* 1997). NYC could also try to reduce the phosphorus loads in the Cannonsville watershed. It could do this in a harsh way by developing stricter watershed rules, posing even more restrictions on the activities in the watershed (option 2), or in a co-operative manner, by assisting the local organisations in their efforts to reduce phosphorus loads (option 3). NYC cannot select any of its options by considering only its own preferences. It also has to account for the risk that the selected option would result in an unfavorable decision being made by EPA. As Table 1 shows, it is of crucial importance to NYC that EPA decides to grant NYC filtration avoidance.

The options of DC have been discussed as part of the structural model. Related to the other actors' strategies, DC's main concern is that there will be no stiffening of existing watershed rules, as this is expected to lead to economic decline.

New York State (NYS) is concerned with the well being of the state, so it has to account for the interests of both DC and NYC. NYS could try to stimulate a co-operative attitude between NYC and DC by supporting phosphorus management activities. If NYC decided to draft new watershed regulations, the approval of NYS

would be necessary to make the regulations legally binding.

EPA is the agency that ultimately makes the decision regarding the need for a filtration plant. EPA is, in this situation, a 'reactive' actor. It will base its actions on those of the other actors involved and it uses the effects of those other actions as input in its decision procedure.

The environmental pressure groups (EG) aim at protecting the environment and they regard pollution reduction, including phosphorus reduction, as necessary, regardless of filtration.

Health interest groups (HG) are primarily concerned about the health risks of an unfiltered drinking water supply. They regard filtration to be necessary, regardless of phosphorus reduction efforts, since without filtration there will always be some remaining health risks related to pathogens that could cause human diseases (Okun *et al.* 1997).

The scenarios that refer to the strategies chosen by the other actors were incorporated in the formal model by combining the options shown in Table 1. There were some constraints as to how the options could be combined. None of the actors could combine their 'do nothing' option with any of their other options. If EPA decided not to grant NYC a filtration waiver (not-option 12), NYC was forced to build a filtration plant (option 4), i.e. not-option 12 had to be combined with option 4. If EPA selected option 13, NYC had to implement option 2 and/or 3. Finally, option 2, stricter watershed rules, was only possible if it was approved by NYS (option 10).

Several scenarios were composed, acknowledging the hard constraints stated above. These scenarios are discussed below.

### Co-operation between government agencies

In this scenario all the government agencies co-operate with the aim of reducing the phosphorus concentration in the Cannonsville reservoir, thus lifting the phosphorus restrictions and avoiding filtration. This could be a stable scenario as long as NYC, DC and NYS trust each other to continue their co-operative strategies. EPA would do nothing until 2002. EG and HG would be dissatisfied with

**Table 1** | The six main actors and their decision options<sup>a</sup>

Actors and options	Preferences of actors related to options					
	NYC	DC	NYS	EPA	EG	HG
NYC						
1. Do nothing	1	0	0	0	0	0
2. Reduce phosphorus load through stricter watershed rules	0	<b>0<sup>b</sup></b>	0		1	1
3. Reduce phosphorus load through provision of technical assistance and funds for phosphorus management	0	1	1	1	1	1
4. Build a filtration plant for the Delaware system	<b>0<sup>b</sup></b>	1	0			1
DC						
5. Do nothing	0	1	0	0	0	0
6. File suit against NYC's restricting watershed rules	0	0	0		0	
7. Reduce phosphorus loads through implementation of phosphorus management measures	1	0	1	1	1	1
NYS						
8. Do nothing	0	0		0	0	0
9. Support phosphorus management through technical assistance and funds	1	1		1	1	1
10. Approve of stricter watershed rules and regulations when proposed by NYC	1	<b>0</b>			1	1
EPA						
11. Do nothing	0		0		0	0
12. Grant NYC filtration avoidance	<b>1</b>		1			<b>0</b>
13. Order NYC to undertake (additional) pollution reduction efforts	0	0			1	1
EG						
14. Try to direct public attention to need for pollution reduction	0	0			1	1
15. Do nothing	1	1			0	0
HG						
16. Try to direct public attention to health risks of non-filtration	0					1
17. Do nothing	1					0

<sup>a</sup>Explanation of cell contents: '1': actor in corresponding column prefers that option is executed by the controlling actor; '0': actor prefers that option is not executed; empty cell: actor is indifferent regarding the option.

