Optimal Management of a Coastal Aquifer Under Saline Intrusion

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EXTENDED ABSTRACT

Fresh groundwater systems have become during the last decades an important source of freshwater throughout the world. The proportion of surface and subsurface freshwater is respectively 78% and 22%. But more than three-quarters of surface freshwater is located in polar regions. Fresh surface water directly available for use is water in lakes, 0.3%, and in streams, 0.003%. These are dwarfed by groundwater, 22%. Moreover, approximately 600 to 700 billions of cubic meters are every year withdrawn from subsurface resources. It represents 25% of total water consumption. This proportion varies, of course, according to the climate and the level of development of the country considered. For example, groundwater represents 23% of total water used in the US, 40% in France and more than 90% in Saudi Arabia.

Therefore, satisfaction of water population needs will more and more depends on durable management of groundwater stocks. This is especially true in arid and semi-arid countries where groundwater is often the only supply source available. Yet, groundwater management is often characterized by overuse. This overexploitation can cause or intensify several problems: aquifer depletion, subsidence and seawater intrusion in coastal aquifers. Currently, about one-fourth of the groundwater withdrawn in the US is not replenished. At the current rate of extraction, Saudi Arabia’s nonrenewable fossil groundwater will be exhausted by 2007. These quantitative problems are very often linked with quality degradation of the resource. For example, when freshwater is withdrawn from an aquifer near a coast faster than it is recharged, saltwater intrudes into the aquifer. The problem of saltwater intrusion has been widely recognized in groundwater utilization for many coastal aquifers in various parts of the world. It is now, given the geographical repartition of needs, one of the main causes of groundwater quality degradation and one of the major constraint affecting groundwater management. In the United States alone, saltwater intrusion has resulted in the degradation of freshwater aquifers in at least twenty of the coastal aquifers. The Connecticut, New-York, Florida, Texas and Hawaii count among the more concerned by these problems. In Europe, the first case of saline intrusions has been reported at the end of the 19th century for London and Liverpool. In the Netherlands, the Amsterdam problem of seawater intrusion has been solved during the 80’s by water conveyance from the Rhine. In France, the most alarming situation deals with the Eocene aquifer in the Bordeaux aquifer. The first technical study has been realized by the Bureau de Recherche Géologique et

¹ According to the Food and Agricultural Organization, at present six out of ten people live within 60 km of a coast and by the year 2000 more than two-thirds of the population of developing countries will live in the vicinity of the sea.
Minière in 1967. From the beginning of the 60’s to the middle of the 90’s, the groundwater level has registered a 80 meters decrease in the Bordeaux area. During the same period, withdrawals have increased fourfold creating risks of saline intrusion at short term. The situation seems now stabilized but water network reorganization is estimated at 400 millions francs (approximately 66.6 millions US$).

Despite the importance of the saltwater intrusion problem, there exists only a few economic works dealing with this problem. First, some models consider aquifer as a bathtub in which water quality goes progressively worth. They do not take into account any spatial aspect of the seawater intrusion problem. This is the kind of model used by [Koundouri, 1997] in order to study the Kiti aquifer on the island of Cyprus. Koundouri introduces a salinity coefficient that measures the loss of freshwater resulting from pumping one unit of freshwater and generalized the result of [Gisser, 1980] by showing that in case of a small natural recharge, efficiency of the central planner over free market is negligible. An other type of model is given by [Tsur and Zemel, 1995]. They consider saline intrusion as an irreversible event occurring as groundwater table declines below some threshold level. Due to the lack of knowledge and measure precision, this threshold level has to be considered as unknown. In this kind of ‘Doomsday model’, Tzur and Zemel compare optimal withdrawals paths under certainty and uncertainty. They show that exploitation policies under uncertainty are more conservative than under certainty. Finally, the only one spatial modeling of seawater intrusion in coastal aquifer in given by [Hart, 1995]. The model is based on a standard moving interface model of the hydrologic literature, [Cummings, 1971]. They specify an interface moving toward the coastline or landward according to withdrawal levels. They study water allocation resulting from the market and taxes and quotas policies.

