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OPTIMIZATION APPROACHES FOR THE CONTROL OF SEAWATER INTRUSION AND ITS ENVIRONMENTAL IMPACTS IN COASTAL ENVIRONMENT

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Abstract: The rational management of subsurface water resources is a key for sustainable development of a coastal region. A variety of classical and heuristic optimization methodologies have been properly adopted by researchers to first describe and then solve the multidimensional water coverage problem that is mainly responsible for the development of seawater intrusion in coastal aquifers. The aim of this paper is an extensive review and discussion of the mathematical characteristics of the various design formulations and the optimization approaches that were applied over the last two decades to explain analyze and manage the evolution of seawater intrusion into coastal aquifers. Special consideration also is given to classify the environmental impacts of seawater intrusion into the natural and anthropogenic coastal environment.

Key words: *seawater intrusion, classical and heuristic optimization methodologies, surrogate models, water resources management, coastal environment, environmental impacts*

Mathematics Subject Classification: *90B50, 90C29, 90C30, 90C56, 90C90*

1 Introduction

The management of natural resources in coastal regions is a priority for federal authorities to preserve the natural environment and the living conditions for more than half of the population that lives and works there worldwide. Coastal regions face a large number of economic, social and environmental problems due to their high value in environmental, cultural, recreational, tourist and economic terms. The quick economic development of these regions mainly based on increased urbanization, poor transport infrastructure and unsustainable development of tourist activities leads to a significant degradation of the coastal ecosystems and environment. The accumulated freshwater, marine and sediment pollution and the continuous and accelerated erosion in coastal regions have tremendous effects on the quality of their natural resources, such as surface and subsurface water, soil and biodiversity. Especially, the water resources quality problem becomes severe in costal regions due to the large number of uncontrolled pollutant sources (i.e., domestic waste, organic matter from aquaculture activity, shipping) resulting in marine sediment and water deterioration (Xue et al., 2004).

The long-term sustainable use of subsurface water in coastal regions in terms of water quantity and quality is the goal for 2015 that the 2000/60 Water Framework Directive (WFD) of the European Union requires for all Member States. Special consideration is paid to the protection and restoration of the subsurface water resources in these regions due to the great extent of seawater intrusion problems that are reported in most of the Member States across the Union, and beyond. Especially in Mediterranean countries where the rate of freshwater replenishment along the coastline is low (i.e., low rainfall rate, extensive pumping), the risk of subsurface water resources depletion is extremely high. Similar policies were adopted by environmental agencies all over the world.

Freshwater quality deterioration is observed in coastal aquifers, especially during the dry summer season when pumping activity is increased to meet the water demand. This deterioration is a serious natural resources environmental problem for these regions and it is directly related to the invasion of seawater into the aquifer along the shoreline. Seawater intrusion is a direct consequence of catastrophic water resources mismanagement in coastal regions. The multiple uses of the coastal water resources and the necessity of maintaining them in good quality require rational design and management in order to satisfy competing interests of different stakeholder groups. The sensible balance between fresh and saline water in a coastal aquifer is dynamic and could be easily disturbed by the continuous and unrestrained pumping activity.

In the first part of this paper, a detailed analysis of the seawater intrusion problem is presented, focusing primarily on standard modeling approaches. The causes and environmental impacts of the seawater front invasion in coastal aquifers are also analyzed. The second part of the paper focuses on the analysis of classical and heuristic optimization approaches and the adopted design formulations that have been applied to control seawater intrusion into a coastal aquifer by rational optimal management of its subsurface water resources.

Part I

2 Theoretical Background of Seawater Intrusion

Under normal conditions, a sensitive equilibrium between fresh and saline water exists along the shoreline that depends on the geological and hydrological characteristics of the coastal region. The movement of saline water from the ocean into coastal aquifers with the simultaneous displacement of freshwater from these aquifers is defined as seawater intrusion. The seawater intrusion phenomenon is typically associated with water over-drafting from the coastal aquifers to cover the increasing water demand in these regions. An indication of seawater intrusion into a coastal aquifer is the increase of chloride ion concentration in the subsurface water. In steady-state conditions the relatively less dense freshwater by floating above the saline water, creates an equilibrium between the two fluids. During the dynamic development of the phenomenon, mixing of fresh and saline water due to hydrodynamic dispersion and molecular diffusion occurs, forming a mixing zone of variable density. Depending on the width of the mixing zone relative to the thickness of the aquifer, two general modeling approaches for seawater intrusion have been developed: a) The sharp-interface approach, according to which the mixing zone between the two fluids is limited to an interface with a small finite width, and b) the density-dependent miscible flow and transport approach, in which the width of the mixing zone between fresh and saline water is significant.

i) Sharp interface approach

The fresh and saline water are treated as two immiscible fluids with different constant densities. The sharp interface between the two fluids is determined by the difference between the hydraulic heads of the saline and fresh water and depended on the volume of fresh water

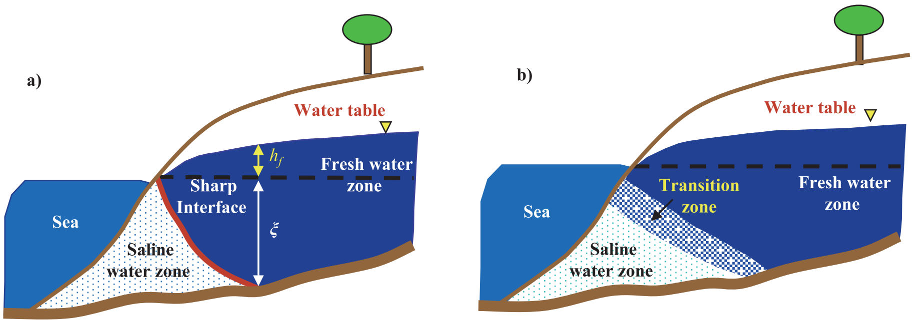

Figure 1: a) Sharp interface and b) transition zone between saline and fresh water (after Karterakis et al., 2007)

that flows from inland sources towards the shoreline. As long as the hydraulic gradient of fresh water in the coastal aquifer is high enough to maintain an adequate flow to the sea, the sharp interface is approximately vertical and located along the shoreline. As the fresh water hydraulic gradient decreases, the sharp interface is becoming less vertical and moves inland.

Ghyben [1888] and Herzberg [1901] were among the first to examine and analyze the nature of the sharp interface between the saline and fresh water. In their analysis they assumed hydrostatic conditions, and they showed that the sharp interface between saline and fresh water with density values of ρ_s and ρ_f, respectively, must be projected onto the aquifer at an angle α <90o (Freeze and Cherry, 1979). Based on this analysis, the Ghyben-Herzberg relationship has been developed, according to which for each meter of fresh water hydraulic head (h_f) above the mean sea level, the interface (ξ) between saline and fresh water is balanced approximately 40 meters below the mean sea level (Figure 1a).

$$\xi = \frac{\rho_f}{\rho_s - \rho_f}\, h_f \approx\ 40\ h_f \qquad (1)$$

where ξ is the location of the interface below sea level, h_f is the hydraulic head of the fresh water above sea level, ρ_f is the density of fresh water and ρ_s is the density of the saline water.

