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Saltwater intrusion processes in coastal aquifers – modelling and management: a review

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A B S T R A C T

Saltwater intrusion in coastal aquifers due to human intervention has become a major challenge in different parts of the world. This review highlights some of the factors influencing saltwater intrusion processes in coastal aquifers, and discusses the methodologies proposed for development of management strategies on a regional scale, utilizing solutions of mathematical models. In recent years, significant advancements have been made in the development of mathematical tools for evolving optimal management strategies aimed at controlling saltwater intrusion in coastal aquifers. This article also reviews different modelling techniques utilized, and offers a brief account of management strategies prescribed by several researchers. Two types of modelling approaches exist in the literature: descriptive models aiming at simulating the physical processes analytically or numerically for evaluating the impact of a chosen management strategy, and prescriptive models for choosing optimal aquifer management strategies. Recent trend is to develop artificial-intelligence-based surrogate models trained by using random inputs and corresponding numerical outputs in order to develop coastal aquifer management strategy. Therefore, different surrogate modelling approaches aimed at reducing the computational burden in a linked simulation–optimization methodology are also highlighted in this review. Furthermore, this review provides a brief outline of the development of methodologies for optimal monitoring network design and sequential compliance monitoring of the real life consequences of implementing prescribed management strategies for coastal aquifers.

Keywords: Saltwater intrusion; Coastal aquifer management; Mathematical modelling; Simulation–optimization; Surrogate models; Monitoring network design; Compliance monitoring; Ensemble models

1. Introduction

Coastal areas attract human settlement by providing abundant food (fisheries and agriculture) and economic activities (trade, harbors, ports, and infrastructure). However, fresh groundwater supply diminishes quickly in these areas due to increased human activities and economic developments, along with increased exploitation of groundwater resources. Seawater intrusion and subsequent deterioration of groundwater quality in coastal aquifers usually result from over extraction of groundwater resources to meet irrigation, domestic, and industrial needs [1]. Although surface water bodies such as rivers, canals, and wetlands are also affected by intruding seawater, saltwater intrusion usually refers to the subsurface movement of seawater [2]. Under natural conditions, freshwater moves toward the ocean and prevents saltwater from intruding into the aquifers. Less dense freshwater flows on top of surrounding or underlying saline groundwater. A transition zone exists that separates freshwater and saltwater zones of coastal aquifers. A gradation from freshwater to saline water occurs in the transition zone. However, this equilibrium is distorted when groundwater withdrawal exceeds the aquifer's ability to recharge and when pathways for natural recharge are reduced. As a result, the transition zone moves inland and saltwater moves toward the freshwater zones of the aquifer.

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Saltwater finds its way toward the freshwater aquifers as a result of the single or combined effect of two main processes such as lateral or horizontal intrusion, and vertical movement or upconing. Lateral or horizontal intrusion occurs when saline water from the coast moves inland due to excessive water withdrawal from the coastal aquifer. Vertical movement or upconing of saltwater can occur near the discharge well when water moves toward the wellhead, and saltwater in the deeper aquifers rises up [3]. The aim of this review is to describe some of the factors influencing saltwater intrusion processes in coastal aquifers, and discuss the state of the art of various methodologies proposed for development of saltwater intrusion management strategies on a regional-scale utilizing solutions of mathematical models.

Natural processes such as tidal fluctuations as well as anthropogenic disturbances, for example, over extraction and sea-level rise lead to degradation of the quality of groundwater in coastal aquifers. As seawater contains high levels of chloride, less than a 2% contribution of seawater mixed with fresh groundwater will raise the chloride concentration above the US Environmental Protection Agency guideline (maximum chloride concentration in drinking water is 250 mg/L) [4]. Pumping-induced saltwater intrusion has been reported worldwide in the last four decades. Over extraction from coastal aquifers is one of the major causes of saltwater intrusion into fresh groundwater formations [5]. Relative sea-level rise as a result of climate change [6] and changes in hydrological regime, for instance, changes in natural recharge triggered by the changes in precipitation and evapotranspiration patterns also affect coastal aquifers. The length of time that aquifer water levels are lowered, fluctuations in tide stages, and seasonal and annual variations in groundwater recharge, and evapotranspiration rates are some of the other factors that affect saltwater intrusion into freshwater aquifers.

