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Optimal control of coastal aquifer pumping towards the sustainability of water supply and salinity

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ABSTRACT

Saltwater intrusion and upconing phenomena affect coastal aquifers worldwide. These phenomena can be partially mitigated by an adequate management of the aquifer. In this work, the optimal pumping schedule for one coastal well has been defined by a decision model that minimizes desalination and pumping costs, while taking into account the aquifer salinity levels near the well. The dynamics of the aquifer is described in terms of two state equations related to salinity concentration in the pumped water and cumulative pumped water up to a specific instant. A case study is presented with application to a well in Hawaii islands.

1. Introduction

Worldwide, development activities and population growth stress coastal water resources (Bear et al., 1999; Werner et al., 2013). A sustainable management of these resources is important to satisfy demand, to maintain supplies, and to sustain associated terrestrial and marine ecosystems. Otherwise, the risk is to increase the salt concentration in water with the consequence of not satisfying the demand of potable water, and of having negative impacts on vegetation (that needs water for its growth). In coastal zones, where the intensive extraction of groundwater may upset the balance between freshwater and saltwater potentials, water resource managers need to satisfy demand while limiting seawater intrusion and saltwater upconing. The definition of appropriate strategies should lead to a sustainable use of water resources minimizing the impacts on water quality.

Seawater intrusion and the related phenomena of saltwater upconing occur when a well, or a set of wells, is pumped so that saline water is drawn into the well's capture zone, thus degrading water quality and useable value. Together with recharge, these water quality problems are often the limiting factors to pumping yield in coastal aquifers. The options if a well becomes saline are: (a) to decrease or stop the rate of pumping to allow water quality recovery, for a period which can be on the order of decades to centuries in low permeability aquifers; (b) to desalt via a treatment process such as reverse osmosis; or (c) to abandon the well. Economic and socio-political costs need to be included in any practical model of groundwater management. The challenge is given by the necessity of incorporating both the hydrology and the economics into a

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realistic, practical and tractable optimization framework. This entails simplifying complicated partial differential equations and embedding the relevant economics, while maintaining the model's reliability and physical-economic validity.

The aim of this paper is to present a dynamic decision model able to define the optimal pumping trajectories for the sustainable management of a coastal, brackish water well that minimizes desalination and pumping costs while dynamically keeping track of salinity levels in the well. The possibility of turning on/off the pump has led to the definition of a binary control variable that indicates when the well is turned off or on. Due to the suitable data obtained during the experimental campaign, unlike most published models on coastal well optimization, pumping is related to salinity via empirical response curves, in particular pumping and rebound behaviors derived from on-site pump tests at Kuki'o, Hawai'I (Duarte et al., 2004). The pumping curve, that is site-specific and rate-specific, is determined by the fitting of data collected for the case study and is used to describe the salinity increase when the binary control variable is set equal to 1. When the binary variable switches to 0 (i.e., there is no pumping in a specific time interval) the rebound curve (obtained in the same way as the pumping curve) is used to describe the salinity decrease. The choice to model the decision (control) variable as binary is due to two main reasons: the experimental campaigns have been performed with a fixed pumping rate; thus it is not possible to consider the pumping rate as a decision variable. Then, a discrete-time state equation for salinity concentration in the pumped water can be written, taking into account the effect of a binary switching control variable, on the basis of the curves that describe pumping and rebound behavior for the aquifer. An additional state equation has to be written in order to represent the dynamics of the cumulative pumped water up to the considered time instant. The performance index to be minimized consists of a weighted sum of economic costs, salt concentration at the end of the time horizon, and water demand dissatisfaction.

The optimization problem is non-linear with continuous state variables and a binary control variable that allows the switching between two different behaviors of the environmental system. Thus, the problem discussed in this paper falls within the framework of optimal control of switching systems.

In this paper, a control-oriented approach is adopted for the case of coastal aquifers affected by saltwater intrusion and upconing phenomena, and feedback strategies are sought. To this end, the application of dynamic programming to solve the optimization problem allows to define a procedure to on-line determine the optimal control action as a function of the current state. For the considered case study, the computational requirements of such a procedure are shown to be compatible with a real-time application. Of course, an approach directly based on the use of a general purpose mathematical programming software tool could also be used to solve the considered problem. However, such an approach would lead in general to the determination of local minima (as the considered optimization problem is non linear). Thus, the attainment of the overall optimum is not guaranteed and there could be the necessity of repeated initializations. Instead, the application of the proposed dynamic programming approach always allows the determination of o (global) optimal solution, and gives two further main advantages: (a) the special structure of the optimization problem is effectively exploited, (b) there is a finite set of reachable values of the state vector (although this vector consists of real-valued variables).

The computational requirements of the proposed solution are of course of the upmost importance, as we are considering the development and application of an on-line decision procedure. In this connection, it will be shown that computational requirements have been experimentally evaluated in connection with a real case study, and have been proven to be compatible with a real-time implementation.

The paper is organized as follows. In the next section, the state of the art is described, as regards coastal aquifer management, whereas in the third section a brief survey concerning the control of switching systems is provided. Then, the system model is presented, and a representation through state equations is provided. In the fifth section, the optimization (control) problem is formalized. The sixth section considers a general type of control problems with a unique binary control variable, and presents a general method to solve such kind of problems via the application of dynamic programming. The seventh section reports the application of the proposed method to the particular control problem considered in this paper, and provides numerical results relevant to a specific real case study. Computational issues are also discussed. Finally, some concluding remarks are presented in the last section of the paper.

2. Coastal aquifer management

Table 1 summarizes some main results from the literature for sustainable coastal aquifer management. In this respect, it is worthwhile to underline that many articles define optimization problems to guarantee the sustainability of strategies of water management. Recent approaches follow the linked simulation–optimization approach, using an Artificial Neural Network Approximation linked to a Genetic Algorithm-based optimization model. However, the performance of this approach is highly dependent on the performance of the saltwater intrusion simulation model, as repetitive simulations are required to achieve an optimal management strategy. The computational time can be reduced through parallel computing, or by some approximation of the simulation model.

With respect to previous literature related to upconing phenomena, in this paper, the curves in case of pumping and well shut-off are derived from experimental campaigns. The curves are used to define a state equation for the concentration behavior as a function of a binary control variable that makes the system switch between the two modes of salinity increase/decrease.