In the sharp interface approach, the physical system is modeled using only the standard groundwater flow equation (Equation 2) and the seawater intrusion front is approximated hydraulically using the Ghyben-Herzberg relationship. The obtained estimation of the sharp interface location is considered to be on the conservative side (Essaid, 1990).

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) = S\frac{\partial h}{\partial t} \qquad (2)$$

where, h is the hydraulic head, K_{xx}, K_{yy}, K_{zz} are the hydraulic conductivities in x, y and z direction and S is the specific storage coefficient.

This approach is generally applicable to regional-scale coastal systems where the width of the mixing zone is small relative to the thickness of the aquifer.

ii) Density-dependent miscible flow and transport approach

The density-dependent miscible flow and transport approach considers the two fluids, saline and fresh water, as miscible. The width of the transition zone between the two miscible fluids is significant and is affected by hydrodynamic dispersion that occurs between two fluids with variable density (Figure 1b). Henry (1964) was the first to quantitatively determine the effects of dispersion and density-dependent flow on saltwater invasion in coastal aquifers. A more realistic representation of the physical processes occurring in a coastal aquifer is obtained using the density-dependent miscible flow and transport approach rather than the sharp interface approach.

The mathematical simulation of density-dependent flow and transport in subsurface water could be expressed in terms of an equivalent freshwater head:

$$h = \psi + z \tag{3}$$

where $\psi = \frac{p}{\rho_o g}$ is the equivalent freshwater pressure head, p is the pressure head, ρ_o is the freshwater density, g is the gravitational acceleration and z is the vertical coordinate directed upward (Huayakorn et al. 1987). The mathematical expression of the coupled nonlinear system of variably saturated flow and miscible salt transport equations is as follows (Gambolati et al., 1999):

$$\sigma \frac{\partial \psi}{\partial t} = \nabla \left[K_s \frac{1+\varepsilon c}{1+\epsilon' c} K_r \left(\nabla \psi + (1+\varepsilon c)\, \eta_z \right) \right] - \phi S_w \varepsilon \frac{\partial c}{\partial t} + \frac{\rho}{\rho_o} q \tag{4}$$

$$\mathbf{v} = -K_s \frac{1+\varepsilon c}{1+\epsilon' c} K_r \left(\nabla \psi + (1+\varepsilon c)\, \eta_z \right) \tag{5}$$

$$\phi \frac{\partial S_w c}{\partial t} = \nabla \cdot (\mathbf{D} \cdot \nabla c) - \nabla \cdot c\mathbf{v} + qc^* + f \tag{6}$$

where, K_s is the saturated hydraulic conductivity tenso at the reference density, $K_r(\psi)$ is the relative conductivity, η_z is a vector equal to zero in its x and y components and one in its z-component, $\sigma(\psi, c)$ is the storage coefficient, t is the time, ε is the porosity, $S_w(\psi)$ is the water saturation, q is the volumetric flow rate, $\mathbf{v}$ is the velocity vector, $\mathbf{D}$ is the dispersion tensor, c^* is the normalized concentration of salt in the injected/extracted fluid and f is the volumetric solute that does not affect the velocity field.

The density ρ and the dynamic viscosity μ of the saltwater solution is written in terms of the reference (freshwater) density ρ_o, the reference viscosity μ_o respectively and the normalized salt concentration c as:

$$\rho = \rho_o (1+\varepsilon c) \tag{7}$$

$$\mu = \mu_o (1+\varepsilon' c) \tag{8}$$

where $\varepsilon = (\rho_s - \rho_o)/\rho_o$ is the density ratio, ρ_s is the solution density at the maximum normalized concentration $c = 1$, $\varepsilon' = (\mu_s - \mu_o)/\mu_p$ is the viscosity ratio, and μ_s is the viscosity of the solution at $c = 1$. The elements of the hydrodynamic dispersion tensor **D** are given as:

$$D_{i,j} = \frac{\alpha_T \mid v' \mid \delta_{i,j} + (\alpha_L - a_T)\, v_i v_j}{\mid v' \mid} + D^*_{i,j} \tag{9}$$

where a_L is the longitudinal dispersivity, a_T is the transversal dispersivity, $D^*_{i,j}$ is the molecular diffusion coefficient and $v\prime$ is average linear groundwater velocity.

The nonlinearity of the coupled system (equations 4-6) is due to a) the dependence of the solution density on concentration, b) the convective and dispersive flux terms in transport equation and c) the unsaturated zone that is included in equation 4. The latter nonlinearity arises from pressure head dependencies in the relative hydraulic conductivity and storage terms (Gabollati et al. 1999). In both modeling approaches, the physical processes that take place in a coastal aquifer are simulated and - depending upon the assumptions and the limitations of each approach - a representative behavior of the physical system is obtained. Herny (1959), Bear and Dagan (1964), Strack (1976), Cheng et al. (2000), and Mantoglou (2003) presented analytical solutions based on the sharp interface approach that approximate the invasion of seawater front into a coastal aquifer under simplified conditions (i.e., steady state conditions, one or two wells). To overcome the case-orientated characteristics of the analytical solutions, many researchers have developed numerical solutions based on the sharp interface approach to hydraulically determine the location of the sharp interface between fresh and saline water in a coastal aquifer (Shamir and Dagan, 1971; Pinder and Page, 1977; Mercer et al., 1980; Essaid, 1990; Bakker, 2003).

A more realistic representation of the physical processes in a coastal aquifer considers spatially variable density of the mixed fluid in the transition zone. Even though in the early '70, the physics of the density-dependent miscible flow and transport were well known and understood (Pinder and Cooper, 1970); the technological advances in computer science in the late '80 gave the opportunity for the development of numerical models that simulate the computationally demanding 3D coupled flow and transport process (Huyakorn et al., 1987; Galeati et al., 1992; Putti and Paniconi, 1995; Simmons et al., 2001; Diersch and Kolditz, 2002; Smith, 2004).

Besides, these two well-established modeling approaches, more simplified approaches have also been adopted to simulate the physical processes in a coastal aquifer. A balance approach that treats the aquifer as a homogeneous unit in which the mixing occurs instantly is adopted by Assouline and Shavit (2004) to examine the effects of management policies on the salinization of a coastal aquifer in Israel. The lumped model approach is another alternative adopted by Shamir et al. (1984), that introduced a multi-cell model, and by Loaiciga and Leipnik (2000), who developed a "tank" model to simulate the physical processes in a coastal aquifer. Carrera et al. (2010) considered the inverse problem of seawater intrusion as an alternative but computationally costly modeling approach.