Mathematical models have been used over the years to understand the relevant processes of saltwater intrusion as well as to locate the position of the saltwater–freshwater interface in coastal aquifers [7–9]. Mathematical models vary from simple analytical solutions to complex numerical models of unsteady flow under different scenarios in the coastal aquifers. In order to accurately solve the flow and transport simulation process, it is essential that the density-dependent flow and transport process be accurately represented in the simulation model. First and subsequent attempts to incorporate coupled density-dependent flow and transport processes in a regional-scale optimal coastal aquifer management model were reported by Das and Datta [10,11]. They utilized the embedding technique to link internally the density-dependent flow and transport models. The computational burden in such an embedded simulation optimization model being enormous, for even decent size study area under transient conditions, further attempts were made to incorporate trained and tested surrogate models as approximate simulators of the flow and transport processes within the linked optimization model [8,12–14]. Also, Das and Datta [15] proposed a new methodology for solving the coupled governing equations for the three-dimensional (3D) density-dependent transient flow and transport processes in a coastal aquifer.

However, the best feasible approach for determining an effective management strategy is the integration of simulation models within an optimization algorithm based on the framework of a linked simulation–optimization model (LSOM) [9,12,16,17]. This most effective approach also necessitates the incorporation of preferably an adequate and accurate numerical simulation model for simulating the complex flow and transport processes in a coastal aquifer. Therefore, this review focuses on the existing numerical simulation models as well as the optimal management models integrating different simulation models. One major issue associated with the application of LSOM is the computational feasibility and efficiency of the linked models, which require very large number of iterations between the optimization algorithm and the numerical simulation model requiring enormous computational time for a typical large regional-scale coastal aquifer study area. Especially, when the coupled density-dependent transient flow and transport processes are considered in the simulation models, the computational feasibility of an LSOM to evolve an effective long-term coastal aquifer management strategy becomes an issue for a large aquifer study area.

In addition, as noted in Datta et al. [18] and Datta and Kourakos [19], computational dimensionality of an optimal search problem tends to increase exponentially with the increase in the number of decision variables. Also, the number of iterations between the optimization algorithm and the externally linked simulation models increases exponentially as the number of decision variables increases when utilizing an LSOM to obtain an optimal or near optimal solution. Therefore, the computational feasibility issue becomes more pressing when more than one management objective need to be considered in order to develop a Pareto-optimal solution. The issue of dimensionality and computational feasibility inspired the development and potential application of artificial-intelligence-based surrogate models that are trained and validated by repeated use of numerical flow and transport simulation models. These surrogate models can be based on artificial neural networks (ANNs), genetic programming (GP) models, and self-organizing maps. This issue is also addressed by using more efficient optimization algorithms, which may contribute to computational efficiency in searching for a global optimal solution. More recently, the emphasis on computational efficiency has also focused on utilizing parallel processing capabilities especially to solve large-scale optimization models for groundwater management [20,21].

In developing a management strategy for a natural system such as a coastal aquifer, it is essential to incorporate the uncertainties associated with the description of the physical system, and prediction of the physical processes. Therefore, in order to consider the uncertainties associated with the modelling and prediction of the flow and transport processes ensemble surrogate models have been proposed recently. Ensemble models are also discussed. Furthermore, a very important and relevant issue is the actual implementation of a prescribed management strategy for sustainable long-term beneficial use of coastal aquifers. Field response to the developed optimal management strategies might deviate from the prescribed values obtained by linked simulation–optimization based groundwater management solutions due to uncertainties resulting from the poor characterization of the groundwater system and field-scale implementation deviation [22]. In this context, the monitoring of the implementation of a prescribed temporal and spatial pumping strategy, compliance with it in the field, and matching of its impact on the intrusion process is very important. This review intends to discuss major causes of saltwater intrusion in coastal aquifers, review recent developments in modelling approaches to develop strategies for managing regional-scale saltwater intrusion, and focus on the scope for future research in this field.

2. Major causes/drivers of saltwater intrusion in coastal aquifers

The previous literature pointed out several causes of saltwater intrusion in coastal aquifers as well as highlighted some of the methodologies useful to develop management strategies. The most common causes are saltwater intrusion due to over extraction for agricultural or other water supply, saltwater intrusion due to tidal effect or inundations caused by storm surges, and saltwater intrusion due to climate change-induced sea-level rise. The following sections provide an overview of some of the efforts in modelling the saltwater intrusion scenario caused by these drivers in coastal aquifers. Table 1 provides a summary of the main factors driving saltwater intrusion in coastal aquifers along with the methodology, modelling data used and the findings associated with the reported studies.

