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Conceptual And Numerical Simulation for Control of Seawater Intrusion: A Review

KEYWORDS: ADR, Optimization, Simulation.

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ABSTRACT *Sea water intrusion is the migration of seawater into freshwater aquifers due to over exploitation of groundwater. The most detrimental effect is that ground water depletion causes lowering of water table and also changes in fresh / saltwater interface. Therefore seawater intrusion should be controlled to protect groundwater resources. Methods for controlling intrusion varies depending on the source of the saline water, the extent of intrusion, geology, water use and economic factors. This review paper presents study on different methods proposed for simulation and optimization in both confined and unconfined aquifers. From the analysis, it was observed that ANN is an economically best model to analyse and ADR provides cost effective methodology for seawater intrusion. Also a coupled density-dependent finite element model developed for simulation of fluid flow and solute transport which has been integrated with an optimization model (GA) gives best results.*

I.INTRODUCTION

Groundwater is a term used to denote all the waters found beneath the surface of the ground and is considered as part of the hydrologic cycle. One-third of the world's drinking water is provided by groundwater. Coastal aquifers generally lie within some of the most intensively exploited areas of the world. About 70% of the world population lives in such areas. They rely on groundwater as their main source of fresh water for domestic, industrial and agricultural purposes. If current levels of population growth and industrial development are not controlled in the near future, the amount of groundwater use will increase dramatically, to the point that the control of seawater intrusion becomes a major challenge to future water resources management engineers. In professional way: Salt water intrusion is the migration of saltwater into freshwater aquifers under the influence of groundwater development [1]. It is a highly non-linear process which is a major problem threatening water resources in many parts of the world. Mixing of 2-3% salinity would render the fresh groundwater resources unsuitable for human consumption. Remediation of groundwater could be very costly and could take a long time depending on the source and level of salinization. As a result, groundwater resources should be protected from seawater intrusion, using suitable measures. A report on the historical development and research on seawater intrusion have been described [2], [3]. The main causes of seawater intrusion include [3] : Over-abstraction of the aquifers, Seasonal changes in natural groundwater flow, Tidal effects, Barometric pressure, Seismic waves, Dispersion and Climate change- global warming associated sea level rise.

Risks of saline intrusion clearly limit the extent to which a coastal aquifer can be developed for water supply. The management of a coastal aquifer is concerned with deciding an acceptable ultimate landward extent of the saline water and calculating the appropriate discharge of freshwater necessary to maintain the seawater-fresh water interface in that position. A number of methods have been proposed to control seawater intrusion [4].

A set of different methodologies are developed for multiple objective management of coastal aquifers. Management of seawater intrusion in coastal aquifers is a critical issue of modern times. According to United Nations Conference on Environment and Development (1992): "More than half the world's population lives within 60 km of the shoreline, and this could rise to three quarters by the year 2020." Thus effective planning is needed for future development in coastal areas. Different management alternatives for seawater intrusion in coastal aquifers are available [5]. Optimization is a simple tool for utilizing the power of linear and nonlinear formulations to solve the large problems concisely and analysing the solutions. In this review, many simulation, optimization techniques are discussed and highlighting the brief of its advantages and disadvantages.

II.SIMULATION OF SEAWATER INTRUSION

Large number of computer codes, software's, models have been developed to study seawater intrusion in coastal aquifers. Widely used are finite element and finite difference method. Table 1 represents the summary of some recently used software codes widely developed.

Table 1: summary of computer codes

S. NO	COMPUTER CODE	2D / 3D	SIMULATION	REFERENCE
1	SUTRA	2D 3D	Finite element code simulate density dependent ground water flow with energy transport or solute transport.	Gotovac et al. (2001) Narayan et al. (2002)S. Shoba et al. (2010)Voss C.I. (2010)

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2	SEAWAT	3D	Combination of MODFLOW and MT3DMS simulate variable density groundwater flow and solute transport.	Jin Lin (2008) Lathashri.U.A (2015) S.K.Pramada (2015)
3	CODESA-3D	3D	Finite element model that can simulate saltwater interface in saturated and variably saturated porous media by solving the convective-dispersive transport equation.	Barrocu et al. (2004) Marta Dentoni et al., (2014)
4	MOCDENS3D	3D	Density-dependant groundwater flow and solute transport.	Oude Essink, (1998) Nathalie VAN MEIR et al. (2002)Willem-Jan PLUG et al. (2002)
5	FEFLOW	3D	Groundwater flow, mass transfer and heat transfer in porous media and fractured media.	Ellen MILNES et al. (2002)C. P. Kumar (2003)

Seawater intrusion problem using numerical code SUTRA is carried out by numerous authors [6], [7], [8], [9]. A modelling study is carried out using SEAWAT in Alabama coast, USA concludes that further seawater intrusion into coastal aquifers can occur severely as the population continues to grow rapidly and the demand for groundwater pumping intensifies [10]. On comparison to monsoon period, the dry period experiences more sea water intrusion takes when conducted analysis in coastal aquifer in Karnataka, India [11]. Even for a small variation of hydraulic conductivity, it was found that there was error in prediction for the length of intrusion [12].