<sup>b</sup>Figures in bold: these options are of crucial importance to the corresponding actor.

this scenario, but they probably would not have enough power to bring about any changes.

### Strict application of rules by EPA

This situation could arise if EPA decides to take action before 2002 and requires filtration and additional phosphorus reduction measures. In this case NYC could respond by implementing options 2 and 4 (stricter rules and building a filtration plant). By implementing option 2, NYC would create a very bad situation for DC. DC's only option that might have some chance of changing this situation would be to challenge the new watershed rules (option 6).

### Co-operation between government agencies, but with a change in NYC's risk perception

This scenario could follow on from the first scenario if NYC perceives the co-operative activities to be insufficient to realise the necessary phosphorus reductions. NYC would then draft new, stricter, watershed rules to increase the phosphorus reductions, which would be bad for DC.

### Capitulation by NYC

This is the scenario where NYC decides to build a filtration plant and to stimulate phosphorus reduction activities in the watershed, with which the other actors co-operate. This scenario releases most of the pressure for DC, as it would receive support and water quality standards could be lowered because the water would be filtered. The scenario would force NYC to spend large sums of money on both filtration and phosphorus reduction.

### Hard play by NYC

NYC could ignore the other actors and execute a strategy based solely on its own preferences. As a result, DC would suffer from increased pressure from stricter watershed rules. If DC chooses to go to court, NYC's position could be weakened by its non-co-operative attitude.

### Inactivity

A situation of inactivity might occur for a limited period, but it would be unstable, as eventually one of the actors would have to act. If the situation would last too long, there would be increasing risks that it would lead to a situation like the second scenario. This final scenario would not seem to lead to any improvement, but it would not require any investment either, and therefore it would be neutral for both NYC and NYS. DC would not prefer this situation as it wants to lift the phosphorus restrictions and inactivity at higher levels of government might prevent that from happening.

Table 2 depicts these scenarios as the combination of options selected by the other actors (marked by 'x' in the table). The last three rows of Table 2 show the possible combinations of scenarios with DC's options. The entries in the cells of these rows are estimated utilities on a scale from 1 (worst) to 10 (best). The first figure in a cell represents the utility for DC, the second the utility for the other actors. The latter represents an aggregated utility, with the highest weight assessed to NYC, as NYC was considered to be the most important of the other actors.

### Analysis of the strategic level problem

The analysis of the formal model was based on security levels, where DC and the other actors were assumed to be two non-co-operative actors that took independent decisions. The security level was defined as the minimum expected utility that a party could achieve, independent of the other party, i.e. the conservative MaxMin strategy (Beroggi 1999a). The use of such security levels helps to gain insight into courses of action that seem likely to occur if actors do not co-operate.

Following this strategy, DC should select option 6, as this maximises its minimum utility at the level of 4. The other actors should choose options E or F, and since option E dominates F, the others should choose option E. The solution would thus be E/6, with utilities of (4, 4), marked by shading in Table 2.

Table 2 shows that there were several solutions dominating solution E/6. Solutions 7/A with utilities (7, 7), 7/D (9, 4), and 5/A (9, 4) were dominating solutions, of which solution 7/A was system optimal. The

**Table 2** | Decision strategies and conflict table for Delaware County and the other actors<sup>a</sup>

Actors	Options	Scenarios					
		A	B	C	D	E	F
NYC	1						×
NYC	2		×	×		×	
NYC	3	×		×	×		
NYC	4		×		×		
NYS	8						×
NYS	9	×	×	×	×		
NYS	10		×	×		×	
EPA	11	×			×	×	×
EPA	12		Not-12				
EPA	13		×	×			
EG	14	×		×			×
EG	15		×		×	×	
HG	16	×		×			×
HG	17		×		×	×	
DC	5	(9,4)	(2,3)	(2,5)	(10,3)	(2,7)	(3,5)
DC	6	(8,3)	(4,2)	(4,3)	(9,2)	<b>(4,4)<sup>b</sup></b>	(5,4)
DC	7	<b>(7,7)<sup>b</sup></b>	(3,4)	(3,8)	(9,4)	(3,8)	(4,6)

