Groundwater management under uncertainty: A multi-objective approach

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Abstract

A methodology is developed for determining a robust optimal strategy for a groundwater hydraulic control problem posed within the framework of stochastic multi-objective optimisation. The methodology explicitly considers uncertainty in hydraulic conductivity and allows decision- makers (DMs) to evaluate trade-offs among three conflicting objectives: aquifer yield, investment and operational cost, and recourse cost (penalties) incurred if the stipulated constraints are violated. The model includes a two-stage decision process in which the first-stage decision (commonly referred to as "here and now") on how many wells, their pumping rates and their locations is made and implemented immediately without the foreknowledge of the outcome of the uncertain parameters. At a later stage, when the uncertain parameters become known, a second-stage decision is taken using the updated data. Applicability of the methodology is demonstrated through a hypothetical (but realistic) example. A post-optimality Monte Carlo analysis is conducted to examine the performance of the model in terms of robustness (stability). Preliminary results show that robust optimisation can be useful in designing a strategy which performs reasonably well whatever the outcome of the uncertain parameters.

Introduction

In recent years, the use of management models has considerably grown in connection with the analysis of subsurface water resources as suggested by the large number of research papers in the literature. This scenario is understandable especially when one looks at the ever-increasing water consumption rates in agricultural, industrial and civil establishments. Closely related to this fact is the realisation that the available groundwater resources are limited to some extent and are to be carefully managed with the aid of appropriate scientific tools if we want to put them to the most beneficial use. To this end, numerical models have been used in combination with optimisation techniques to design optimal strategies. One of the most challenging problems associated with the simulation-optimisation approach to groundwater quantity management, especially when confronted with a problem encompassing multiple conflicting objectives, is how to incorporate the effects of flow modelling uncertainty into the optimal decision-making process. To date, most aquifer management models used to design optimal groundwater management in a multi-objective environment have been assumed to be deterministic. However, just like any other resource management, groundwater management is generally carried out in an environment of uncertainties. For example, natural geological formations that form aquifers are naturally heterogeneous. It is due to this heterogeneity, in combination with lack of data to fully characterise the aquifer, that solutions based on deterministic methods are put into question.

The objective of this paper is, therefore, to present a regional groundwater planning model which explicitly considers uncertainty in hydraulic conductivity in a multi-objective optimisation problem. The solution method is predicated on robust optimisation (which is essentially an extension of classical stochastic programming), which incorporates the DM's preferences (in terms of risk of penalties due to violation of constraints) and allows consideration of nearly feasible solutions in a multiple objective framework. This approach has been used by Wagner et al. (1992).

Aquifer management models that combine simulation with optimisation help in understanding how social and economic forces interact with the water resource allocation. Just as a simulation model is a tool to understand the physical/chemical behaviour of an aquifer system, a management model can be thought of as a tool, which provides insight into the economic and social consequences of institutional changes. The combination of these two methods has been achieved in at least two ways; through the response matrix approach, and through the embedding approach. In the response matrix approach, the influence of a unit change in an independent decision variable such as pumping or recharge at a pre-selected well location upon a variety of dependent variables like drawdown and velocity at specified observation points, is determined. Superposition is then performed to calculate their total response at specified points resulting from all decision variables. Its main drawback is the number of simulations required to generate the responses as well as recalculate the response matrix when the boundary conditions and well locations change. This approach has been used by Maddock and Lacher (1991); Heidari (1982); Wanakule et al. (1986); Willis and Finney (1985); and Van Tonder et al. (1998). Other applications of this method have been made by Gorelick and Remson (1982); Theodossiou and Tolikas (1995); Galeati and Gambolati (1988); Maddock (1972); Herrling and Heckele (1986); and Willis and Liu (1984). In the embedding approach, numerical approximations of the flow equations are included directly as constraints in the optimisation model. Discretisation is based on either the finite difference method or the finite element method. In this method, the unknown groundwater variables (heads and source/sink) become decision variables in the optimisation method. This method, not only solves the problem once (as opposed to the response matrix approach), but also provides lots of information regarding the behaviour of the aquifer.

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