The Coupled Density-dependent variably Saturated groundwater flow and miscible salt transport 3D model was used [13] to conduct analysis of seawater intrusion in Gaza strip coastal aquifer, Palestine. It was identified as an optimal scheme for the spatial distribution of water abstraction from the municipal wells for the 2011–2020 period. Studies have been conducted to predict salinity in groundwater in Arborea (Central – Western Sardinia) [14] allowed to reconstruct the groundwater levels for the shallow aquifer under different conditions to evaluate the effects of irrigation, pumping and seasonal fluctuations in recharge.

MOCDENS3D enhances the knowledge of salt water intrusion and anticipate on the salinization process [15]. Resistance of the existing fresh water against shrinking and influence of geology and geomorphology is demonstrated using MOCDENS3D [16]. Movements of the brackish zone are managed by saline extraction [17].

Spreading of the low concentration iso-contours in the central area was observed using FEFLOW [18]. A two-dimensional control volume finite-element method transport model has been described successfully simulate the saltwater intrusion into the aquifer system at Gooburrum [19].

Many other codes like SWIFT, SHEMAT, SHARP, HST3D, SUFT, Quasi three dimensional finite element model have also been used for simulating seawater intrusion.

Management models are developed and solved based on the advective-dispersive density dependent miscible flow and transport processes [20]. The coupling of fluid flow and solute transport in unsaturated soil is modelled using two sets of equations. The first set of equations describes water flow and air flow and the second set describes solute transport. The nonlinear governing differential equations of fluid flow and solute transport are solved using the finite element method in the space domain and a finite difference scheme in the time domain [21]. This method provide best result when compared to other models including computer codes for simulation of seawater intrusion.

III.OPTIMIZATION MODELS FOR SEAWATER INTRUSION

Table 2: Summary of optimization models

MODEL NAME	REFERENCE
Genetic Algorithm	Kirkpatrick et al., 1983; Liu et al., 2008; Halhal et al., 1997; El Harrouni et al., 1998; Aly and Peralta 1999; Dhar and Datta, 2009; Cheng et al., 2000; Bhattacharjya and Datta, 2005; Qahman et al., 2005; Park and Aral, 2004; Mantoglou et al., 2004; Rao et al., 2003, 2004a; Karterakis et al., 2007.
Linear Programming	Ahlfeld and Heidari, 1994; Mantoglou, 2003; Mantoglou et al., 2004; Hallaji and Yazicigil, 1996; Azaiez and Hariga, 2001.
Non- Linear Programming	Gorelick et al., 1984; Finney et al., 1992; Chiu et al., 2010.
Artificial Neural Network	Johnson and Rogers, 1995; Rao et al., 2004b; Rajib Kumar Bhattacharjya et al., 2004; Mohamed Seyam et al., 2010.

Genetic Algorithm

The genetic algorithms (GA) has been demonstrated as a valuable tool for solving complex optimization problems during the recent past [22] [23]. The two objectives of the model were: maximize reliability and minimize cost of the hydraulic containment system. The GA has been applied to problems such as pipe network optimization [24], groundwater parameter determination [25] and groundwater cleanup [26]. The main advantage of GA is that it does not require differentiability of objective function or/and constraint. It does not assume unimodality of the objective function and it can handle large number of constraints as compared to the classical optimization techniques because it uses population-based approach. They combined a numerical model, for prediction of the seawater intrusion due to flow perturbations, and a GA. Over the years different versions of GA have been used in seawater intrusion management [27], e.g., structured messy GA [28], real coded GA [29], simple GA [30] and real coded progressive GA [31]. Application of evolutionary algorithm (EA) [32] [33], simulated annealing (SA) [34], [35] and differential evolution [36] have also been used in recent years. The GA-based optimization approach is particularly suitable for externally linking the numerical simulation model within the

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optimization model.

Linear programming

Linear programming (LP) techniques, because of its easy formulation and application, were extensively used by many researchers for the management of seawater intrusion [37], [38]. The MINOS algorithm for the optimal management of a coastal aquifer in southern Turkey [39]. Their quadratic objective was to minimization of the total pumping costs. They proposed six LP models for steady state and transient state, and one quadratic optimization model for steady state management of the aquifer system. [40] A multi-reservoir system model was considered as high penalty costs for pumping groundwater in order to reduce the risk of total depletion of the aquifer, quality degradation, and seawater intrusion. They considered the inflow to the main reservoir and the demand for irrigation water as stochastic.