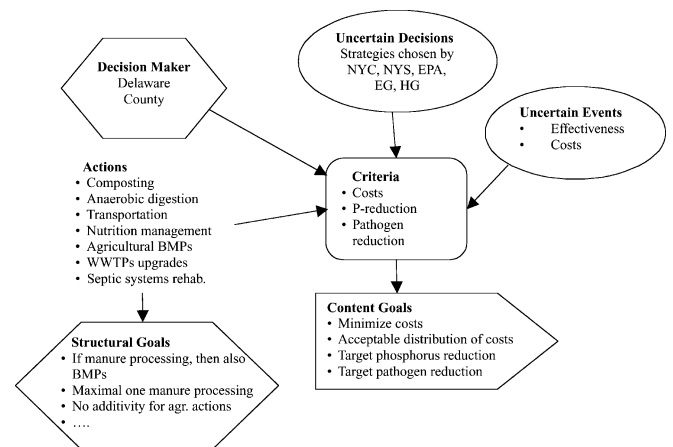
<sup>a</sup>Explanation of cell contents: × in a cell means that an option is selected by an actor as part of a scenario. Last three rows contain utilities for DC and others in case a scenario is combined with option of DC (utility DC, utility others).

<sup>b</sup>Utilities in bold are system optimal resp. MaxMin solutions.

actors could arrive at this solution if they would be willing to co-operate to improve their utilities from (4, 4) to (7, 7).

### Implications of strategic level analysis for Delaware County

The strategic level analysis shows the benefits of a co-operative strategy for both DC and the other actors.

**Figure 2** | Structural model of the Delaware County phosphorus management problem.

The analysis also shows that the system optimal co-operative solution would only be stable as long as all the participants are indeed willing to co-operate. The co-operative scenario is the scenario that is being executed by the actors involved, after some other scenarios were tried initially (Hermans 1999). In this way, the strategic level analysis clarifies the boundaries within which the tactical level problem occurs. Delaware's part in the scenario is to reduce phosphorus loads, which brings us back to the tactical level problem: how to reduce the phosphorus loads in the Cannonsville basin.

## TACTICAL ANALYSIS

### Structural model of the phosphorus management problem

The tactical level problem of Delaware County is depicted in the structural model in Figure 2. The structural model indicates that DC does not specify a set of explicit measures to solve the problem. Instead, implicit actions are defined which, in combination, make up feasible solutions. In the case of explicitly defined solution measures, multicriteria decision models would be the appropriate analytic methods. In the latter case, however, concepts from mathematical programming are appropriate.

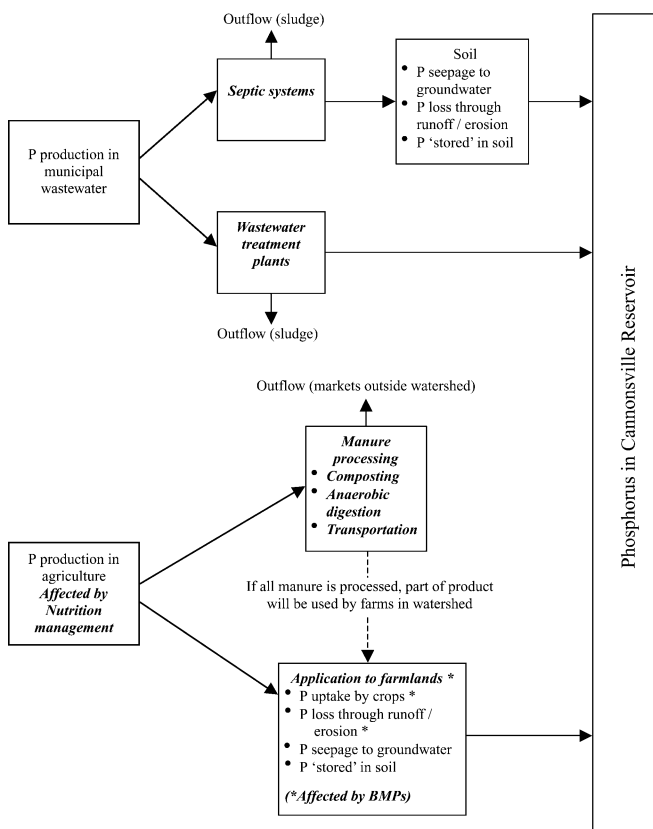


Figure 3 | Phosphorus flows related to the actions at the tactical level.

