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An analysis of different strategies for the prioritization of groundwater quality prediction studies with a sequential numerical game

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Abstract Groundwater quality prediction studies are carried out to increase the reaction time when drinking water companies have to respond to breakthroughs of contaminants. Drinking water companies exploit numerous wells and need to decide on research priorities for these wells, as budgets are limited. The reliability and accuracy of predictions improve if more funds are invested in data-collection and prediction studies, but there is no clear decision model available to determine the required level of (un)certainty. Hence, it is unclear which prioritization strategy is optimal. Unnecessary losses can occur if inappropriate strategies are followed. A decision analysis of strategies for prioritizing prediction studies is presented in this paper, where the problem is posed as an optimization problem with an explicit loss function. A sequential numerical game was set up in order to assess the effectiveness of different strategies. There were significant differences between the performances of strategies. The most successful strategy used the anticipated uncertainty reduction of additional studies as one of the prioritization criteria and takes the uncertainty of predictions in to account.

Keywords decision making under uncertainty; groundwater quality; groundwater transport; system operation and management

INTRODUCTION

Predictive studies of the chemical composition of pumped groundwater are carried out in order to reduce the risks of failure of drinking water production wells, due to groundwater contamination. These studies function as an early warning system. They provide time for taking counter measures in the event that a contaminant causes the pumped groundwater quality to be unsuitable for drinking water production, and thus reduce the potential consequences. Contamination of wells can lead to high economic costs because the construction of a new well at a different location involves considerable investments in time and infrastructure. If contamination reaches a well before a replacing well becomes available, then the required capacity needs to be temporarily made up from other wells. This may also involve high costs. In the worst situations there may be insufficient time or spare capacity and the supply is affected. Such a worst case scenario implies not only a high economic cost, but also important damage to the customer confidence. Generally, the number of feasible remedial actions decreases if the available reaction time is reduced and the costs of the remaining options increase. Early recognition of an upcoming breakthrough can therefore reduce the adverse impacts.

Due to agricultural and industrial activities over the past decades, the quality of groundwater has deteriorated in many regions. National and international standards for drinking water quality have become more stringent and prediction studies have therefore gained importance. As a result, many drinking water companies need to spend substantial amounts on monitoring and prediction of groundwater quality. Yet, there seems to be no uniform strategy for the prioritization problem of prediction studies. Prioritization of research is required as budgets are limited, but which prioritization strategy to choose is not a trivial question: What is a suitable operational definition of the risk of well failure? Should decision makers aim for minimizing total risk or minimizing maximum risk? How should decision makers account for the uncertainty of predictions? Rational methods are needed in order to spend available budgets efficiently. However, prioritization of prediction studies is often based on *ad hoc* strategies, as more advanced strategies require complex assessments due both to the inherent uncertainty in predictions of pumped groundwater quality, and to the complexity of many present-day regional drinking water supply systems. Best professional judgment, expert judgment and educated guesses may result in suboptimal prioritization.

Freeze *et al.* (1992) developed a method for assessing of value of data in groundwater contamination problems. Finkel & Evans (1987) evaluated the benefits of uncertainty reduction in environmental health risk management. Reichard *et al.* (1990) provided a health risk oriented benefit-cost analysis as a conceptual framework for groundwater management under uncertainty. These studies emphasized that it is essential that the value of data-collection strategies can and should be expressed in terms of their expected impact on decision making. The problem of trend detection in water quality data and the optimal design of monitoring networks and sampling strategies has received considerable attention over the past decades (see e.g. Dixon & Chiswell, 1996). The aforementioned studies focused on methods for determining the cost and value of information, rather than methods for determining the optimal distribution of an already specified budget, as is the subject of this paper. In a more general sense, decision making under uncertainty has been addressed in mathematics by probability theory and utility theory. In contrast with the rare literature on prioritization of prediction studies, many papers have been dedicated to quantifying the uncertainty of predictive simulations. Monte Carlo simulations, Kalman filtering, kriging and other techniques have been applied for assessment of the uncertainty of data and model results (e.g. Delhomme, 1978; Carrera *et al.*, 1984; van Geer, 1987). The use of some of these techniques is currently on its way to becoming common practice in applied research, but it is unclear how decision makers should use this information in the prioritization of prediction studies. The integration of the achievements of the latter studies in decision making strategies for prioritization of prediction studies has thus become an interesting option, and forms the starting point of the analysis that is presented in this paper.

The next section discusses the objectives of predictive studies and gives some operational definitions of system properties. The analysis results in the identification of possible criteria for prioritizing of groundwater quality prediction studies. This section is followed by a description of the general set-up and results of the numerical game experiment that was used as a model for testing the performance of a number of strategies. The paper ends with a discussion of the results and conclusions.