3 Environmental Mechanisms and Effects of Seawater Intrusion

Various classifications of saline water are reported in the literature in terms of mineral salt concentration dissolved in water (salinity) and chloride ion concentration in water. The seawater intrusion front is defined by a chloride concentration value of ~1500mg/l. A representative classification of water type and use, in terms of salinity and chloride ion concentration is shown in Table 1 (Robinove et al., 1958; FAO, 1992).

Water Type	**Salinity (mg/l)**	**Chloride Ion Concentration (mg/l)**	**Water Use**
Fresh	< 1000	< 500	Potable
Slightly saline	1000-3000	500-1,500	Irrigation
Brackish	3000-10,000	1,500-7,000	-
Saline	10,000-35,000	7,000-19,000	-
Seawater	$> 35,000$	$> 19,000$	-

Table 1 Saline water classification

The quality of the subsurface water resources in coastal regions is affected by a series of natural and anthropogenic factors (Figure 2). The sea level rise due to tidal fluctuation (Ataie-Ashtiani et al., 1999) and tectonic changes of earth terrain in conjunction with the particular geomorphology of the coastal aquifer force the seawater front to intrude further inland, creating a thicker interface between fresh and saline water. Papadopoulou et al. (2010a) have shown that the evolution of the seawater intrusion front is affected by the existence of geological discontinuities (faults) resulting in water table drawdown at locations within a close proximity of the faults. The faults orientation with respect to the coastline and the penetration depth affect the flow field especially during the wet season. Particular attention for the invasion of seawater into an aquifer should be paid to the connection between sea and aquifer due to the presence of preferential flow paths (Carrera et al., 2010).

The seasonal changes in precipitation and evapotranspiration as well as the influence of natural effluence of temporary and/or permanent rivers and channels could also affect the extent of the seawater intrusion. Mahesha and Nagaraja (1996) have established a relationship between the seawater front motion and the intensity and duration of uniform recharge to estimate the reduction of the seawater intrusion that is obtained due to natural recharge. In addition, human activities such as aquifer water mining and exploitation of natural resources (e.g., oil, natural gas) may dramatically accelerate seawater intrusion. Also, decisive factors in the quality of water resources in coastal regions are the terrain topology in conjunction with the land uses. The increasing urbanization along the shoreline results in significant increase of surface run-off without improving the natural enrichment of subsurface water resources via infiltration.

The environmental impacts of seawater intrusion have multidimensional characteristics. The sensible dynamic balance between fresh and saline water in coastal aquifers is mainly disturbed by extended pumping, resulting in lowering of the water table along the shoreline below the mean sea level and affecting the subsurface water quality. The sudden lowering of the water table also affects the hydraulic connection between surface and subsurface water. The qualitative deterioration of subsurface water is quantified by the increase of chloride concentration that is mainly related to seawater intrusion, but may also be related to salts leaching from the unsaturated zone.

Qualitative changes in surface and subsurface coastal waters due to the increase on chloride concentration have also an effect on the development of coastal ecosystems and hydro-biotopes. The increasing salinity level in subsurface water caused by the reduced frequency of fresh water flushing threatens the biodiversity in coastal aquatic systems. Especially during drought periods and periods of low natural flow, accumulation of salt is observed in surface coastal water bodies resulting in the elimination of native aquatic biota. In some cases, aquatic organisms are transubstantiated into more resistant species in order to survive in higher than the normal salinity level (Nielsen et al., 2003).

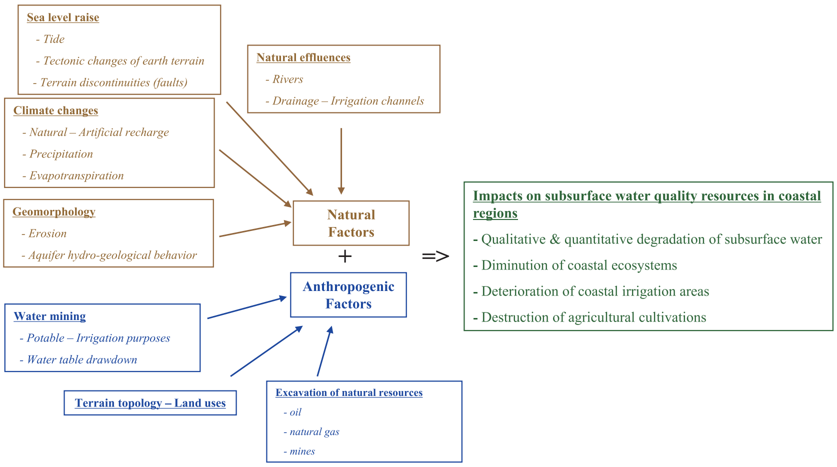

Figure 2: Factors influencing the quality of subsurface water resources in coastal environment

In addition, the economical and environmental impacts on agricultural development and activity in coastal regions are reported due to the poor subsurface water quality used for irrigation. The continuous use of water with high salt concentrations results in destruction of agricultural cultivations and field crops. The protection and restoration of rural land require time and recess from any agricultural activity without ensuring restoration of the soil quality to its initial levels.

Part II

As discussed above, the use and consumption of low quality freshwater in coastal regions have tremendous economic and environmental impacts and require the development of rational subsurface water resources management strategies that are mainly focusing on the control of seawater intrusion. Numerical models are powerful tools to simulate complex physical systems such as coastal aquifers affected by seawater intrusion. Classical derivative-based and derivative-free optimization methodologies have been widely used for the solution of subsurface hydrology problems such as water resources, water quality management and subsurface water protection and restoration design problems. Mayer et al. (2002) introduced a set of supply and remediation design "community problems" available to the research community to compare various optimization approaches. The main characteristic of these "community problems" is that classical optimization methods could be trapped in local optima due to the nonlinear and non-smooth shape of the objective functions. According to the classification of Mayer et al. (2002), the seawater intrusion problem is considered a "community problem" not only due to the mathematical complexities that arise in describing the complex physical processes in a coastal aquifer, but also due to its significant social-economic and environmental impacts previously described.

4 Management Approaches

Extensive reviews of the various optimization design models that have been developed to manage and remediate subsurface water systems are presented by Mayer et al. (2002) and Da Conceicao Cunha (2002). The development and success of a management model rely primarily on the accurate representation of the physical system by a simulation model and then on the definition of the management model objectives. As it is well presented by Gorelick (1983), there are three main approaches to incorporate the information obtained from a physical simulation model into the optimization design model: a) the embedding approach where the finite-difference and finite-element equations are embedded into the constraint set of the optimization model; b) the response matrix approach that is based on the principle of superposition; the development of the response coefficient matrix requires the solution of the simulation model for each potential remediation well and the evaluation of the physical system response subject to a set of perturbations that is stored in the response coefficient matrix; and c) the simulation/optimization (S/O) approach where a sequential link between the simulation model of the physical system and the optimization management model is established. The S/O approach allows the successful management of a coastal system that has complex nonlinear characteristics mainly related to the unconfined density-dependent flow and transport process. Even though the embedding and the response matrix approaches are valid only for linear, linearized or slightly nonlinear systems, many coastal management models have been developed using these approaches (Hallaji and Yazicigil, 1996; Nishikawa, 1998; Zhou et al., 2003; Abarca et al., 2006; Karterakis et al., 2007).

