Optimal Management of Groundwater Withdrawals in Coastal Aquifers

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Abstract In this work, an optimisation model has been developed for planning and managing saltwater-intruded coastal aquifer systems. We apply this model, which uses the simulation / optimisation approach, for managing water resources in coastal areas. The management model finds the best policies to maximize the present value of economic results of meeting water demands and to keep under control the saltwater intrusion. The idea of security distance to a control point provides the establishment of a trade-off relationship between the increased management cost and the desired level of protection. The model was applied to a typical case with interesting results. It was also crucial to have an understanding of the tradeoffs between groundwater withdrawals, positions of the wells from the coast line, and the security distance. This model allows the sustainable use of coastal water resources.

Keywords: Seawater intrusion. Security distance for wells. Coastal groundwater withdrawals.

1. Introduction

The freshwater demand in coastal areas and islands are increasing due to population and tourism growth. Coastal aquifers are an important water resource in these areas. Under natural conditions an equilibrium gradient exists in the aquifer with excess freshwater discharging to the sea. Because the lower costs of groundwater usage there is a great interest in capturing as much as possible the water from the coastal aquifers. In these areas the increase water withdrawals can cause seawater intrusion. Trying to extract the maximum quantity before experiencing saltwater intrusion is very risky. So there is a need for developing withdrawals management methodologies for determining the number of viable locations for wells and the quantities of water which can be pumped from coastal aquifers while protecting the wells from seawater intrusion, in order to satisfy the demand (social dimension), maximizing the economic benefits (economical aspects) and controlling the saltwater intrusion (environmental concern). The management of the water supply systems that use groundwater from aquifers prone to saline water contamination is a complex task. Such management models at varying degrees of success have been reported in the literature (Shamir et al. 1984; Essaid 1990; Finney and Willis 1992; Emch 1995; Hallaji and Yazicigil 1996; Nashikava 1998; Benhachmi et al. 2003).
The solution to the problem of optimized location and management of extractions from aquifers potentially subject to saltwater intrusion consists in determining the best well location with a specific flow rate.

2. Methodology

The management model presented in this paper combines optimisation techniques and simulation models of the physical processes. Ferreira da Silva (2003) defends a methodology that associates optimisation techniques (A gradient method and genetic algorithms) and simulation of coastal intrusion in a cascade of increasing degree of complexity. The simulation models like those by Strack (1989) and Bakker and Schars (2002) anticipate the behaviour of the aquifer in relation to the alternatives generated by the optimisation tools. The assumed sharp interface between freshwater and saltwater is proved to be conservative (Essaid 1990), i.e., the solutions of the groundwater management system are on the secure side. The governing equations of the movement of water in a porous media in each side of the interface freshwater/saltwater can be defined by:

$$\frac{\partial}{\partial x}\left[\left(K_{xx}\right)_d \frac{\partial h_d}{\partial x}\right]+\frac{\partial}{\partial y}\left[\left(K_{yy}\right)_d \frac{\partial h_d}{\partial y}\right]-\frac{\partial}{\partial z}\left[\left(K_{zz}\right)_d \frac{\partial h_d}{\partial z}\right]+Q_d=S_d \frac{\partial h_d}{\partial t} \qquad (1.1)$$

$$\frac{\partial}{\partial x}\left[\left(K_{xx}\right)_s \frac{\partial h_s}{\partial x}\right]+\frac{\partial}{\partial y}\left[\left(K_{yy}\right)_s \frac{\partial h_s}{\partial y}\right]-\frac{\partial}{\partial z}\left[\left(K_{zz}\right)_s \frac{\partial h_s}{\partial z}\right]+Q_s=S_s \frac{\partial h_s}{\partial t} \qquad (1.2)$$

Where: x, y - coordinates, d - freshwater; s saltwater; h - piezometric head, Q - pumping rate, S - storage coefficient, t - time.

Strack (1976 and 1989) demonstrated that for a homogeneous, isotropic aquifer of constant thickness, the potential is defined, using the method of the images, for:

$$\phi=\frac{q}{K}x+\sum_{i=1}^{n}\frac{Q_i}{4\pi K}LN\left[\frac{(x-x_i)^2+(y-y_i)^2}{(x+x_i)^2+(y-y_i)^2}\right] \qquad (2)$$

where: q - uniform freshwater outflow rate; K - hydraulic conductivity; Q_i - pumping rate of well i; (x_i, y_i) - well coordinates; n - number of wells.