METHODS

We constructed a conceptual sequential game model to investigate the effectiveness of various prioritization strategies, measured in terms of losses due to breakthroughs. Apart from the strategies, the game consists of a “stochastic well properties generator”, including time series of concentrations of pumped groundwater, an uncertainty reduction function and a loss function, related to the impact of an upcoming transgression of a concentration limit. By allocating research budgets to wells, the virtual players/decision makers can reduce the uncertainty of predictions of the future concentration of pumped groundwater from these wells. Uncertainty reduction results in an increase of the expected *minimum reliable reaction time* and sometimes in a sufficiently reliable prediction of a transgression of a quality standard for drinking water, i.e. a prediction of the *maximum reliable reaction time* (Figs 1 and 2).

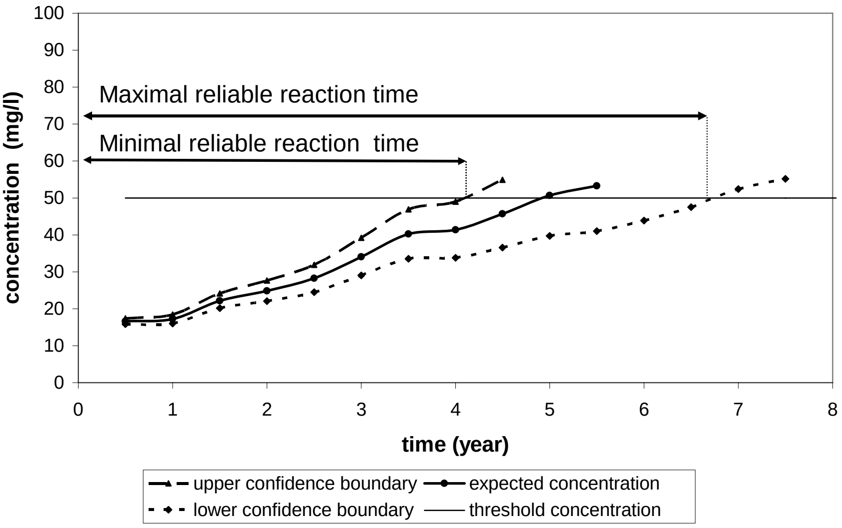

Fig. 1 Minimum and maximum reliable reaction times.

The loss function of the game consists of a function of impacts (costs) that depends on the maximum potential impact of failure of a particular well and the reaction time that is available when an upcoming breakthrough is sufficiently reliably predicted (Fig. 1). The shorter the available reaction time, the higher are the costs of remedial actions. If the reaction time is 50 years or more, impact is 0. If a player is “taken by surprise” by a transgression then the reaction time is 0 and the impact is maximal. A total number of eight game runs were carried out. Every run consisted of 1000 simulated well failures.

Strategies

The following prioritization strategies were defined, each with a different method for the ranking of investment options by calculation of the priority score.

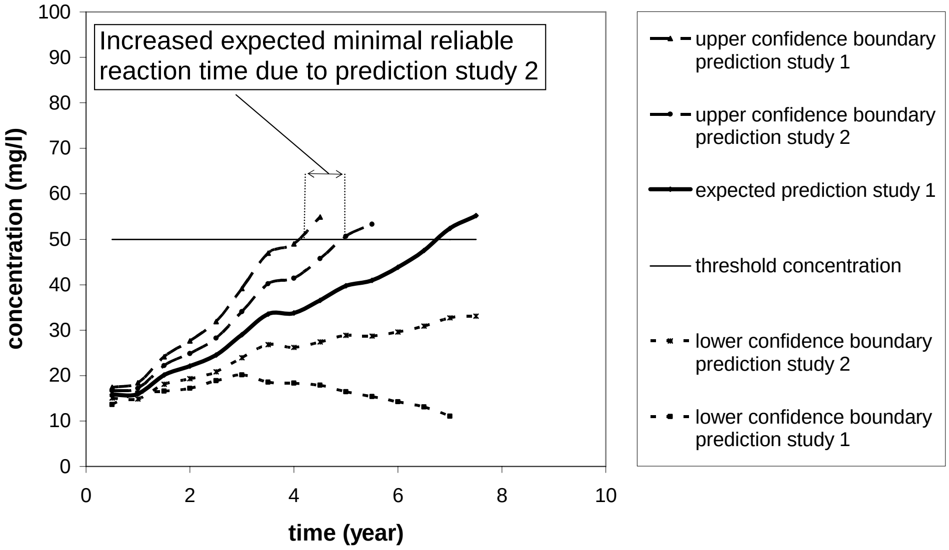

Fig. 2 Increased expected minimum reliable reaction time due to an additional prediction study.

1. Priority score = random. To provide a reference performance for the experiment the first strategy denotes the random strategy. It represents a player/decision maker who assigns priorities for allocation of research budgets at random.
2. Priority score = 1/(threshold − current concentration); represents an "*ad hoc*" decision maker who allocates budgets according to the difference between the threshold concentration and the current concentration of pumped groundwater.
3. Priority score = potential failure impact; represents a decision maker who allocates budgets according to maximum potential failure impact (that varies among wells).
4. Priority score = 1/minimum reliable reaction time; represents a decision maker who applies priorities for maximizing the minimum reliable reaction time.
5. Priority score = failure impact × anticipated change of reaction time/minimum reaction time; represents a decision maker who allocates budgets for maximizing the minimum reliable reaction time, weighted for potential failure impact and taking anticipated uncertainty reduction in account. The relations between allocated budget and reduced uncertainty of predictions as they are defined in the game are known by this player.
6. Priority score = anticipated impact reduction/anticipated budget requirements; represents a decision maker who allocates budgets for early reliable prediction of breakthroughs. Maximization of early reliably predicted breakthroughs implies investments in research where chances are best to make the lower boundary of the confidence intervals intersect with the threshold concentration. The relations between allocated budget and reduced uncertainty of predictions, as they are defined, in the game are known by this player.