An analysis of the principal sources of phosphorus in the watershed led to a selection of actions for DC related to dairy farming and municipal wastewater. Dairy farming is an important source, mainly because of the phosphorus contained in the dairy cows' manure, which is applied to the farmlands. A part of this phosphorus would be used for uptake by the crops, but a considerable amount would runoff to watercourses or would contribute to an increase of phosphorus in the soil. One possibility to reduce the phosphorus loads produced by the dairy farming was related to the processing of manure, either by composting or anaerobic digestion. The products could then be sold as fertiliser to interested parties outside the Cannonsville watershed. Another possibility would be to simply transport the raw manure to places outside the watershed where there is a demand for low-value fertiliser. Other options were to improve the nutrition of the dairy cows to reduce the amount of phosphorus that the animals

excreted, and to improve agricultural management practices, mainly by reducing the phosphorus loads by controlling rainwater runoff from farmlands. Municipal wastewater could be addressed through rehabilitating the large number of septic tanks that are expected to be malfunctioning, or by upgrading the larger wastewater treatment plants to reduce the phosphorus concentration in the treated effluent.

The relations between the actions and their effects on the phosphorus flows in the watershed are illustrated in Figure 3.

The criteria identified to evaluate the possible phosphorus management strategies were estimated costs, distribution of these costs over different parties, reduction of phosphorus loads in the short term (before 2002), reduction in the long term, related to sustainability of the solutions, and reduction of pathogens. The reduction of pathogens was included in the model as the water quality standards for the Cannonsville reservoir also required a reduction of pathogens, albeit less urgently (NYSWRI & NYCDEP 1997). Phosphorus management measures that also reduced the number of pathogens would be beneficial to DC, because they would save money and effort required to implement separate measures to control pathogens.

The content goals described the aspirations of the decision maker, which were minimisation of costs, equal distribution of costs over the various actors and reduction of phosphorus loads and pathogens below certain target levels. The structural goals were related to the combinations of actions that could form management strategies. DC could select several options at the same time, but just summing up the effects was not possible for all of the options. For example, manure processing actions must be combined with agricultural best management practices (BMPs) to prevent negative impacts on crop growth due to phosphorus shortages. And the additivity of effects did not hold for agricultural actions, as they all address the same source of phosphorus. Decreasing the amount of phosphorus in the manure due to balanced dairy cow nutrition will also decrease the phosphorus reduction realised by processing this manure.

The uncertainty on the tactical level was incorporated in the model by referring to the uncertainty in the related



strategic level model, i.e. the decisions of the other actors, and by the two parameters that appeared to account for most other types of uncertainty: costs and effectiveness of actions. The uncertainty related to the other actors was primarily included as a reference to the boundary conditions within which the tactical level analysis was performed; if the other actors would select non-co-operative strategies, the tactical level analysis would have to be reconsidered.

### Formal model using integer programming

Observation of the structural model showed that it would fit a static optimisation approach. The formulation of actions in the structural model led to the choice for an integer programming (IP) approach, as the decision variables related to the actions would be integer or binary variables.

The details of the constructed integer programming model are presented in Appendix A. The model was composed by translating the structural model into linear mathematical expressions, using assumptions of proportionality and additivity (Hillier & Lieberman 1995).

The structural model showed that the additivity assumption did not hold for agricultural actions. Several decision variables were needed to incorporate some of the agricultural actions in the IP model. The action of upgrading wastewater treatment plants was included in the model by means of four binary decision variables. These four binary variables represented the larger plants in the watershed, located near the villages of Walton, Delhi, Stamford and Hobart. The IP model included a total of 20 decision variables (see Appendix A).

The values of some of the coefficients contained in the model were subject to the uncertainty related to 'costs' and 'effectiveness'. Three scenarios were considered to incorporate this uncertainty, based on most optimistic, most pessimistic and most likely estimations of the uncertain coefficients.

The values for the content goals were not a given but depended on the uncertain outcomes of a political negotiation process. Different values were used to explore possible situations within the three scenarios defined above.