The scope of this paper is to determine what the optimal use of a coastal aquifer under saline intrusions should be. We develop an economical analysis of this kind of problem set on an analytical model of a sharp interface between saltwater and freshwater. This type of mathematical model, developed in the 60’s by hydrologists, provides a basis for understanding the complicated mechanisms that cause seawater intrusion and affect the shape of the transition zone from freshwater to saltwater. In most cases, these models allow to derive analytical solution for the length of saltwater intrusion and the interface position. Notice that due to their simplified assumptions, these analytical solutions normally do not directly solve ‘real-world’ problems. Nevertheless, they are useful as a tool for first-cut engineering analysis or as benchmark for testing numerical models. Finally as we show in the paper, they are quite well fitted to be used in an economical analysis.

As a consequence, we consider a coastal unconfined freshwater aquifer hydraulically connected with seawater. The class of groundwater systems addressed herein consists of a saturated porous medium containing a coastal aquifer in a layered environment, Fig 1. Two superposed layers constitute this groundwater system. The upper one crops out and is homogeneous. The lower one is an impermeable substratum. Depth, measured from the sea level, between these two layers is constant and equal to $H_0$. Aquifer is recharged by freshwater entering at the landward boundary, at a distance $X_0$ to the coast. $R$ denotes the instantaneous recharge rate, i.e., the net water inflow excluding extraction. At the seawater
boundary, there is an influx of seawater which migrates to the bottom of the aquifer and displaces the freshwater upward because of greater density. Figure 1 describes this two-dimensional model of coastal aquifer under saline intrusion conditions.

When pumping occurs, only a part of the freshwater recharge discharges to the sea. This determines a new hydrostatic equilibrium between freshwater and saltwater. As water extraction rate increases, the interface moves landward and upward. Saltwater moves to the bottom of the aquifer and displaces the freshwater upward. In the same time, the water table decreases and the freshwater lens goes thinner. Hence, well discharge near the coast becomes saline to a degree governed by location of the wells, discharge rates and local hydrologic conditions. Such a kind of discharge can obviously not be considered as a long-run extraction plan. Thus wells located in coastal areas have to be excluded from the water supply system because they may not ensure potable water. Population of coastal areas must in that case support extra costs in order to get freshwater. It follows that users far away from the coast create a negative externality on users located nearer. How is possible to make people internalize this externality? Does a single price for all users allow to implement an optimal allocation of water? Do we require a spatially differentiate price system? This is the kind of questions we try to answer in this paper by assuming that the social planner objective is to maximize net social surplus.

The coastal aquifer is exploited by $I$ agglomerations located at the aquifer surface. The social planner program consists in defining the location of the pumping well and the water discharge of each agglomeration such as the welfare is maximized and the extraction constraints are satisfied. We consider three different cases. We first deal with aquifer exploitation by a single agglomeration, $I=1$. Resource exploitation by a single agglomeration puts in light a delicate problem of
marginal cost discontinuity. The two-agglomerations case, \( I=2 \), allow us to emphasize the type of externalities create by aquifer users. The model is finally generalized to the case of \( I>2 \).

The main findings of our analysis may be resume as follows. Optimal management of coastal aquifers under saline intrusion conditions may entail to a tax system. Although agglomerations exploit the same aquifer, a spatially differentiate tax schedule in generally required. For a take of simplicity, we have assume that resource valorization is the same for all consumers. It follows that optimal consumption per capita for an agglomeration is the more important as it is located near the coast. The reason is that the more an agglomeration is near the coast, the more water access costs are high in case of scarce resource. In a more realistic model taking into account heterogeneity of consumers, this result may no more hold because agglomeration with high access costs may have high valuation for water. Nevertheless, the result of spatially differentiate taxes still remains: they result from externalities created by agglomerations the ones on the others. Finally, there is no simple relation between taxes asked to agglomerations and generic parameters of the model. Yet, the tax system offers a particular characteristic that may set problems under some circumstances. Taxes aim at correcting differences between social marginal costs and private marginal cost. Now, the more population size of an agglomeration is small with respect to the total population, the more this difference is important. It follows that smaller agglomerations will be asked higher taxes.

References


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