2.1. Saltwater intrusion due to over extraction of groundwater

Due to their close proximity to saltwater, coastal groundwater supplies are particularly vulnerable to chloride contamination. The situation becomes worse when groundwater resources in coastal aquifers are overexploited by intensive pumping leading to the inland movement of freshwater–saltwater interface that results in a high salt concentration in the aquifer water. Groundwater pumping has enormous influence on the lateral or horizontal as well as vertical saltwater intrusion processes in coastal aquifers. Qi and Qiu [53] considered saltwater intrusion as a natural hazard and indicated that irrational human activity such as overexploitation of groundwater resources in coastal aquifers would aggravate the extent of this natural hazard. While many studies pointed out that groundwater abstraction is more significant cause of saltwater intrusion than the rising sea levels [28,36,54], others [55,56] argued that groundwater extraction alone may not be the major cause of seawater intrusion.

Datta et al. [32] utilized a finite-element-based flow and salt transport numerical simulation model under limited data availability to predict future seawater intrusion scenario due to uncontrolled use of groundwater in a real life coastal aquifer system in Andhra Pradesh, India. The effectiveness of the pumping strategies was evaluated using calibrated and partially validated model. Modelling results demonstrated that present rate of pumping would have a detrimental effect on the aquifer, and that a carefully planned pumping strategy is needed to control the spatial and temporal saltwater intrusion process. Hugman et al. [23] attempted to evaluate the impact of pumping in coastal aquifers on saltwater intrusion utilizing numerical modelling approaches to simulate different past and present scenarios of groundwater pumping. Four different groundwater abstraction scenarios such as natural state/no abstraction, abstraction for public supply, abstraction for public and private supply, and abstraction for private supply were evaluated. Seawater intrusion as a result of overexploitation of groundwater and insufficient recharge was also reported as the predominant factor controlling groundwater salinization in the coastal region of the South China Sea near the Leizhou peninsular [57]. They reached this conclusion by conducting a hydrogeologic investigation using combined hydrochemical and isotopic approaches to provide primary insight into seawater intrusion and groundwater circulation. They noticed the leakage caused by inadequate sealed measurements during drilling works is also responsible for groundwater salinization in the study area in addition to serious salinization resulting from direct contact with seawater.

Sherif et al. [24] evaluated three different pumping scenarios (maintaining the current pumping rates, reducing the current pumping rates, and increasing the current pumping rate) to quantify saltwater intrusion and salinity distribution in the coastal aquifer of Wadi Ham, United Arab Emirates. Their results indicated that seawater intrusion process is accelerated by any increase in groundwater pumping, and an increase in the pumping rate by 50% would cause a significant landward movement of the transition zone. On the other hand, reducing the pumping rate by 50% would have a positive result, and would result in the mitigation of seawater intrusion and improvement of groundwater quality after 10 years of reduced pumping. Reduced pumping from the wells and placing the wells further away from the coast with a better distribution of water withdrawal was proposed by Nocchi and Salleolini [1]. Paniconi et al. [26] simulated different pumping regimes and recharge scenarios and concluded that pumping is the main cause of saltwater intrusion in the "Korba" aquifer of the eastern coast of Cap Bon in northern Tunisia.

Pham and Lee [30] assessed the impact of sea-level rise and groundwater extraction on seawater intrusion in the coastal aquifers using SEAWAT model for a period of 90 years assuming no change of hydraulic parameters and future hydrologic conditions over the study period and neglecting the tidal effect and change of shoreline. They considered three different scenarios of sea-level rise and groundwater extraction. They concluded that sea-level rise due to climate change has a very little effect in the magnitude of seawater intrusion, and groundwater extraction is the main cause of seawater intrusion. Different scenarios of groundwater pumping and tidal effects were considered in developing a 3D density-dependent numerical model using FEFLOW code to simulate the seawater intrusion in the coastal aquifer of Shenzhen city, China. Model results demonstrated that while tide-induced saltwater intrusion is significant near the estuarine Dasha River, groundwater exploitation up to a certain limit can also decrease the tendency of seawater intrusion into the aquifer [31]. Intense groundwater pumping for irrigation since 1980 created saltwater intrusion problem in the central part of the Korba aquifer at the east of the Cap Bon peninsula in Tunisia [25]. A 3D transient density-dependent groundwater model for the area showed that the aquifer is overexploited and if the current rate of exploitation continues for the next 50 years, it would take at least 150 years to return to its natural condition if no exploitation was permitted for this period.