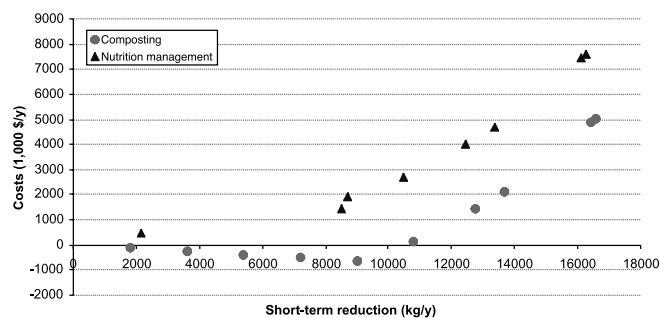


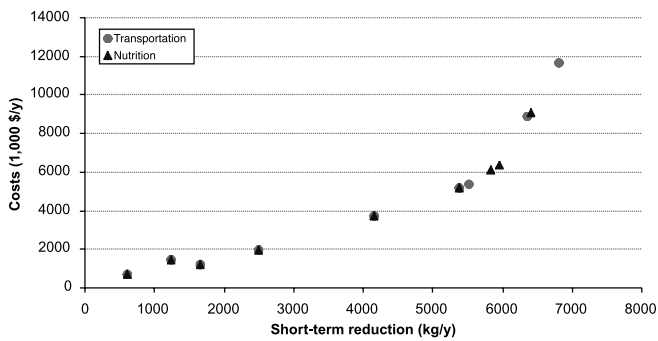
Figure 4 | Cost-effectiveness of strategies for optimistic scenario.

The target for the short-term reduction of phosphorus was the most important content goal. If this goal would not be met, then the phosphorus restrictions would not be lifted and DC's problem would not be solved. The short-term reduction target was expressed as a reduction of the average annual load, in accordance with the official standards defined in the NYC watershed rules. The estimated target was based on standards proposed by NYC's Department of Environmental Protection, which resulted in a target reduction of approximately  $17,000 \text{ kg y}^{-1}$  (Hermans 1999; Kane 1999).

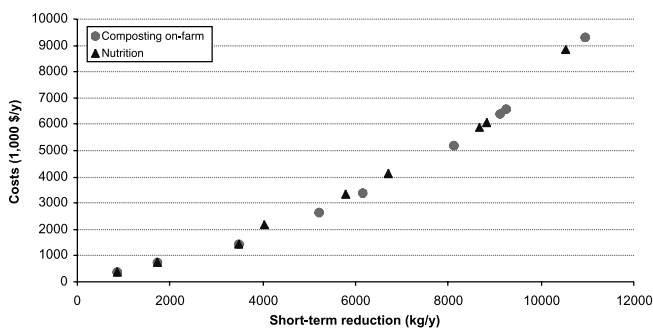
### Analysis of the tactical level problem

The computations were done in MS Excel because of its general availability and ease of future use or adaptation by interested parties. The model was solved for different scenarios, and the results were presented using graphs and tables. The most important result was the insight into the cost-effectiveness of possible solutions regarding short-term phosphorus reductions. Figures 4–6 illustrate these results.

Each point in the graphs of Figures 4–6 represents a solution, consisting of a certain combination of actions. The solutions in these graphs from left to right usually consist of increasingly different actions, which explains the increase in both costs and reductions. The solutions at the right end of each graph represent the maximum possible reductions that can be reached in a particular scenario.



**Figure 5** | Cost-effectiveness of strategies for pessimistic scenario.

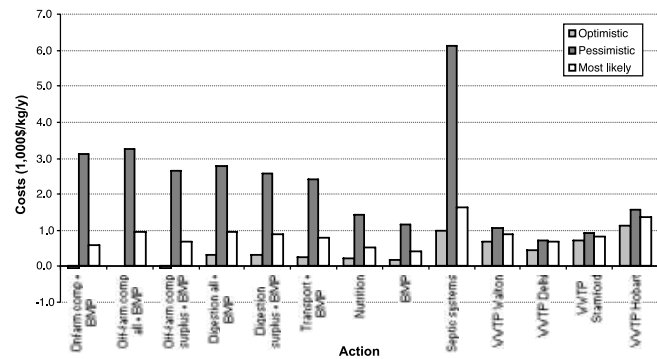


**Figure 6** | Cost-effectiveness of strategies for most likely scenario.

Manure processing was contained in most solutions, but it was not clear if there was indeed a good market for compost or manure. Therefore, solutions without manure processing were also depicted, to account for the case in which there would be no market for (treated) manure. The bullets in the graphs in Figures 4–6 correspond to solution series that include manure processing and triangles represent solution series without manure processing.