Over the last two decades, significant research work has been reported in the literature associated with the sustainable management of subsurface water resources in coastal regions mainly addressing the problem of seawater intrusion. In Figure 3 the optimization models that have been developed over the last 25 years for optimal subsurface water resources management by maintaining control of seawater intrusion into coastal aquifers (hypothetical and real-case applications) are summarized. Information related to the mathematical characteristics of the simulation approach of the physical system, the applied optimization algorithm and the objective function formulation is also presented.

4.1 Linear Solution Approaches

The response coefficient matrix approach was used by many researchers (Hallaji and Yazicigil, 1996; Nishikawa 1998; Zhou et al., 2003; Reichard and Johnson, 2005, Abarca et al., 2006) to solve linear formulation management problems that were mainly focused on the minimization of the drawdown at locations close to the coast, maximization of the extracted freshwater volume, minimization of the monetary costs a) to cover the water demand (supply water cost) and/or b) to raise the water level along the coast (delivery cost). Hallaji and Yazicigil (1996) developed a density-dependent finite-element model of the Erzin plain in southern Turkey to manage the subsurface water resources and to cover the water demand by maintaining the freshwater levels. Their analysis concluded that for the minimization of the pumping costs the wells with low static lifts should be operated whereas for the minimization of the total drawdown the wells at highly conductivity areas and close to the head boundaries should be turned on. Also, by imposing a minimum pumping rate for the production wells, the total pumping cost is increased. The optimal management policy suggested the fresh water from the most productive wells should be transported to areas where the water demand could not be covered by the local less productive wells.

Nishikawa (1998) developed a MODFLOW finite-difference model for the Santa-Barbara

Year	Authors	Simulation Approach	Formulation	Optimization Algorithm
1984	Shamir et al.	multicell model		
1988	Willis & Finney	Sharp-interface		
1992	Finney et al.	Sharp interface	Quadratic convex	-Box Algorithm (sequential search) - MINOS
1995	Reichard	Quasi 3D (Hydraulic surrogate)	Nonlinear	MINOS
1996	Hallaji & Yazicigil	FE Density-dependent (SUTRA)	Linear	Response coefficient matrix
1998	Emch &Yeh	Sharp interface	Nonlinear Multi-objective (constrained)	MINOS
1998	Nishiwaka	MODFLOW (equivelent fresh water)	Linear	Response coefficient matrix
1999a	Das & Datta	Density-depedent	Nonlinear Multi-objective (constrained)	MINOS
1999b	Das & Datta	Density-depedent	Nonlinear Multi-objective (constrained)	MINOS
2000	Cheng et al.	Sharp-interface (Strack formulation)	Nonlinear	Structured Messy GA
2001	Gordon et al.	FE (negleting density effects)	Nonlinear multi-objective Multi-period design	Bundle-Trust Algorithm (modified gradient method)
2003	Mantoglou	Sharp-interface (Strack formulation) – Analytical solutions – MODFLOW	Nonlinear	Sequential Quadratic Algorithm (SQA)
2003	Zhou et al.	Quasi 3-d FE	Linear	Response coefficient matrix
2004	Mantoglou et al.	Sharp-interface (Strack formulation)	Nonlinear	Sequential Quadratic Evolutionary Algorithm
2004	Park & Aral	Sharp-interface (Strack formulation)	Nonlinear multi-objective (weighted)	Progressive GA
2004	Rao et al.	Sharp interface (ANN as surrogate model)	Nonlinear	Simulated Annealing
2005	Bhattacharjya & Datta	ANN (3d variable density surrogate)	Nonlinear Multi-period design	Genetic Algorithm (GA)
2005	Katsifarakis & Petala	Boundary element method	Penalty	Genetic Algorithm (GA)
2005	Reichard & Johnson	3D equivelent fresh water (MODFLOW)	Linear	Response coefficient matrix (Lindo)
2005	Reinelt	Sharp-interface	Nonlinear	Gradient Search
2005	Quhman et al.	Density-depedent	Single objective Multi-objective (weighted)	Genetic Algorithm (GA)
2006	Abarca et al.	2d linear	Linear	Response coefficient matrix
2007	Ferreira da Silva & Haie	Sharp-interface	-	Evolutionary Algorithm (EA)
2007	Karterakis et al.	Sharp-interface	Linearized form	Simplex Method Differential Evolutionary Algorithm (DE)
2008	Bray & Yeh	Density-depedent	Scheduling problem Well allocation	MINOS GA
2008	Mantoglou & Papantoniou	Sharp-interface	Nonlinear - Simultaneous - Two stage	GA GA and SQA
2009	Dhar & Datta	ANN (3D variable density surrogate)	Nonlinear multi-objective	Non-dominated Sorting GA II
2010	Papadopoulou et al.	ANN (Sharp interface)	Linearized form	Differential Evolutionary Algorithm (DE)

Figure 3: Optimization approaches applied to control seawater intrusion

aquifer and used a freshwater-equivalent hydraulic head form to overcome nonlinearity issues (density-dependent mass transport) and to obtain practical results to the water resources management problem. The management problem was formulated as minimization of the water supply cost subject to water capacity, hydraulic head, water demand and pumping distribution constraints. The optimal operating management policy proposed continuous operation of the inland production wells and part-time operation for the coastal wells. In this formulation, the timing of water distribution (water availability) versus the water demand is the key for an optimal cost-effective pumping strategy. The availability of adequate quantities of supply-water at the time of high demand results in an optimal strategy with reduced water-supply cost. Similarly, Zhou et al. (2003) used the Simplex method to obtain optimal exploitation subsurface water schemes that would prevent seawater intrusion into the Leizhou Peninsula in Southern China by imposing water level constraints along the coast. In their analysis, the location of the water supply wells was randomly distributed. Also, Reichard and Johnson (2005) achieved a cost-effective way to improve control of seawater intrusion along the coast of Los Angeles by a) increasing the injection into barrier wells and/or b) delivering of surface water to replace current pumping. Assumptions associated with cost structure, necessary maintained water level, future conditions, and boundary/model parameter are imposed in the formulation of the management model. The obtained optimal operating policy proposed as optimal cost-effective solution the purchase of surface water to cover the water demand rather than the water injection into the barrier to maintain a minimum water level since the latter is extremely expensive.