A variety of both linear and nonlinear optimisation models have been developed for the management of coastal groundwater systems. Emch (1995) make use of the program MINOS witch is based in an augmented Lagrangian algorithm in conjunction with a reduced-gradient algorithm to construct a management model of the extractions from aquifers under conditions of potential intrusion. Evolutionary optimisation methods have been used successfully in a variety of cases. Goldberg (1989) explains general structures of Genetic Algorithms and shows their relative simplicity. In groundwater optimisation systems, Benhachmi et al. (2003) have also been successful using such methods.

3. Problem Formulation

In a regional conception and dimensioning of the groundwater extraction and water supply systems, there are various components that introduce investment and operational costs depending on the location and the quantity of the groundwater withdrawals.

Extraction points condition the length of the main water supply system that transports groundwater to the treatment station. The maximum values for withdrawals determine the diameters of the mains, the capacity of the reservoir for pumping regulation, the selection of water treatment equipments, the selection of electro-mechanic equipments for the pumping station, and the capacity of the reservoir for distribution regulation, etc. (Figure 1).

The management model defines the rules for the extraction and the recharge that satisfies the demand, respects the restrictions, takes into consideration the economic aspects, and maintains saltwater at distance. In other words, the problem is to maximize the economic return while controlling the saltwater intrusion. This objective is mathematically represented by maximizing the difference between the total benefits (B) and costs (C) in a region:

$$\max Z=\left(B_{total}-C_{total}\right) \qquad (3)$$

The total cost of the project is based on the expenditures associated with the groundwater withdrawals, the surface and/or imported water, and the systems linked to degradation prevention and environmental rehabilitation (like artificial recharge).

The existence of each component of the water supply system and/or artificial recharge (wells, pumping stations, treatment plants, pipes, reservoirs) implies costs with the construction work and the equipment installation. These investments can be expressed by tables or aggregate models of the type:

$$\left(CIC\right)_S=\sum_{f=1}^{N_F}\upsilon_t\left(c_s+a_s H_{s,n}^{\alpha_s}Q_{s,n}^{\beta_s}\right)\varepsilon \qquad (4)$$

υt - Factor that transforms a future value to a present one; c_s; α_s; β_s - Cost coefficients; H_s - Elevation height (m); Q_s - Flow rate, extraction, withdrawal (m^3/s); ε - Factor related to the commercial strategy of the constructor or installer and the market situation.

The operating costs during the life of the project and according to the source of the water depend on the flow regime, length of the pipes, elevation height, and a number of other parameters. The complete characterization and quantification of the costs and benefits involved in the management of coastal systems can be found in Ferreira da Silva (2003).

If the groundwater extraction cost is the minor of the water supply costs, then the mathematical expression of the objective function can be written as:

$$\max Z = \sum_{s=1}^{N_s} Q_s \tag{5}$$

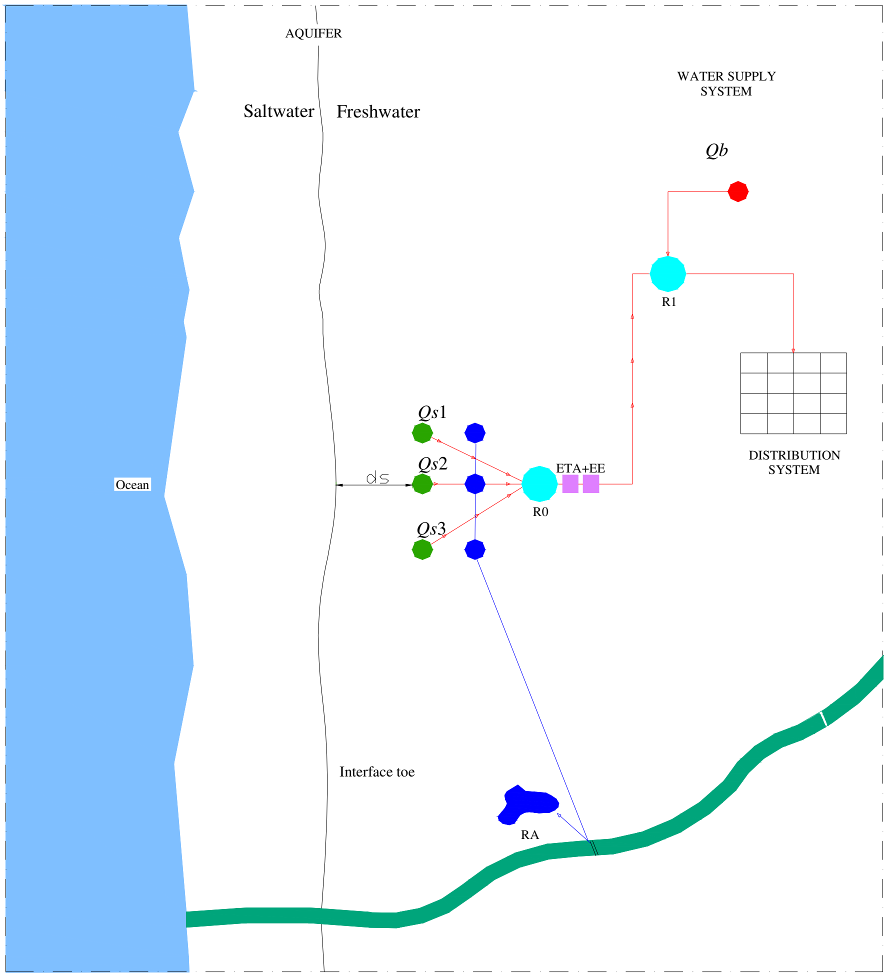

Fig. 1. A general scheme for a groundwater withdrawals and water supply system in a coastal region

To elaborate mathematically the restrictions on the system, the notion of the distance between the toe of the interface (between freshwater and saltwater) and one or more control points (N_{cp}) was introduced. These could be the wells that condition the solutions and their eventual locations near the ocean. If a number of extraction points are intended to be implemented, generally the control points should be defined as those that are more centrally located. In order to protect the control points from the invasion of saltwater, the following expression was defined:

$$\left(X_{toe}\right)_s \le \left(X_{cp}\right)_s - \left(ds\right)_s \qquad \forall s, \quad s = 1,2,\ldots,N_{cp} \tag{6}$$

Besides this constraint on the advance of the toe of the interface, it is also necessary to define other restrictions such as related to the satisfaction of the total demand, limits of each well withdrawal, and minimum piezometric heads:

$$Q_{s,\min} \le Q_s \le Q_{s,\max} \qquad s = 1,2 \ldots, N_s \tag{7}$$

$$h_s \ge h_0 \qquad s = 1, \ldots, N_s \tag{8}$$

X_{cp} - Distance of each control point from the coast (m); X_{toe} -Distance of the toe of the interface from the coast (m); ds - Security distance (m); N_{cp} - Number of control points; Q_s - Flow rate, withdrawal (m^3/day); $Q_{s,\text{mín}}$ - Minimum withdrawal race for well s (m^3/day); $Q_{s,\text{máx}}$ - Maximum withdrawal race for well s (m^3/day); N_s - Number of groundwater extraction points; h - piezometric head (m).

4. Applications

In the following studies, the topography of the system represented in Figure 1 has been used with a general slope of 0.5% towards the ocean. The WTP (water treatment plant) and the PS (pumping station) have been positioned in the middle of aquifer some 3,500 m from the coast. Let us assume that the main supply line can be implemented in straight lines and it has a length of 1,000 m between PS and RDR (reservoir for distribution regulation). It is estimated that at the start of the undertaking, the average daily demand is 3,500 m^3/day with a rate of increase of 3% for the first phase and 1.87% for the second half of the 20 year life span (a linear growth has been considered). The average actual price of energy is 0.0848 €/kWh, admitting a growth following the equation for composite interest with a rate of 2%. For economic analysis, the criterion of present value has been adopted with a 5% value for money. The aquifer has a thickness of 14 m, hydraulic conductivity of 100 m/day and specific flow of 0.6 m^3/m.day. Without any groundwater extraction, the toe of the interface is located at 418 m from the ocean. As such allowing successive values for the security distance (ds = 100 m, 200 m,...), extraction locations should be implemented at distances (X_s) not less than 520 m, 620 m,..., respectively.