It is useful to compare the cost-effectiveness of actions across scenarios, in addition to the analysis of results within scenarios. Figure 7 shows the cost-effectiveness of the actions for different scenarios, again related to short-term phosphorus reductions. Note that manure processing actions in this graph are always combined with agricultural BMPs because of the model's structural goals.

A sensitivity analysis revealed that the model solutions were sensitive to estimations regarding the costs for composting and the contribution of failing septic



**Figure 7** | Costs of short-term phosphorus reductions per action for different scenarios.

systems to phosphorus loads in the watershed. Most of the other uncertain variables seemed to be effectively included in the scenarios.

### Implications of tactical level analysis for Delaware County

The tactical level analysis led to several valuable insights for DC for addressing its water quality management problem. The most important observation was that the target for short-term phosphorus reductions was not met. Only in the most optimistic scenario was the target value of  $17,000 \text{ kg y}^{-1}$  approached. The model contained actions that addressed only the major sources of phosphorus. Including minor sources could lead to some additional phosphorus reduction, but hardly enough to secure realisation of the target.

The study also revealed that implementing agricultural BMPs was the most promising individual action, that upgrading the municipal wastewater treatment plants of Delhi, Stamford and Walton was likely to produce robust and reasonable results, that off-farm processing of only surplus manure would be better than processing all manure, that rehabilitation of septic systems was, in general, the least attractive option and that an additional exploration of potential markets for compost was urgently required.

The sustainability of solutions was assessed based on estimations of the balancing of phosphorus loads in the long term. The exact period within which these reductions should be reached could not be determined, because the

soil capacity for phosphorus uptake was unknown. However, the results did indicate that actions of manure processing and the rehabilitation of septic systems showed potential for meeting the sustainability demands.

Generally, enough financial funds seem to be available for the implementation of phosphorus management strategies. These funds have been made available by NYC, NYS and Federal government institutions (Hermans 1999). However, it is important that DC indeed succeeds in acquiring its share of these funds and that NYC maintains its earlier promise to pay the costs for the upgrade of the municipal wastewater treatment plants.

The most important conclusion of the tactical level analysis was that short-term reduction targets for phosphorus would be very difficult to realise. There was a high risk that the Cannonsville watershed would remain phosphorus restricted. This would impair economic development in DC and would have a negative influence on the EPA determination on filtration avoidance. One way to deal with this situation would be to evaluate the target values, which were based on the official standards. Official standards specified thresholds for the annual loads of total phosphorus, based on concentrations of total phosphorus in the reservoir. Using modified targets might be a more suitable approach, since the problem related to phosphorus-limited algae growth seems to be influenced more by dissolved phosphorus, which is only a small part of total phosphorus. Seasonal effects also seem to play an important role (Auer *et al.* 1998; Hermans 1999).

### INTERACTION BETWEEN STRATEGIC AND TACTICAL LEVEL RESULTS

The strategic level results of the third section indicate that the implementation of phosphorus reduction measures in co-operation with NYC and NYS might be a beneficial strategy for DC, as long as the grounds for co-operation are clear for these three actors. However, with current standards, there is a considerable risk that the co-operative strategy could fail. If DC cannot reduce the phosphorus loads to meet the official standards as expected by other actors, the others, especially NYC, might turn against DC. Thus, failure would mean, return-

ing to the strategic level analysis, that scenarios C, B, or E would be more likely to occur. DC would then be better off with a confrontational strategy, such as filing a lawsuit against NYC. The combination of strategic and tactical level analysis in this way points to the importance of a serious evaluation of the official phosphorus standards.