The main advantage of linear optimization approaches in seawater intrusion problem is the simplifications that those methods require in the development of the design formulations resulting in fast solutions. On the other hand, these simplifications (e.g. linearized water table, freshwater equivalent hydraulic head) may overestimate the behavior of the physical system resulting in expensive design solutions.

4.2 Nonlinear Solution Approaches

Classical nonlinear optimization methodologies were applied to propose successful subsurface water resource management policies that would prevent further seawater intrusion. These nonlinear management problems were mainly solved by MINOS (Murtagh and Saunders, 1987; 1998), an augmented Lagrangian algorithm that reduces the nonlinear constrained problem to a series of linear sub-problems that are then solved using a reduced-gradient algorithm. Finney et al. (1992) used MINOS to solve a quadratic convex management problem in the Jakarta aquifer. Unfortunately, the response surface of the optimization model was relatively flat with a large number of local minima, preventing MINOS to differentiate between stationarity points and local minima. To overcome this difficulty, a sequential-search algorithm (Box's algorithm) was applied. Their analysis proved that redistribution of the production pumping wells and implementation of artificial recharge may significantly effect the movement and extent of the seawater intrusion. Reichard (1995) also used MINOS to solve a nonlinear formulation that employed hydraulic levels and gradients constraints as surrogates to consider water quality issues at the Santa Clara-Calleguas Basin in Southern California. In this optimization model, the uncertainty in the surface water availability was also explicitly included. The model results indicated that reduction in the current pumping schemes with simultaneously artificial water recharge into the groundwater system may obtain control of the seawater intrusion. In order to successfully achieve complete containment of the seawater plume more localized measures, (e.g. barrier wells) are necessary.

Gordon et al. (2001) solved the multi-objective and multi-period design water resources problem in a non-homogeneous regional aquifer in Israel using the Bundle-Trust algorithm which is a modified classical nonlinear optimization method applicable to non-smooth, non-differentiable and sometimes non-convex objective functions. In their analysis, a finite-element subsurface flow model was developed, and since the aquifer salinity was not high enough, the density effects on the flow were neglected. The two components of the design was the maximization of the water volume and the minimization of the total pumping and treatment cost of the extracted water. The increase of pumping in some locations led to decrease of salt concentration in other wells because of the change in the direction of saline water front.

Mantoglou et al. (2004) developed a numerical simulation model of an unconfined aquifer on the Kalymnos Island in Greece based on the sharp-interface approach expressing the freshwater flow equations using a single potential formulation (Strack, 1976). The optimization objective was to maximize the total pumping rate subject to imposed nonlinear constraints that maintain a secure distance between the pumping well and the toe of the interface. The problem was successfully solved by a sequential quadratic programming method with low demand in CPU time compared to the solution obtained by an evolutionary algorithm (EA) but there was always the possibility to be trapped on local optima. The obtained optimal strategies were very sensitive to any variation of pumping and/or injection rate. By imposing restrictions in the flow potential instead of the distance between the pumping well and the toe the proposed optimal policies were significantly more conservative. In this work, an additional constraint that determines the line connecting the closest to the coast wells with the model boundaries was proposed and showed that a small reduction of the total pumping was sufficient to prevent the advancement of the seawater front.

A gradient search method was applied by Reinelt (2005) to solve a multi-stage dynamic optimization design problem in Monterey County CA where the imposed constraints were sequentially satisfied through time. The model solution proposed spatial distribution of optimal pumping based on spatial variable extraction cost and seawater intrusion economic impacts. In this particular area, alternative management policies were examined considering property issues revealed that in intruded areas landowners could not longer exercise their water rights. The nonlinear flow and transport formulation of an optimal scheduling problem that will determine the minimum amount of injected water to maintain an established hydraulic barrier along the shoreline was also solved using MINOS (Bray and Yeh, 2008). The performance of the management model is improved if the injection barrier is broken into pieces. In this work the optimal placement of the injection wells was also examined showing that the mass transport criteria are less sensitive to existing wells than hydraulic criteria.

A variation of management problems could be examined using classical nonlinear optimization methodologies considering not only hydraulic but also mass transport constraints. The problem formulation is more complex to be solved but at the same time it represents better the actual management problem. The nonlinear accurate mathematical representation of the management problem may lead to a complex form objective function and it may be trapped on local optimal solutions. Also the computational cost and the complexity tremendously increase as the number of decision variables also increases.

4.3 Multi-objective Solution Approaches

The first multi-objective attempt to obtain an optimal operation policy for the subsurface water resources of a phreatic coastal aquifer in Israel was presented by Shamir et al. (1984). The study aquifer was simulated using a multi-cell model, in which a flow mass balance was imposed at each model cell to constrain the water demand, and a linear approximation of the interface movement was adopted. A multi-objective optimization problem was formulated, considering linear objectives to minimize the distances between real and desired a) water levels b) locations of the interface toe and c) chloride ion content in each cell, and to minimize d) the total chloride ion concentration and e) the energy cost. This multi-objective problem was solved by the constraint method to determine a non-inferior solution set:

$$\min \mathbf{Z} = [Z_1(\mathbf{x}), Z_2(\mathbf{x}), ..., \ Z_p(\mathbf{x})] \tag{10}$$

subject to

$$g_i(\mathbf{x}) \geq 0, \ i = 1, ..., m \tag{11}$$

$$\mathbf{x} \geq \mathbf{0} \tag{12}$$

where $\mathbf{Z}(\mathbf{x})$ is the multi-ojective function, $Z_k(x)$ are the different individual objective functions, g_i are constraint functions and $\mathbf{x}$ is decision variable vector.

A feasible solution is defined as a non-inferior solution if there is no other feasible solution with a better objective function value with respect to any one objective without having a worse value in at least one other objective (Ravelle et al. 1997). According to the constraint method, one objective function Z_r is arbitrarily chosen to be optimized, whereas the other objectives Z_k are included into the constraint set with bounds (L_k). At each iteration, a single-objective optimization problem is solved to identify an optimal non-inferior solution to the multi-objective problem.

$$\min \ Z = Z_r(\overline{\mathbf{x}}) \tag{13}$$

subject to

$$Z(\overline{\mathbf{x}}) \leq L_k \quad \ for \ all \ k \neq r \tag{14}$$

The solution of this problem produces a non-inferior solution to the original multi-objective problem when the constraint (equation 14) is binding. Their problem was tightly constrained by the existing wells and the aquifer hydraulic behavior therefore the multi-objective formulation results were limited.