Table 1
Summary of different factors causing saltwater intrusion in coastal aquifers and few associated studies

Factors/drivers	References	Methods/data used/techniques followed	Place of study	Major findings
Over extraction	[23]	Numerical modelling approaches to simulate different past and present scenarios of groundwater pumping (four different scenarios)	Algarve region in South Portugal	Withdrawal of up to 3.31×10^6 m^3/year can prevent saltwater intrusion
	[24]	Three different groundwater abstraction scenarios	Wadi Ham, United Arab Emirates	An increase in the pumping rate by 50% would cause saltwater intrusion, and reducing the pumping rate by 50% results in mitigation of seawater intrusion. Groundwater quality improves after 10 years of reduced pumping
	[1]	Numerical model using FEFLOW code to forecast the impact of fish farming on saltwater intrusion	Ansedonia promontory (southern Tuscany, Italy)	Reduced pumping and placing the public supply wells further away from the coast would reduce saltwater intrusion. Withdrawal of water for fish farms only affect local saltwater intrusion whereas public supply wells affect sustainability of the aquifer
	[25]	Numerical modelling	Korba aquifer at the east of the Cap Bon peninsula in Tunisia	If the current rate of exploitation continues for the next 50 years, it would take at least 150 years to return to its natural condition if no exploitation was permitted for this period
	[26]	Simulation of different pumping regimes and recharge scenarios	"Korba" aquifer of the eastern coast of Cap Bon in northern Tunisia	Groundwater pumping is the main mechanism of saltwater intrusion
	[27]	Four different scenarios of sea-level rise, recharge, and groundwater abstraction	Hypothetical circular aquifer system	Sustainable pumping from the aquifer can prevent upconing of the freshwater–saltwater interface. They recommended four different pumping rates for the four scenarios to prevent saltwater intrusion
	[28]	Two different pumping scenarios and three different sea-level rise scenarios	Coastal area near the city of Monterey, California, USA	Groundwater abstraction is the main reason of seawater intrusion
	[29]	Concept of extraction zones instead of well pumping from point-well locations	Kish Island of the Persian Gulf	This concept provides better flexibility to local water authorities and consumers in implementing the management plan
	[30]	Impact of sea-level rise and groundwater extraction using three different scenarios of sea-level rise and groundwater pumping using SEAWAT model	Nam Dinh Province, Vietnam	Groundwater extraction is the main cause of seawater intrusion whereas sea-level rise has very little effect
	[31]	Numerical model using FEFLOW code	Shenzhen city, China	Near the estuarine Dasha river, groundwater exploitation up to a limit of $1.32 \times m^3/d$ can decrease the tendency of seawater intrusion into the aquifer
	[32]	Prediction of future seawater intrusion scenario due to uncontrolled use of groundwater	Nellore district of Andhra Pradesh, India	Hydraulic control measures influence the spatial and temporal distribution of saline concentration

(*Continued*)

Table 1 (*Continued*)