RESULTS

The results of the simulations show that strategy 6 performs best in all conditions that were investigated (Fig. 3). The difference between the average relative performance of Strategy 6 and other strategies was in all cases larger than 30%. The largest differences occurred when a type 2 impact-reaction time function was applied. The success of the strategy of player 6 considered both the percentage of breakthroughs that were predicted reliably and the average reaction time at the instant of reliable prediction. Strategy 5 resulted in the largest total minimum reliable reaction throughout a game run, but this did not result in minimal losses. Differences between the performance of Strategy 6 and other strategies decrease when the number of wells increases, because all experiments were carried out with a fixed total budget. As a result, the available average budget per well decreases if the number of wells is increased. This feature is confirmed by the trivial notion that all strategies have identical results if the available budget per well is reduced to nil.

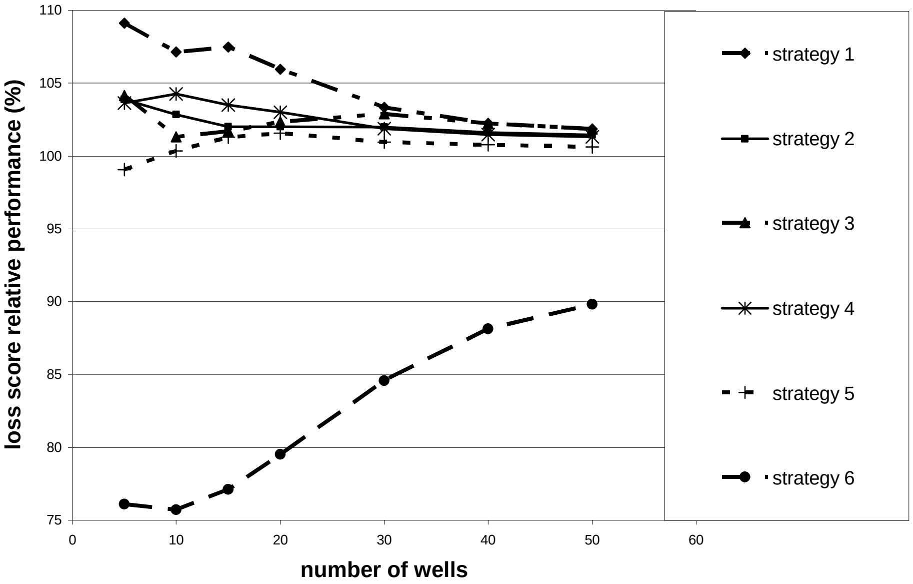

Fig. 3 Performance of strategies relative to average loss score of all strategies.

DISCUSSION AND CONCLUSIONS

Significant differences in performance were shown to exist between the various strategies that were investigated. It pays to formulate strategies carefully: strategies are suboptimal if the objective function of a strategy differs from the loss function, or in this case, loss function of the well. Since the uncertainty of a prediction is important to the loss function, it should be taken in to account in the strategies for prioritization, as is shown in the relatively good results of strategies 4, 5 and 6, where the uncertainty of predictions is taken in account. Confidence boundaries of time series of predicted groundwater concentration can be used to improve the effectiveness of prioritization of prediction studies. The concept of "reliable reaction time" can contribute to a better integration of prediction studies and decision making.

The definition of appropriate strategies requires explicit and accurate loss functions. Maximization of minimum reliable reaction time (Strategy 5) may seem intuitively a good strategy for minimization of total risk, but was less successful than Strategy 6, which is better focused on the loss function. The uncertainty within risks often consists not only in the probability of events, but also in the consequences. Both risks and loss functions are therefore often hard to define accurately. Berger (1985) states: "The fact remains, however, that the risk function is not necessarily a good measure of loss for a statistical problem". It is therefore desirable that the prioritization problem described in this paper is approached with a formalized, explicit and rational strategy. By gradually introducing a more scientific approach to this decision problem results will become reproducible and gradual improvement of strategies becomes feasible. Eventually, it may become possible to determine the optimal level of prediction uncertainty in absolute terms and hence the size of the optimal total budget for risk reduction.

The use of numerical game experiments helped assessing the effectiveness of different strategies. Application of Strategy 6 requires both that prediction studies include quantitative uncertainty assessments and that the cost–uncertainty reduction functions of the wells can be assessed. Therefore, prioritization in practice could be improved if methods become available for assessing (in advance) how much uncertainty reduction can be achieved by carrying out additional studies.

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