The constraint method was also applied to solve nonlinear multi-objective management problems: a) Emch and Yeh (1998) considered the minimization of the intruded saltwater volume into the coastal system and a cost-effective allocation of surface and subsurface water. Their results proved that significant decrease of total cost can be obtain in relative low saltwater volumes if a minimal increase in the volume is allowed. In their simulation, they applied a sharp interface approximation of the seawater intrusion front; and b) Das and Datta (1999a) and (1999b) considered the maximization of total withdrawal from production wells to cover the water demand, minimization of total withdrawal from wells close to the coastline to control seawater intrusion, and minimization of the maximum aquifer salinity pumped from the production wells. In their work, the nonlinear finite-difference approximations of the density-dependent miscible flow and transport were embedded into the management model as constraints. The main outcome of their analysis regarding the proposed management policies to protect the coastal aquifer from seawater intrusion was that the trade-off between maximum withdrawal and maximum permitted salinity of pumped water is extremely high when the salinity level is very low.

An alternative to the constraint method addressing multi-objective problems is the weighted method. According to this method the multi-objective problem is transformed to a single scalar objective function which is the weighted sum of each objective function.

$$\begin{aligned} &\max\ Z_1 = Z_1(\mathbf{x}) \\ &\max\ Z_2 = Z_2(\mathbf{x}) \\ &\max\ Z_3 = Z_3(\mathbf{x}) -> \max\ \mathbf{Z}(w_{1,...,}w_k, \mathbf{x}) = w_1 Z_1(\mathbf{x}) + ... +\ w_k Z_k(\mathbf{x}) \\ &\qquad\quad .... \\ &\max\ Z_k\ = Z_k(\mathbf{x}) \end{aligned} \tag{15}$$

A multi-objective formulation for the water resources planning management of the Yun Lin basin was expressed as a weighted sum of the water supply extracted volume, the recharge volume and the location of the interface. The control problem was solved applying a) the influence coefficient matrix algorithm allied with quadratic programming and b) a reduced-gradient/quasi-Newton algorithm that obtained at least linear convergence and stable solutions. The results of the analysis proved that a given set of weights each time could significantly affect the water supply and recharge volumes. Also, changes in the pumping/recharge schedules produced little change in the response surface of the optimization model (relative flat surface). Issues related to local optimality characteristics of the management problem were also raised in this analysis due to the nonlinearity and nonconvexity response of the aquifer (Wills and Finney, 1988). In their analysis, Abarca et al. (2006) addressed the design of corrective measures to restore subsurface water quality in an already salinized aquifer with a multi-objective formulation. The goals of the design were a) the maintenance of the pumping activity at the current level and b) the improvement of the subsurface water quality to a satisfactory level obtained by the imposed corrective measures (i.e., recharge). A linear formulation considering constrained heads to prevent seawater intrusion and a nonlinear formulation associated with minimal changes in the current pumping activity that would preserve water rights considering concentration constraints were examined. The imposed weights varied the relative contribution of each objective depending upon the priorities of the decision-maker, creating different policies. Both formulations proposed reduction of the current pumping activity, artificial recharge and the development of a hydraulic barrier along the coast as corrective measures to control seawater intrusion. The nonlinear formulation led to a more efficient solution regarding the pumping activity and the quality of extracted water. Also the development of a coastal hydraulic barrier not only protects the existing water resources but also contributes in new ones.

Multi-objective formulations allow the simultaneous evaluation of conflicting objectives in order to obtain an optimal management policy that will protect the existing subsurface water resources from the risk of seawater intrusion. In a multi-objective formulation various objectives with respect to technical characteristics (e.g. installation/operation costs, energy requirements), environmental issues (e.g. resources lifetime limitations, spatial allocation) and social-economical issues (e.g. water rights, price) could be included. Unfortunately, the ability to consider many objectives does not always lead to an optimal environmental solution but to a non flexible solution that satisfy more the various stake-holders that impose the objectives.

4.4 Heuristic Solution Approaches

As is shown above, the majority of the classical optimization methodologies required the computationally expensive calculation of the objective and constraints functions gradient. In many cases, the highly nonlinear nature of the seawater intrusion process and the irregular shape of the response surface yield optimal solutions that are sensitive to the starting point of the search procedure. In the decision-making process, the design and control parameters that describe the corresponding management problem to achieve control of seawater intrusion could vary in a certain range, resulting in a non-straightforward solution. Furthermore, the efficiency of gradient-based optimization models also decreases as the number of decision variables increases (Bray and Yeh, 2008).

Recent advances in computer sciences in the last decade were crucial for the development and use of heuristic optimization methodologies for the solution of environmental design and management problems. Fowler et al. (2008) introduced several derivative-free deterministic sampling methods for the solution of constrained optimization problems with nonlinear, non-smooth objective functions and applied them to a subset of the "community problems". Many attempts, in the area of control and management of seawater intrusion problems, were recently reported in the literature. In their approach, Cheng et al. (2000) adopted a structured messy genetic algorithm (SMGA) to determine the maximum volume of extracted water without causing the seawater front to reach the pumping well locations. At this point, it should be mentioned that in most genetic algorithms (GA) the design parameters are encoded onto a data string, analogous to a chromosome in nature and then an individual solution to the problem is represented by a string of numbers. SMGA is based on progressively building up the complexity of the individuals by increasing the length of the string in successive solution populations (Halhal et al. 1997). Their analysis proved that it is obligated to reduce the number of pumping well locations when the well field is crowded in order to achieve water adequacy. The solution search space is considerably large yielding near optimal solutions. Park and Aral (2004) used a sharp interface, single potential formulation to represent the evolution of the seawater intrusion front into a hypothetical test-aquifer. Then, the nonlinear multi-objective problem to achieve the maximum pumping rates and the suitable extraction well locations was solved by a progressive genetic algorithm (PGA). The basic idea behind this method involved a minimum search to get a trend of the solution in a sub-domain; the optimal solution was defined through a sequence of sub-domain solutions. In most engineering problems the search in the whole domain of interest is unnecessary; following this approach the required simulation runs were significantly reduced. In this formulation, Park and Aral (2004) introduced, as decision variables, the perturbation of pumping rates and well locations rather than the actual pumping rates and well locations in order for the PGA to be more flexible and efficient. The simultaneous optimization of well location and the corresponding pumping rates produced more efficient management policies.