4.1. Extractions versus Location Points

4.1.1. Optimized extractions in a three well system

It is interesting to know for any possible location, what are the optimum withdrawal and security distance. With the intention to determine the optimized extractions in function of the eventual place of implantation and for each distance of security a procedure was developed that calculates, also, the partial costs associates to the well system, to the water supply system and to the control of the saline intrusion system. The best politics of withdrawals for the set of the three wells, when in the distance of security (ds) it is 300 m, are in the following table:

Table 1 - A three well system and optimized extractions *versus* X_s and ds=300 m

Local	Qs_1	Qs_2	Qs_3	Sum Qs
(m)	(m^3/dia)	(m^3/dia)	(m^3/dia)	(m^3/dia)
820.00	190.7	135.6	190.7	517.0
(...)				
900.00	311.5	213.6	311.5	836.6
(...)				
1000.00	439.5	289.3	439.5	1168.4

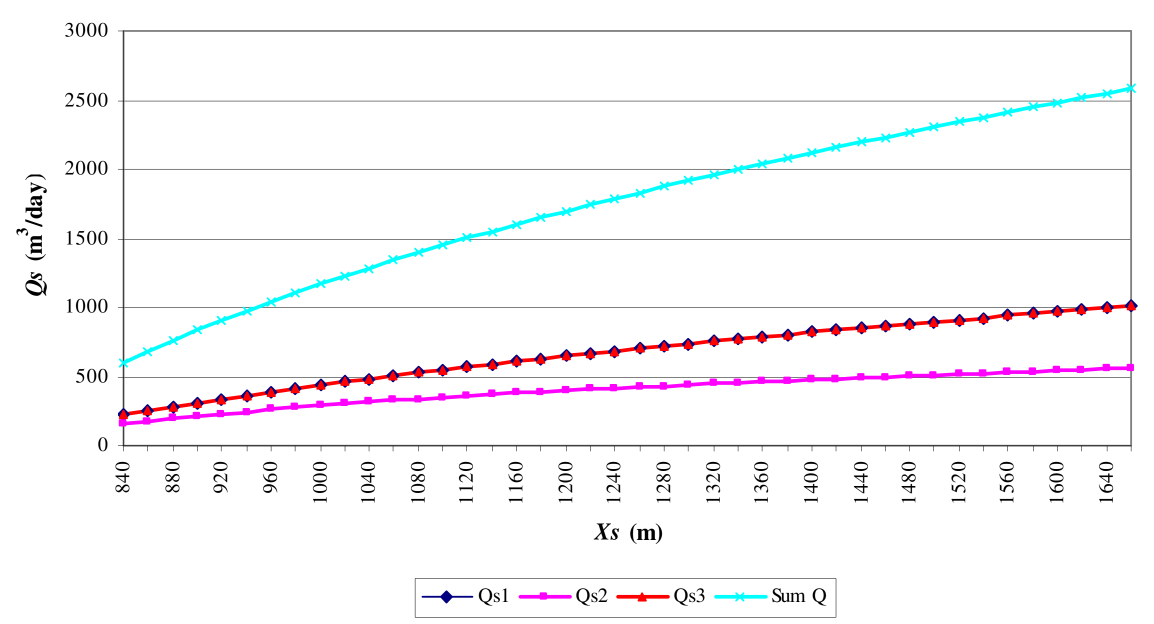

Fig. 2. Extractions for 3 wells versus location X_s and security distance ds = 300 m

The analysis of the previous figure allows to evidence that the model determines the best politics of extractions attributing the same value to the lateral wells (Q_1 and Q_3) and reducing the amount to remove of the central well, or either this origin constitutes the point of bigger control of the phenomenon of the saline intrusion.

The costs for a three well system and optimized extractions *versus* X_s and *ds*=300 m are in the table 2 and in next figures.