### DISCUSSION OF PROBLEM-ORIENTED ANALYSIS TO SUPPORT DECISION MAKING

The problem-oriented approach illustrated above clearly has some benefits and limitations. The approach aims to support decision makers by collecting, structuring and analysing the available information on a certain issue, in our case water quality management in Delaware County. This means that the results of the analysis, as with all analyses, are limited to what is known at a given time. This has some important implications that should not be overlooked.

The strategic level analysis includes only the most important actors and their preferences, from the perspective of DC. The input information used for this analysis may be incomplete or incorrect, and certainly will be outdated in future. Values and preferences of actors change over time, new actors may enter the scene and new decision options will emerge. As the analysis is naturally affected by this uncertain decision environment, the results of this analysis can only serve as a guideline for analysts and decision makers. The analysis can be improved by showing a sensitivity analysis, for instance related to the estimated preferences of actors, but this is considered to be outside the scope of this paper, which aims to illustrate the usefulness of applying a problem-oriented approach to complex decision problems. Even within the limitations posed by the complex and uncertain environment, the analysis still has some important benefits, as it does structure the available information in a way that clarifies the position of different actors and which enables the explanation of past and contemporary events. To cite Howard: 'Of course, this is "probable" only. You know no more than you know, and can be surprised. But at least you will not be like the United

States at Pearl Harbor – and lesser decision makers since – in not using what you know.’ (Howard 1989, p. 246).

The tactical level analysis is also limited by the current state of knowledge, but based on this, the structural model for this level is believed to be an adequate representation for the problem. This structural model is analysed using a linear optimization technique, which is, of course, not the most sophisticated technique available for analysing complex problems. The VIDEMO approach also accommodates techniques such as probabilistic influence diagrams, group decision making, dynamic programming, multicriteria decision modeling and conflict resolution (Beroggi 1999*b*), and it also allows for inclusion of other techniques such as fuzzy logic and probabilistic approaches, as long as the resulting decision models are problem, rather than tool, oriented.

From the possible range of techniques, integer programming has been chosen here because of its fit with the structural model for the problem at hand. In line with the problem-oriented approach that is central to VIDEMO, a good argument can be made for using the simplest technique that will do the job, rather than a more complex method. A technique that makes it easier for decision makers to follow the general line of reasoning in arriving at conclusions is preferred to one that is harder to understand, even if of more interest to the research community. The selected linear optimization approach produces the insights that are useful to the decision makers.

## CONCLUSIONS

The paper demonstrated an application of a problem-oriented approach to analysing a complex and sensitive political problem, that of managing water quality in one of New York City’s watersheds. The problem was addressed at both the strategic and the tactical level. The step-by-step VIDEMO approach allowed the allocation of the problem to the analytic tools, rather than vice versa. In this way, the bias that a specific technique would be likely to introduce in the definition of a problem was circumvented. Narrowing the analytic framework too early in the process could result in an emphasis on certain aspects of

the problem, while ignoring others that might be of equal relevance.

The modeling approach can help Delaware County gain additional insight into the water management problems it faces. Other actors were also incorporated in the model on the strategic level, not to model and predict their behaviour right down to the smallest detail, but to help Delaware County grasp some of the policy network it finds itself in and that sets the stage for its water-related problems. A problem-oriented modeling approach helps decision makers structure the information that they have and to derive some useful insights and policy guidelines from this information.

Solving the more specific models resulted in some practical recommendations for Delaware County, such as to upgrade its wastewater treatment plants and to seriously consider the possibilities for composting dairy cow manure. Furthermore, an important new insight was obtained on the feasibility of the phosphorus reduction targets. The analysis called for a close evaluation of these targets, as they appeared to be a serious threat to the success of any phosphorus management effort in the watershed.

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## APPENDIX A. INTEGER PROGRAMMING MODEL

This appendix contains the integer programming model that was used to analyse the tactical level problem. The following decision variables were defined:

$C_{onf}$	number of units engaging in on-farm composting all the manure.
$C_{all}/C_{sur}$	number of units engaging in off-farm composting where <i>all</i> , resp. <i>only the surplus</i> , of the manure of a farm is composted in a facility in the watershed.
$D_{all}/D_{sur}$	number of units engaging in off-farm anaerobic digestion where <i>all</i> , resp. <i>only the surplus</i> , of the manure is digested in a facility in the watershed.
$T$	number of units engaging in the transportation of untreated surplus manure to locations outside the watershed.
$N_{no-wm}$	number of farms engaging in nutrition management without manure processing or transportation.
$N_{C-onf}, N_{C-all}, N_{C-sur}, N_{D-all}, N_{D-sur}, N_T$	number of farms engaging in nutrition management together with manure processing or transportation.
$B_{no-n}$	number of farms implementing agricultural best management practices (BMPs) without nutrition management or manure processing.
$B_{nutr}$	number of dairy farms implementing agricultural BMPs together with nutrition management.
$S$	number of malfunctioning septic systems that would be rehabilitated.
$W_W, W_D, W_S, W_H$	upgrading of the wastewater treatment plant (WWTP) located at Walton, Delhi, Stamford, or Hobart. Yes or no.

Units for  $C_{onf}$  and  $T$  consisted of groups of five dairy farms that would share the necessary capital equipment. Units for  $C_{all}$ ,  $C_{sur}$ ,  $D_{all}$  and  $D_{sur}$  consisted of off-farm facilities that would each process the manure of 32 dairy farms. Surplus manure referred to the part of the manure that was not needed for crop growth. Farms always referred to dairy farms, of which it was estimated that there were some 160 dairy farms where actions could be implemented. The integer programming model is stated below:

### Content goals

Minimise total costs:

Minimise

$$Z = c_1 C_{onfarm} + c_2 C_{all} + \dots + c_{20} W_H$$

Targets should be realised for reduction of short-term phosphorus, long-term phosphorus and pathogens:

$$a_{x1} C_{onfarm} + a_{x2} C_{all} + \dots + a_{x20} W_H \geq target_x$$

Acceptable distribution of costs over different groups was required:

$$c_1 C_{onfarm} + c_2 C_{all} + \dots + c_{15} B_{nutr} \leq Cost_{farms}$$

$$c_{16} S \leq Cost_{septics}$$

$$c_{17} W_W + c_{18} W_D + c_{19} W_S + c_{20} W_H \leq Cost_{WWTPs}$$

### Structural goals

Selection of at most one manure processing action, with  $M$  representing a very large value:

$$C_{onfarm} - My_{C-onfarm} \leq 0$$

$$C_{all} - My_{C-all} \leq 0$$

...

$$y_{C-onfarm} + y_{C-all} + y_{C-surplus} + y_{D-all} + y_{D-surplus} + y_T \leq 1$$

Number of farms with nutrition management could not exceed total number of farms:

$$5C_{onfarm} + 32C_{all} + 32C_{surplus} + 32D_{all} + 32D_{surplus} + 5T + N_{no-wm} \leq 160$$

Nutrition management on farms with or without manure processing must be divided correctly:

$$N_{C-onfarm} - 5C_{onfarm} \leq 0$$

$$N_{C-all} - 32C_{all} \leq 0$$

...

Manure processing must be combined with agricultural BMPs:

$$B_{no-nutr} + B_{nutr} \pm 5C_{onfarm} - 32C_{all} - 32C_{surplus} - 32D_{all} - 32D_{surplus} - 5T \leq 0$$

Agricultural BMPs and nutrition management must be combined properly:

$$B_{nutr} - N_{C-onfarm} - N_{C-all} - N_{C-surplus} - N_{D-all} - N_{D-surplus} - N_T \leq 0$$

$$B_{nutr} - N_{no-wm} - N_{C-onfarm} - N_{C-all} - N_{C-surplus} - N_{D-all} - N_{D-surplus} - N_T \leq 0$$

$$N_{no-wm} + N_{no-wm} + N_{C-onfarm} + N_{C-all} + N_{C-surplus} + N_{D-all} + N_{D-surplus} + N_T + B_{no-nutr} \leq 160$$

Number of units is limited by number of dairy farms/mall-functioning septic systems:

$$B_{no-nutr} + B_{nutr} \leq 160$$

$$C_{onfarm}, T \leq 32$$

$$C_{all}, C_{surplus}, D_{all}, D_{surplus}, \leq 5$$

$$S \leq 2,500$$

All decision variables are non-negative integer variables. The variables  $W_W$ ,  $W_D$ ,  $W_S$ ,  $W_H$  and all  $y_i$  are binary.

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