Genetic algorithms were also introduced by researchers (Katsifarakis and Petala, 2005; Quhman et al. 2005; Mantoglou and Papantoniou, 2008; Bray and Yeh 2008) to obtain the optimal management of coastal regions adopting nonlinear, multi-objective, multi-period formulations. Katsifarakis and Petala (2005) introduced a penalty term in their objective function formulation to consider seawater invasion into the pumping wells for each proposed pumping scheme. The form of a penalty term that considers both the number of violated constraints and the actual constraint violation is efficient guaranteeing more adequate management policies. In their test aquifer, Quhman et al. (2005) tried different objective functions formulations depending upon the goals and the priorities of the decision-makers. In order to overcome difficulties in finding a global solution, a GA was applied instead of a gradient based method. A genetic algorithm was also used by Mantoglou and Papantoniou (2008) in a two-stage management formulation involving search of the optimal well locations at the first stage, followed by a sequential quadratic algorithm to define the optimal pumping rates at each generation of the genetic algorithm. The two stage solution approach yields a slightly better solution to the maximization of the total pumping than the one stage approach that determines simultaneously the optimal well locations and the corresponding pumping rates. The computational time associated with the two-stage approach was considerably larger than the single one. Besides the nonlinear optimal scheduling problem, Bray and Yeh (2008) analyzed the optimal wells allocation problem using a genetic algorithm in order to improve the performance of an existing hydraulic barrier along the coast by installing new injection wells. The obtained optimal policy suggested the placement of the new injection wells is more sensitive to the constraint locations (observation points) than the existing well locations.

Ferreira da Silva and Haie (2007) used an evolutionary algorithm to determine an optimal operation policy including optimal well locations that will maximize the economic return of the optimal policy while controlling the seawater intrusion. From a managerial point of view the cost of using groundwater supplies is lower than any other sources (i.e. water transported, desalination, recyclable water). In their analysis, they proposed management policies that should have been focused on the extraction of maximum water volume by simultaneously maintaining the interface at a safe distance from the control points. A Differential Evolution (DE) algorithm, which adds the weighted difference between two population vectors to a third vector, is used by Karterakis et al. (2007) to obtain hydraulic control of seawater intrusion in a coastal aquifer in Crete. In DE algorithm, distance and direction information is extracted from the population to generate random deviations, which results in an adaptive scheme with excellent convergence properties (Storn and Price, 1995). The DE algorithm was able to reach a global optimal solution.

4.4.1 Surrogate Models

A very large number of iterations between the simulation and the optimization model is required by most of the above mentioned heuristic optimization approaches to reach an optimal solution. The external linking of the “precise” numerical simulator within the optimization model is an extremely computational demanding process especially when the invasion of the seawater front is estimated by a density-dependent miscible flow and transport simulator. The computational time associated with the simulation runs could be reduced through parallel processing or by an approximation of the time-consuming exact and accurate numerical model so-called surrogate model. These models may be either physical by solving the same problem with more simplistic approximations, or mathematical by approximating the solution surface over the search space that has been previously determined from runs of the expensive simulation (Torczon et al., 1998; Giannakoglou, 2002). The use of a surrogate model is very inexpensive whereas its construction may require extremely large amount of computational time. Surrogate models can be used either ”off-line” or ”on-line”. Off-line models are global models, in the sense that a single model covers the entire search space. Such models are built prior to the beginning of the optimization procedure, using available data either from physical experiments, or from successive calls to an "exact" physical model. On-line models are built-into the evolutionary algorithm (EA) and evolve with its population. They are "re-trained" in each generation of the EA, taking into account the recent information about the search space, provided by the current population. In that sense, they are local approximation models; as a result increased accuracy is expected, compared to the off-line ones (Papadopoulou et al., 2010b). During the optimization procedure the use of surrogate models to compute the objective functions, without any need of using the "exact" physical model is desirable (Nikolos et al., 2008). This approach that involves the use of a surrogate model instead of the exact numerical model was recently adopted by researchers (Rao et al., 2004; Bhattacharjya and Datta, 2005; Dhar and Datta, 2009; and Papadopoulou et al., 2010b) to develop management policies for the control of seawater intrusion.

In their work Rao et al. (2004) developed a conjunctive use model to cover the water demand at a deltaic area where the availability of surface and subsurface water resources varied in space and time. The computational time associated with the simulation of a deltaic aquifer was eliminated by a trained Artificial Neural Network (ANN). A near-optimal solution to the management problem is obtained using a Simulated-Annealing (SA) algorithm suitable for discrete decision variables. Their analysis proved that a) the computational time arising from the simulation process could be significantly reduced whereas the time associated to generate a feasible configuration under equilibrium conditions depends upon the formulation of the problem and the annealing parameters; and b) the proposed methodology may determine management policies for conjunctive use in time that are directly associated with the aquifer properties. A trained ANN was also developed by Bhattacharjya and Datta (2005) to approximate the 3D density-dependent miscible flow and transport processes in a hypothetical coastal aquifer. The management problem that was solved by a genetic algorithm was formulated to maximize the subsurface water withdrawal to cover the water demand, while maintaining the salt concentration at pumped locations under pre-specified levels. The performance of the ANN-GA management model is highly depended on the successful training and accuracy of the ANN approximation model. The training of ANN becomes a computationally intense procedure if applied to a real aquifer where uncertainty associated with the aquifer parameters occurs.

In some works (Rao et al., 2004; Bhattacharjya and Datta, 2005; Nikolos et al., 2008), the use of an off-line ANN as a surrogate model with a derivative-free optimization method (eg., GA, SA, DE) allowed for fast and easy testing of different sets of constraints for the same optimization problem, without the need for retraining the ANN model. However, the initial training of the surrogate model was computationally costly. To overcome this difficulty, Dhar and Datta (2009) developed an ANN as a surrogate of the accurate numerical model and they used it as an initial screening model to determine the non-dominated solution front during the optimization process that had a better performance in terms of convergence and objectives variation compared to the numerical model. The screening model was computationally efficient in proposing management policies to control seawater intrusion.

Papadopoulou et al. (2010b) also proposed an on-line surrogate model to approximate the objective function, based on a Radial Basis Function (RBF) ANN. The surrogate model is completely integrated within the DE algorithm to provide a local approximation of the search space, by using the local information from the recently evaluated candidate solutions; the surrogate model is thus retrained in each generation of the DE algorithm. Their solution approach was implemented in a karstified aquifer in Crete with serious water quality problems caused by the seawater intrusion phenomenon. This meta-model use of the Radial

Basis Function ANN surrogate model enabled the speed-up of solution convergence, without sacrificing the robustness of the DE optimization algorithm.

As the number of objectives and constraints increases, the need for more flexible methodologies that incorporate the design complexity is imperative (Nikolos et al., 2010). Heuristic methodologies are able to successfully deal with a large number of decision variables and nonlinear function formulations. The addition of penalty terms in the objective function creates discontinuities in search space that have serious effects in the solution process of a classical optimization methodology. Using heuristic methodologies that problem is overcome due to their ability to decompose the solution space to sub-domain and to fast search for sub-optimal solutions. In most engineering problem, a sub-optimal solution is acceptable as long as it is achieved within reasonable computational time. The use of parallel processing that is an option in many heuristic methodologies could significantly reduce the computational time requirements. The cost that researchers should pay using these methodologies is related to the computational resources availability.