Factors/drivers	References	Methods/data used/techniques followed	Place of study	Major findings
Sea-level rise/ climate change	[33]	Numerical modelling study	Low-lying Dutch Delta, Netherlands	Sea-level rise increases the hydraulic heads; impact of sea-level rise is confined within 10 km of the coastline and main rivers
	[34]	Numerical study using SEAWAT to evaluate effects of sea-level rise on saltwater intrusion processes in both confined and unconfined coastal aquifer systems	Conceptual model	Sea-level rise would have no long-term effect on the steady-state movement of salt wedge; saltwater intrusion due to sea-level rise have self-setback mechanism
	[35]	Three scenarios of sea-level rise (0, 0.5, and 1 m) for both homogenous and highly permeable aquifer systems	Jeju Island, Korea	A sea-level rise of 1 cm contributed to an inland seawater encroachment of 11 m, and 6–8 m for homogenous and highly permeable aquifer systems, respectively
	[36]	Effect of coastal topography (horizontal and vertical slopes) and sea-level rise on movement of the freshwater–seawater interface	Mediterranean and Dead Sea coastal aquifers	A horizontal slope of 2.5‰ would cause 400 m inland shift of the freshwater–saltwater interface with a sea-level rise of 1 m in around 100 years whereas a vertical slope would yield no shift within the same period
	[37]	Three types of sea-level rise scenarios, such as no rise, a rise of 0.5 m per century, and a fall of 0.5 m per century	Noord-Holland province, the Netherlands	A relative sea-level rise of 0.5 m per century would increase the saltwater intrusion
	[38]	Numerical simulation study using constant sea-level and different sea-level rise scenarios	Southeastern Florida, USA	A saltwater intrusion of about 1 km for about 25 cm sea-level rise during the simulation period (105 years, from 1900 to 2005)
	[39]	Various combinations of different scenarios such as groundwater recharge, abstraction, and sea-level rise	Sandstone coastal aquifer at Richibucto region of New Brunswick in Atlantic Canada	Sea-level rise has the least significant effect on saltwater intrusion in the sandstone aquifers in Atlantic Canada
	[30]	Three different scenarios of sea-level rise and groundwater extraction; assuming no change of hydraulic parameters and future hydrologic conditions over 90 years of the study period	Nam Dinh Province, Vietnam	Sea-level rise due to climate change has a very little effect in the magnitude of seawater intrusion while groundwater extraction is the main cause of seawater intrusion
	[40]	Two scenarios such as, the influences of mean sea-level rise of 1 m in the next 100 years and a storm surge event	Bremerhaven, northern Germany	1 m sea-level rise in the next 100 years would move the seawater/freshwater interface 1,250 m farther toward inland direction. They also observed 2,050 m landward expansion of the salinized area
Tidal effects/ storm surges	[41]	Numerical simulation modelling	Conceptual modelling approach	Tidal activity in the intertidal zone lead to the landward migration of saltwater–freshwater interface in an unconfined aquifer
	[42]	Numerical simulation model SUTRA to define the current and potential extent of seawater intrusion	Burdekin Delta Irrigation Area, North Queensland, Australia	The effect of tidal fluctuations on groundwater levels is limited to the areas close to the coast

(*Continued*)

Table 1 (*Continued*)

Factors/drivers	References	Methods/data used/techniques followed	Place of study	Major findings
	[43]	Quantify tidal impacts on solute mixing and spreading in seawater intrusion problems. Simulations performed using SUTRA	An idealized homogeneous coastal aquifer of finite areal extent	Tides have significant impact on the shape and location of the freshwater–saltwater interface when the tidal mixing number is ≤600
	[44]	Combined effects of tidal oscillations and heterogeneity in the hydraulic conductivity	An idealized heterogeneous aquifer	The combined effect of tidal oscillations and heterogeneity on mixing and spreading of the interface reduces as the degree of heterogeneity increases
	[45]	Tide-induced groundwater flow dynamics under different beach slopes; numerical modelling using FEFLOW. Simulation results are validated by laboratory experimental data	Laboratory experiment and conceptual modelling	The effects of tide on a milder beach are much greater than on a vertical beach
	[46]	Tide-induced seawater–groundwater circulation in shallow beach aquifer using a dimensionless tidal period and a dimensionless beach slope of 10%. Numerical simulation modelling using MARUN	Conceptual modelling approach	The major portion of the seaward groundwater seepage usually occurs in the shallow part of the submerged beach
	[47]	Effects of tides, lunar cycle, and beach profile on saltwater intrusion. Field measurements in combination with numerical modelling	Waquoit Bay, Massachusetts, USA	High-tide elevation largely controls recharge to the intertidal saline cell. More freshwater discharges and less deep saltwater discharges occurs when the low-tide elevation is relatively high
Other factors	[48]	Water sampling from the field and laboratory experiments	Guanahacabibes Peninsula of Pinar del Rio Province, western Cuba	Aquifer salinization can occur from the karst structures developed as a result of bacterial reduction of the dissolved sulfate
	[49]	Numerical modelling using FEFLOW combined with sharp-interface approximation and the Ghyben–Herzberg relationship	Krastified coastal aquifer in Crete, Greece	Orientation of fractures and fluid density is responsible for seawater intrusion
	[50]	Vulnerability of the coastal aquifers using Geographic Information System (GIS)-based DRASTIC model	Coastal aquifer of the south west coast of Kanyakumari district in Tamil Nadu, India	Unregulated beach placer mining is responsible for saltwater intrusion in the study area
	[51]	Statistics (correlation matrix, principal component analysis), GIS, and hydrogeochemical investigations	Aousja-Ghar El Melh and Kalâat el Andalous, north-eastern of Tunisia	Aquifer salinization occurs due to the combined effect of water–rock interaction, evapotranspiration, irrigation return flow, sea aerosol spray, and agricultural fertilizers
	[52]	Field measurements and numerical modelling approach, SEAWAT applied in a coral island	Grande Glorieuse, a low-lying coral island in the Western Indian Ocean	Combined effect of sea-level rise and climate change (rainfall and evapotranspiration) would result in an average increase in salinity of 140% (+8 kg/m^3) whereas the increase in salinity could reach up to 300% (+10 kg/m^3) in low-lying area with high vegetation density