Non Linear programming

The inability of LP models to handle nonlinear problems and difficulty in attaining global optimal solution of other algorithms propels to use nonlinear programming models (NLP) [41]. [42] Applied a Quasi three dimensional optimal control model for groundwater management in the Jakarta coastal aquifer basin. They considered nonlinear programming for solving the problem. The objective function of the model was a function of freshwater and seawater heads, and locations and magnitudes of groundwater pumping or artificial recharge. They concluded that MINOS was unable to differentiate between stationary points and local solutions and thus terminated with unusually large reduced gradients. Nonlinear optimization method for solving the embedded governing equations for simulation of seawater intrusion is proposed [43]. An optimal pumping and recharge strategy for a planned conjunctive use project was proposed by [44]. They formulated the model with a linear objective function and nonlinear constraints. The objectives were to remove the high-nitrate concentration while maintaining groundwater levels at desired elevations at specified locations as well as meeting water demand.

Artificial Neural Networks (ANN)

Artificial neural networks (ANN) are used for modelling the organizational principles of the central nervous system. The ANN performs the function of human brain by acquiring knowledge through learning process, which involves finding of an optimal solution. A general introduction was given by [45]. GA and neural network is used for selecting the optimal well locations and pumping rates in a remediation design problem [46]. ANN is used to approximate a three-dimensional variable density model (SEAWAT) and applied it in an optimization framework [47]. ANN model was utilized as analytical tool to study the influence of input variables on chloride concentration proving that it is reduced by decreasing abstraction average rate and increasing recharge rate and aquifer thickness [48]. With incorporation of field measurement errors in the training data, the predicting capability of ANN model was more accurate than other methods and therefore can be applied for simulating the flow and transport processes in a coastal aquifer [49].

The management models used considered mainly are the objectives of maximization of pumping rate, minimization of drawdown, minimization of pumped water, minimization of seawater volume into the aquifer, and/or minimization of pumping cost. Multiple objectives were also considered by some researchers. The linear programming (LP) techniques were extensively used because of its easy formulation and application. However, the inability of LP models to handle nonlinear problems propels the use of nonlinear programming models. Moreover salt intrusion in coastal aquifers is a highly nonlinear and complex process. The genetic algorithm (GA) has been used to solve complex nonlinear no convex optimization problems. The main advantage of using GA is that it does not require differentiability of objective function or and constraint. The artificial neural networks (ANN) are used for modelling the organizational principles of the central nervous system. The ANNs linked to GA-based optimization models is useful in evolving management strategies for coastal aquifers. The ANNs can be used as surrogate models to approximate complex numerical variable density models.

IV.LINKED SIMLULATION OPTIMISATION MODEL

A Linked simulation – optimization model is then developed to link the trained ANN with the GA-based Optimization model for solving seawater management problems. The performance of the developed Optimization model is evaluated and results show the potential applicability of the developed methodology using a GA- and ANN-based linked optimization– simulation model for optimal management of coastal aquifer [50].

Two different surrogate models based on genetic programming (GP) and modular neural network (MNN) are developed and linked to a multi-objective genetic algorithm (MOGA) are derived to optimal pumping strategies for coastal aquifer management [51].

The simulation-optimization model developed in this work is based on the integration of a GA with a coupled transient density-dependent FE model for flow and solute transport to study the control of seawater intrusion in coastal aquifers using three management models. [52], [53].

V.CONTROL METHODS OF SEAWATER INTRUSION

Study on controlling seawater intrusion is essential in order to protect groundwater resources. The key to control seawater intrusion is to maintain a proper balance between water being pumped from the aquifer and water recharged to the aquifer. Over the years, a number of methods have been used to control seawater intrusion in coastal aquifers. [4] Various methods of preventing seawater from contaminating groundwater sources including:

Reduction of pumping rates
Relocation of pumping wells
Use of subsurface barriers
Abstraction of saline water
Natural recharge
Artificial recharge
Combination techniques

ADR method is a combination of two methods; abstraction of saline water and recharge of fresh water in addition to desalination of abstracted water and treatment to be ready for recharge or domestic use. The combination of abstraction and recharge techniques is considered one of the most efficient methods to control seawater intrusion [52] [53] [54]. It is capable of completely preventing saltwater intrusion because it increases the volume of fresh groundwater and decreases the volume of saltwater, while considering economic aspects, environmental impact and sustainable development of water resources [55].

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A new integrated methodology Abstraction Desalination and Recharge- Treated Waste Water was proposed to control seawater intrusion in unconfined aquifers [56]. ADR-TW, provides the least cost and least salt concentration in the aquifer and in the meantime, it maximizes the retardation of fresh / salt water interface [57].

VI.CONCLUSION

The literature review revealed that the researchers from the worldwide have developed and applied various simulation and optimization techniques to solve the seawater intrusion management problems of coastal aquifers. The reviews on the different programming techniques used for the management of seawater intrusion problems of coastal aquifers was done and presented in this paper. This review provides the basis for the selection of appropriate methodology for the management of seawater intrusion problems of coastal aquifers. Based on observations, coupled transient density-dependent finite element model developed for simulation of fluid flow and solute transport is the best model used to simulate problem which has been integrated with an optimization model (GA) gives satisfactory results which is used from olden days. ANN is an economical method to simulate seawater intrusion which is recently developed technique provides optimum results. ADR provides cost effective methodology to prevent seawater intrusion. There is scope for further discussion about the subjects covered in this review.

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