5 Discussion

Even though the goal in all the optimization models is the optimal subsurface water resources management by restraining the seawater intrusion front, the way that the objectives of each management model is formulated varies depending upon the priorities of the decision-makers, the aquifer data, the physical system simulation and the computational availability. The adoption of an optimization methodology to obtain an optimal water resources management policy in a coastal region is site-oriented. For that reason, the direct comparison between the different optimization solutions obtained for different coastal regions is not possible.

In all the management formulation presented here, different engineering approaches were applied to obtain meaningful policies for the sustainable management and the seawater intrusion protection of subsurface water resources. A critical issue in the formulation of an optimization model is the control of the seawater intrusion front that is obtained by the optimal spatial allocation and temporal operation of the pumping/injection wells. Complete control of the seawater front could only be achieved with localized measures such as hydraulic barrier (Reichard, 1995; Bray and Yeh, 2008). In many cases, the transfer of fresh water to coastal areas is preferred rather than the overdraft of local production wells that may significantly disturb the sensible dynamic balance between fresh and saline water in an aquifer. Also small reductions in the pumping activity may significantly improve the lifetime of the existing subsurface water resources. Especially in areas with low salinity levels, the controlled invasion of the seawater front is an alternative but then issues related to water rights could be raised by landowners in the intruded areas that also need to be considered in the design.

The coverage of the water demand in coastal regions was mainly expressed as maximization of water supply/agricultural withdrawal volume and alternatively as minimization of the drawdown, or the water supply cost or the salinity of pumped water. The maintenance of the water table within acceptable levels works as a surrogate constraint that ensures the quality of the extracted water. To enhance the applicability and the performance of their optimization models, many researchers introduced multi-objective formulations that simultaneously consider conflicting objectives to obtain more reasonable solutions to their management problems. In Table 2, representative single- and multi-objective functions are summarized for the solution of the subsurface water resources management problem under seawater intrusion conditions. In the single objective formulation, maximization and minimization expressions were used depending upon the design needs. In the multi-objective formulations, many objectives are imposed serving different design requirements, in order to achieve an optimal solution.

Single Objective Formulations	**Multi-objective Formulations**
Max water supply	a. Determine mean distance between
Max agricultural withdrawal	- injection and pumping wells
Min supply cost	- wells & aquifer boundaries
Min salinity of pumped water	
Min drawdown	b. - Allocation of water supplies
Min total extrected cost (including pumping ant treatment)	- Min saltwater intrusion
Min total salt mass extrected	c. - Min need for water supplement
	- Min water use reduction
	- Min changes in current pumping

Table 2 Representative single- and multi-objective function formulations

The performance of the optimization models was also determined by the mathematical form of the imposed constraints and the way they were included into the solution procedure (Table 3).

	Constraint Function Formulations
1.	Location of stagnation point
2.	Pumping limitations (Upper-Lower bounds)
3.	Control of drawdown
4.	Control of “toe” location
5.	Maintaining water level/salt concentration at desired level
6.	“Potential” Constraint (maintaining potential at well > potential at toe)
7.	Total volume of extracted water
8.	Total volume of injection water
9.	Cover monthly water demand
10.	Temporal balance constraint
11.	Total transfer of water from/to aquifer
12.	Water routing

Table 3 Commonly used constraint function formulations

In early works that have been reported in the literature, the linear formulation of the constraints was commonly used and then these constraint formulations were embedded into the solution process. The difficulty in formulating and evaluating a constraint function in such a management problem arises from the complexity of physics that is necessary to be considered to accurate estimate the movement of seawater intrusion front. By adopting the sharp interface approach to simulate the behavior of a coastal physical system, the imposed constraints had a linear or a linearized form that could easily included in a linear optimization model. On the other hand, the nonlinear density-dependent miscible flow and transport equations are important to represent the complex physics of a coastal aquifer and to accurately estimate the movement of the seawater intrusion front but are also crucial with respect to the computational time requirements for the optimization model to reach an optimal solution. Most of the nonlinear optimization models presented here were only able to converge to local optimal solutions.

Researchers also should focus on the development of surrogate/approximation models to accurately represent the computationally intense response of a coastal physical system. The surrogate models can be used either "off-line" or "on-line", the former being global models covering the entire search space, built prior to the optimization procedure, the later being local models, retrained during the optimization procedure, which take into account the recent information about the search space. In seawater intrusion management problems, the simulation of the nonlinear coastal system may produce non smooth cost functions, very difficult to be approximated using a global surrogate/approximation model. As a result, the application of a global (off-line) surrogate model to a heuristic optimization methodology may lead to a false solution, due to its inability to accurately approximate all the characteristics of the "exact" cost function (Papadopoulou et al., 2010b). The adoption of local (on-line) surrogate models can enhance the approximation accuracy, with a marginal rise to the computational cost of the optimization procedure.

6 Conclusions

The analysis of all the subsurface water management models applied to coastal aquifers discussed in this paper showed that the proposed optimal strategies/policies were only able to control the invasion of the seawater front and not to completely protect them. The restoration of a coastal aquifer that suffers from seawater intrusion is a very difficulty, time consuming and cost-inefficient process that in combination with the water scarcity in these regions lead to irrevocable situation for the quality of their subsurface waters.

From an engineering point of view, the priority in all the optimization models is to maintain a hydraulic barrier along the coastline to prevent further seawater intrusion into the aquifer that may damage subsurface water reservoirs. To accomplish this goal, the maintenance of the freshwater table along the coastline is necessary by controlling artificial water recharge and the subsurface water drawdown. The transfer of fresh water from other places and the conjunctive use of coastal surface and subsurface water are common practices to achieve water quantity and quality adequacy in coastal regions. Management models that will involve not only water transfer but also water recycling and water re-use systems in their formulations may lead to smaller volumes of extracted water from the coastal aquifers and to a more efficient use of subsurface water resources.

From a decision-making point of view, the conflicting interests of the different beneficiary groups in a coastal region should be considered in the development of a water resources management policy. In coastal regions, not only quantity (i.e., water demand coverage) but also quality issues (i.e., seawater intrusion) associated with the subsurface water resources should be equivalently considered during the design process by multi-objective formulations. Researchers should focus on multi-objective frameworks that will consider the uncertainty in the simulation of the coastal physical system and in the accomplishment of the design objectives. Estimation of physical characteristics/parameters that are key factors for the accurate representation of the system is important in order to avoid simplifications that yield overestimated management solutions.

From an optimizer point of view, the increscent concern worldwide to protect subsurface water resources in coastal regions is a motivation for the research community to explore more areas of heuristic optimization. The advances in computer sciences in conjunction with the “smarter” formulation of the optimization problem could lead to more efficient solutions of the seawater intrusion problem in coastal regions. Besides the multi-objective formulation, the successful control of a seawater intrusion is directly related to the dynamic evolution of the phenomenon so multi-stage management approaches that consider intermediate water quality and quantity goals should be investigated in the future.

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