Unsal et al. [27] assessed the effects of climate change (sea-level rise and decreased recharge) and over extraction for a hypothetical circular aquifer system considering both quantity (groundwater reserve) and quality (freshwater–saltwater interface movement in the lateral and vertical directions) of groundwater resources for evaluating long-term sustainability of aquifer systems. A comparison of the effects of groundwater abstraction and 21st century sea-level rise to seawater intrusion in a coastal area near the city of Monterey, California, USA, revealed that groundwater abstraction is the main reason of seawater intrusion [28].

Ataie-Ashtiani and Ketabchi [58] proposed an approach where they utilized an improved elitist continuous ant colony optimization (ECACO) in combination with simplified analytical and numerical simulation of saltwater intrusion problem. The developed coastal aquifer management model maximizes total water extraction rate and minimizes drawdown limits thereby preventing saltwater intrusion. Based on the results of the management model for a hypothetical case, they concluded that simulation model-ECACO could be applied as a useful tool for optimal extraction management in coastal aquifers.

Ataie-Ashtiani et al. [29] introduced the concept of extraction zones instead of well pumping from point-well locations and thus developed a management model by optimizing extraction from a number of extraction zones. They concluded that the concept of extraction zones provides better flexibility to local water authorities and consumers in implementing the management plan. The performance of the developed ANN–genetic algorithm (GA) based management model was evaluated for a real unconfined coastal aquifer in Kish Island of the Persian Gulf. Later, Ketabchi and Ataie-Ashtiani [21] extended the work of Ataie-Ashtiani et al. [29] by introducing the impacts of climate change such as sea-level rise, land surface inundation caused by it, and recharge rate variation to determine optimal groundwater extraction from management zones for a large-scale coastal aquifer system in Kish Island, Iran. They used continuous ant colony optimization in combination with numerical code SUTRA to develop the management model. To reduce computation burden of the simulation–optimization approach, they implemented parallel computing strategy, and obtained a speedup ratio of 3.53 on an 8-core processor when compared with serial computing strategy. They also observed the relative superiority of continuous ant colony optimization over particle swarm optimization and GA when considering solution quality and computational time criteria.

2.2. Saltwater intrusion due to sea-level rise

According to the present best estimate of the global mean sea level, a rise of 50 cm will be observed in the coming century [59]. This will have a serious effect on the today's vulnerable coastal aquifers with an increase in the salinization process of coastal aquifers. The most significant impacts of climate change on the coastal groundwater resources are sea-level rise, decreased recharge, more storm surge events, etc. Climate change is likely to have an effect on sea-level rise, and it is anticipated that a rise of 50 cm by the year 2100 will lead to an increased seawater intrusion in the coastal aquifers of many parts of the world [60]. Climate change-induced sea-level rise imposes additional saline water heads at the seaside, leading to expectation of more seawater intrusion in coastal aquifers [40]. Low-lying sandy coastal aquifers are especially more susceptible to the effect of sea-level rise [61]. It is presumed that increase in sea-level rise due to climate change is also a cause of saltwater intrusion in coastal aquifers though anthropogenic activities such as over extraction, and excess paving in urbanized areas are the major causes of saltwater intrusion [27].