Table 2 - Costs for a three well system and optimized extractions *versus* X_s and *ds*=300 m

Local	*CIC*	*CIR*0	*CIETA*	*CIEE*	*CIACR*0	*CIA*	*CIR*1	*CIT*	*CET*	*CT*
(m)	(10^3 €)	(10^3 €)	(10^3 €)	(10^3 €)	(10^3 €)	(10^3 €)	(10^3 €)	(10^3 €)	(10^3 €)	(10^3 €)
820.00	178.9	18.84	117.0	49.25	397.53	59.86	66.49	887.9	5741.6	6629.5
(...)										
900.00	183.5	27.0	118.9	57.6	386.7	74.2	93.6	941.5	5497.5	6439
(...)										
1000.00	188.8	34.7	120.8	65.5	405.7	74.2	119.3	1009.0	5186.1	6195.2

Where: *CIC* - Cost of investment in the groundwater withdrawal (Euro); *CIEE* - Cost of pumping system (Euro); *CIT* - Total investment Cost (Euro); *CET* - Total management cost (Euro); *CT* - Total Cost (Euro).

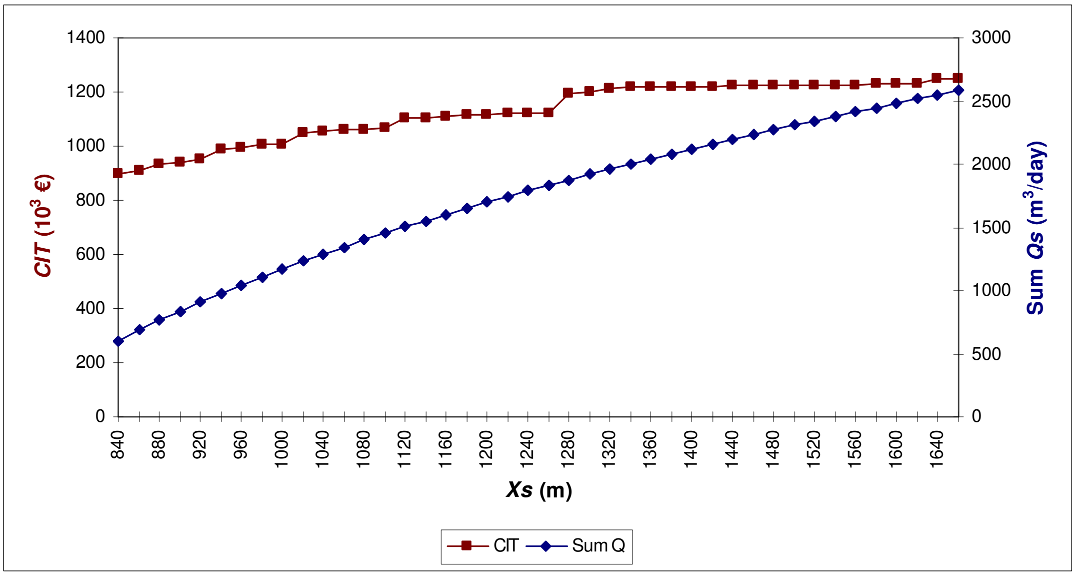

Fig. 3. Investment costs for 3 wells versus location X_s and security distance *ds* = 300 m