A numerical modelling study in the low-lying Dutch Delta in the Netherlands indicated that sea-level rise would indeed increase the hydraulic heads in groundwater system and the impact of sea-level rise would be confined within 10 km of the coastline and main rivers [33]. On the other hand, Chang et al. [34] demonstrated that sea-level rise would have no long-term effect on the steady-state movement of salt wedge. In addition, their transient confined-flow simulation results revealed that the formations affected by saltwater intrusion due to sea-level rise have self-setback mechanism, and the intruded salts could be driven back to the original position. In contrast, Webb and Howard [62] showed that sea-level rise-induced saltwater intrusion is more problematic for aquifer systems and several centuries would be needed to equilibrate after the sea-level rise has ceased. Sea-level rise results in high ratio of hydraulic conductivity to recharge and high effective porosity in the aquifer systems. This high ratio of hydraulic conductivity to recharge and high effective porosity is responsible for developing a large degree of disequilibrium in the aquifer systems. In contrast, aquifer systems with a low ratio of hydraulic conductivity to recharge and low effective porosity required only decades to equilibrate after the termination of sea-level rise [63].

For a confined alluvial aquifer with fine-medium sands and with a normal recharge rate, for example, the shallow coastal Golden Grove aquifer of Jamaica, the effect of sea-level rise and storm surge on saltwater intrusion is not significant [60]. In contrast, Chang et al. [34] demonstrated that the influence of sea-level rise on saltwater intrusion is less in unconfined aquifers compared with that in confined aquifers. The presence of highly permeable layers in aquifer systems can control the seawater intrusion processes due to sea-level rise. For instance, Kim et al. [35] evaluated homogenous and highly permeable aquifer systems and showed that aquifer with highly permeable layer is less sensitive to sea-level rise compared with the homogenous aquifer. They investigated three scenarios of sea-level rise (0, 0.5, and 1 m) for both aquifer systems in Jeju Island, Korea. Their result showed that a sea-level rise of 1 cm contributed to an inland seawater encroachment of 11 m, and 6–8 m for homogenous and highly permeable aquifer systems, respectively.

Recent studies on the impact of sea-level rise due to climate change mainly focused on various hydrogeological settings and sea-level rise scenarios. However, land-surface inundation due to sea-level rise has more extensive impact on saltwater intrusion than the effects of pressure changes at the shoreline in unconfined coastal aquifers with realistic parameters [64]. In addition, the relative importance of sea-level rise, groundwater extraction and groundwater recharge largely depends on the specific location considered [39]. The effect of sea-level rise on saltwater intrusion or movement of the freshwater–seawater interface toward inland direction in coastal aquifers largely depends on the coastal topography next to the shoreline [36]. In the Mediterranean and Dead Sea coastal aquifers, Yechieli et al. [36] showed that a horizontal slope of 2.5‰ would cause 400 m inland shift of the freshwater–saltwater interface with a sea-level rise of 1 m in around 100 years. They also found that a vertical slope would yield no shift within the same period, and reduced recharge or over extraction of groundwater would enhance the inland shift of the interface. The following paragraphs will outline some of the recent works conducted on saltwater intrusion in the coastal aquifers due to sea-level rise.

A study utilizing three different scenarios of future climate change in the Nile Delta aquifer in Egypt, and the Madras aquifer in India revealed that a 50 cm rise in water level in the Mediterranean Sea and in the Bay of Bengal will cause an additional intrusion of 9.0 km in the Nile Delta aquifer and only 0.4 km in the Madras aquifer, respectively [54]. Essink [37] showed that a relative sea-level rise of 0.5 m per century would increase the saltwater intrusion in all low-lying areas of the northern part of the Noord-Holland province. They used three types of sea-level rise scenarios, such as no rise, a rise of 0.5 m per century, and a fall of 0.5 m per century. A sea-level rise in excess of 48 cm over the next 100 years would result in chloride contamination in the well fields of the coastal aquifer in Broward County, Florida, USA [65]. Giambastiani et al. [66] demonstrated that a sea-level rise of 0.475 m per century in an unconfined coastal aquifer would result in an increase of 40% salt load and 800 m inland shifting of the mixing zone between fresh and saline groundwater.