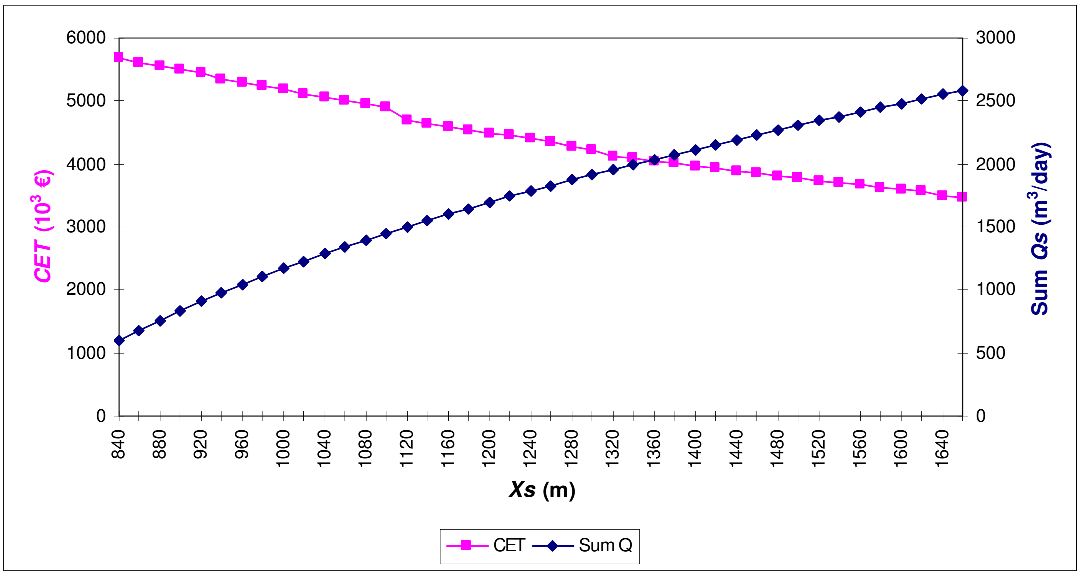

Fig. 4. Management costs for 3 wells versus location X_s and security distance *ds* = 300 m

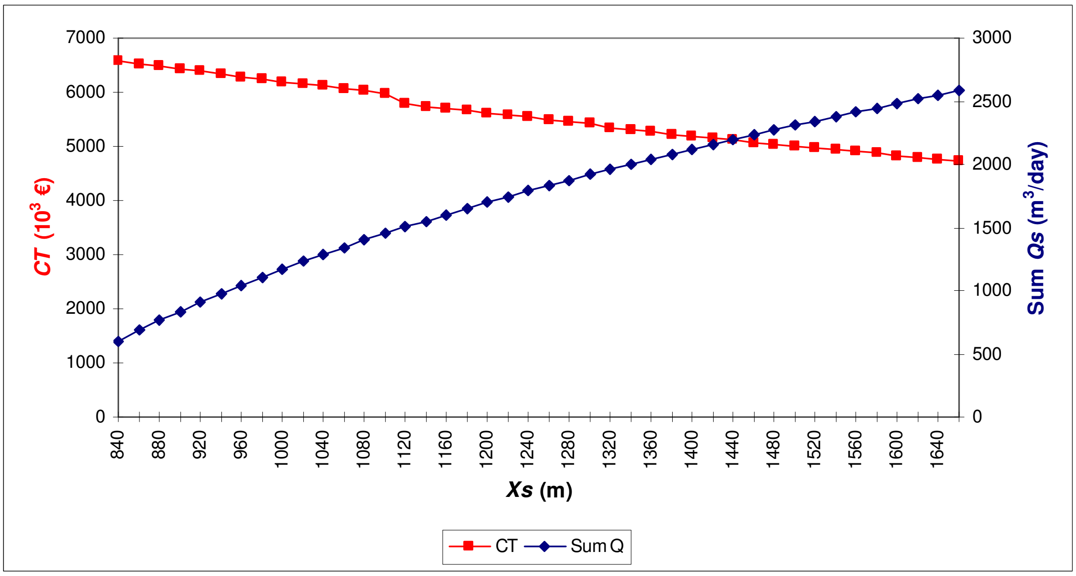

Fig. 5. Total costs for 3 wells versus location X_s and security distance *ds* = 300 m

Widening the work to other distances of security a set of results was gotten that is represented in the following figure:

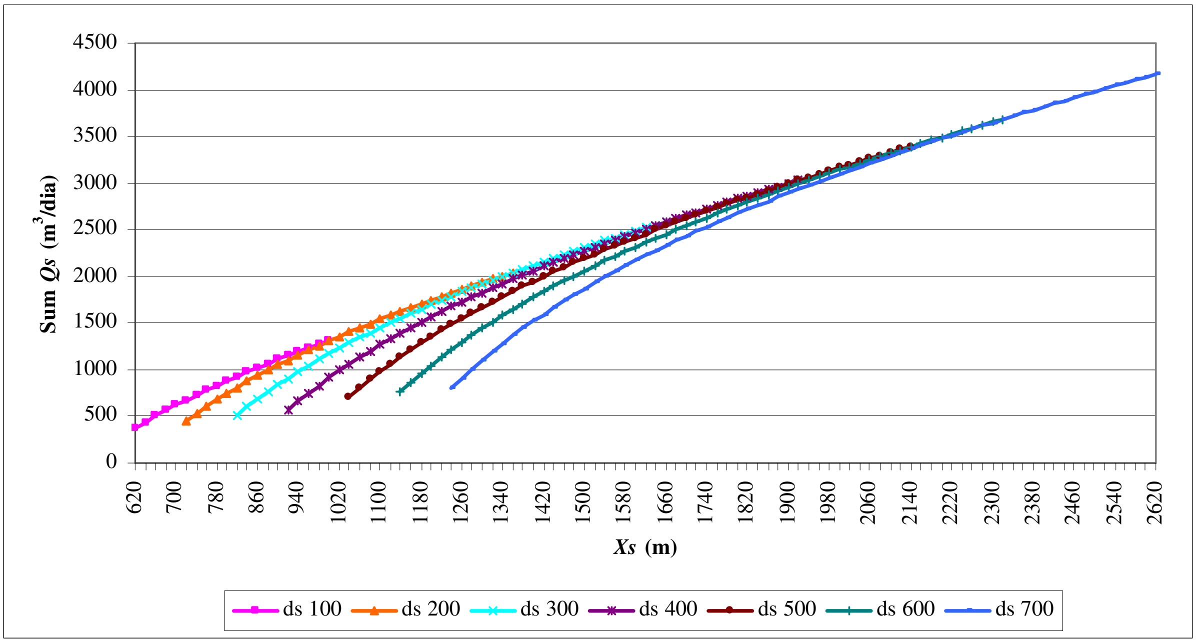

Fig. 6. Extractions for 3 wells versus location X_s and security distance *ds* =100,200,…, 700 m

The decision maker should decide on the security distance which in turn can indicate the location and the corresponding maximum extraction. These figures give more interesting information about the phenomenon under study. For example due to non-linearity, the security can be reasonably increased by a small inward move of the location of the wells. Or that such movement causes the interface to jump further from the wells. Another example is that the comparative analyses of these figures shows the distance from the coastline that the location of the wells are of less interest in relation to seawater intrusion.

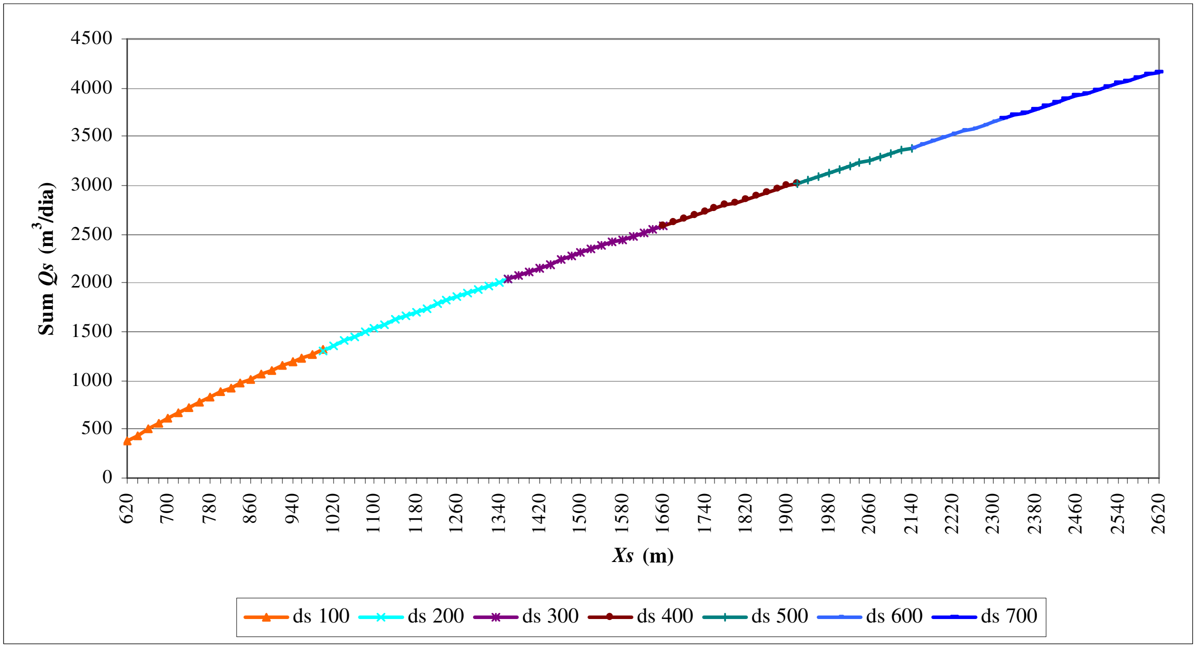

Fig. 7. Maximum extractions for 3 wells versus X_s and security distance ds=100,200,…,700 m

4.1.2. Maximum withdrawals with the same Qs in a three well system

To have an easier maintenance and operation, it is generally interesting to install equipments with the same characteristics such as having the same Q_s. So the problem is to know the location of the wells while maximizing the economic return and respecting the security distance (ds). The following extra restriction should be applied:

$$Qs_1 = Qs_2 = Qs_3 \tag{10}$$

One of the major decisions is about the distance between the toe of the interface and the control point (well) before it gets invaded by saltwater. This is particularly important, as there is non-linearity in the system. Logically, for a particular location, the maximum extraction occurs immediately before the invasion. Figure 8 shows the maximum allowable extraction and the distance between the toe of the interface and the control point before invasion for each eventual location.

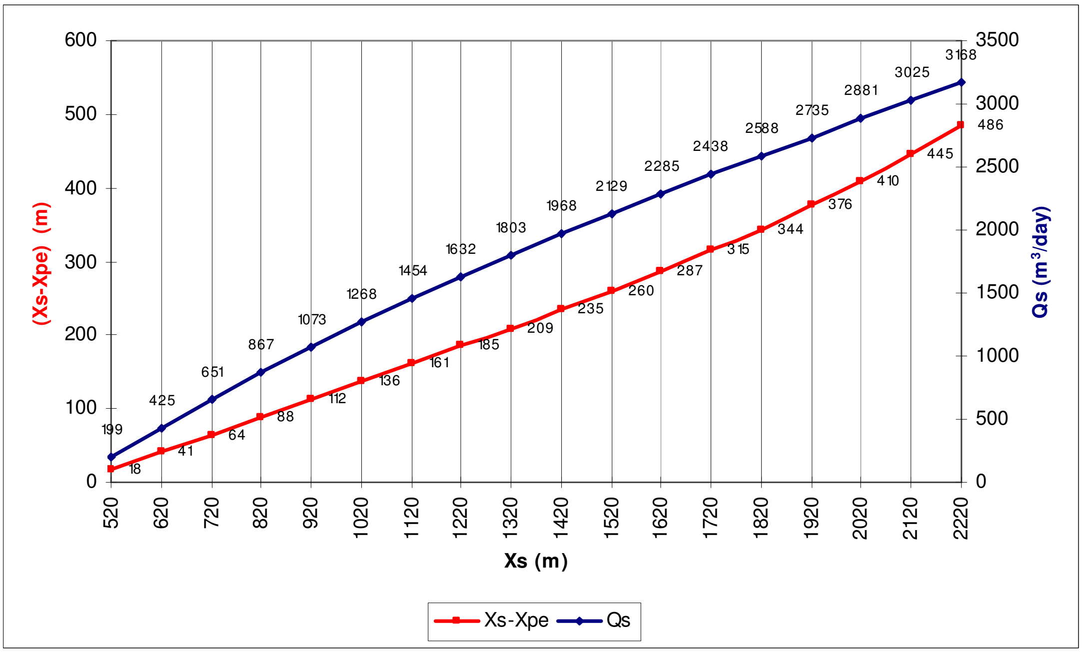

Fig. 8. Maximum withdrawals (Q_s), the distance between the toe of the interface and the control point before invasion (X_s-X_{toe}) and the location (X_s) for three wells

4. Conclusions

In this paper we have presented an optimisation/simulation model that has been developed for the management of the groundwater withdrawals in coastal aquifers under conditions of potential seawater intrusion. This model is a management tool that allows defining the position and withdrawals of wells in a sustainable manner. The case studies showed that the model is capable of performing optimized planning and management of the locations of extraction points in a coastal aquifer.

This paper showed some results relating different domain variables and their non-linear behaviour. Locations were analyzed as a function of groundwater withdrawal and security distance. The maximum allowable extraction and the distance between the toe of the interface and the control point before invasion were studied for each eventual location. It was found that the security of water resources systems can be reasonably increased by a small inward move of the location of the wells. In all these situations, the non-linearity within the system has to be taken into account. The final products of this work are a trade-off curves that allows the manager to assess the relative importance of each variables (location versus maximum extraction or versus security distance). Trying to extract the maximum quantity before experiencing saltwater intrusion is very risky as the saline interface goes through a sharp jump and invades the wells.

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