Langevin and Zygnerski [38] demonstrated that seawater intrusion near the well field in a shallow coastal aquifer system in southeastern Florida, USA was dominated by abstraction of water from the well field, and that historical sea-level rise could exacerbate the extent of saltwater intrusion. They reported a saltwater intrusion of about 1 km for about 25 cm sea-level rise during the simulation period (105 years, from 1900 to 2005). Green and MacQuarrie [39] simulated various combinations of different scenarios (two groundwater recharge scenarios: 40 and 85 mm/year; two sea-level rise scenarios of 0.93 and 1.86 m; pumping: increased by a factor of 2.3) for the period from 2011 to 2100 for a sandstone coastal aquifer at Richibucto region of New Brunswick in Atlantic Canada. They concluded that sea-level rise has the least significant effect on saltwater intrusion in the sandstone aquifers in Atlantic Canada. Yang et al. [40] investigated two scenarios such as, the influences of mean sea-level rise of 1 m in the next 100 years and a storm surge event on groundwater quality for a two-dimensional (2D) cross-sectional coastal aquifer near Bremerhaven, northern Germany considering the aquifer heterogeneity. Their results indicated that 1 m sea-level rise in the next 100 years would move the seawater/freshwater interface 1,250 m farther toward inland direction. They also observed 2,050 m landward expansion of the salinized area. However, they found the salinization effect in the deeper and highly conductive layers of the aquifer. Results of the impact of a storm surge under a dyke failure situation demonstrated that the overtopping seawater infiltrated into the aquifer and only the top part of the aquitard is salinized, while the groundwater in the deeper aquifer remained unaffected.

Saltwater intrusion problem can also be represented as the loss of freshwater reserve in the coastal aquifers. In a coastal aquifer in Israel, changes in the groundwater head for an assumed sea-level rise of 0.5 m accounted for about 23% of the freshwater loss in the aquifer [67]. The relationship between sea-level rise and global groundwater depletion rate are well demonstrated by Wada et al. [68], who states that global reserve of groundwater is depleted at a rate of 0.8 mm/year (one-quarter of sea-level rise) against a sea-level rise of 3.1 mm/year. In contrast, Rozell and Wong [69] found an increase of 1% of freshwater lens volume in a Shelter Island, New York State, USA, even in an unfavorable climatic conditions of sea-level rise (0.61 m) and decreased groundwater recharge (2% precipitation decrease). The scenario of the most favorable condition (15% precipitation increase and only 0.18 m sea-level rise) resulted only a 3% increase in the freshwater lens volume. The aquifer is underlain by a clay layer restricting the maximum depth of the aquifer and allows for this unexpected groundwater-volume increase under unfavorable climate change conditions. Land surface inundation due to sea-level rise has a considerable impact on the fresh groundwater lenses in small oceanic circular islands. However, aquifer recharge, thickness of the aquifer and hydraulic conductivity have more profound influence on the volume of fresh groundwater lenses compared with sea-level rises [70].

Saltwater intrusion also depends on the nature of the inland boundaries. Saltwater intrusion due to sea-level rise is more pronounced in aquifers with head-controlled inland boundaries compared with an aquifer system with flux-controlled inland boundaries because head-controlled systems are associated with maximum seawater intrusion as a result of sea-level rise [71,72]. In addition, Werner et al. [72] confirmed that in constant-discharge confined aquifers, seawater intrusion is not induced by sea-level rise. Mazi et al. [73] used a generalized analytical solution for an unconfined coastal aquifer to investigate the effects of climate-driven scenarios of sea-level rise on saltwater intrusion. They considered both flux and head control conditions and concluded that the flux control case is far more resilient than the head control case in terms of initial seawater intrusion. They found high non-linearity between the sea-level rise and seawater intrusion and introduced three important thresholds or tipping points such as, spatial, temporal, and managerial tipping points. The aquifer responses to sea-level rise would shift abruptly from a stable state of mild change responses, to a new stable state of large responses to even small changes that lead rapidly to complete (deep) seawater intrusion if these tipping points were passed. Lu et al. [74] derived analytical solutions to predict the distance of interface toe movement in response to 1 m sea-level rise in confined and unconfined coastal aquifers with a general-head boundary condition. They also compared the results with those obtained from using constant-head (upper bound) and constant-flux (lower bound) inland boundaries with the same initial system condition. Depending on the values of two general-head boundary parameters (hydraulic conductance and reference head), the predicted values of the interface toe movement lies between those using a constant-head (upper bound) and constant-flux (lower bound) inland boundaries.

Watson et al. [75] investigated the transience of saltwater intrusion with regard to sea-level rise in an idealized unconfined coastal aquifer system subjected to an instantaneous sea-level rise. A simplified conceptual framework comprising homogeneous aquifer conditions and constant aquifer stresses was considered in order to extend the findings of recent studies concerning the saltwater intrusion response to sea level changes. It was observed that the simplified steady-state sharp-interface solution overestimates the 100-year landward toe movement for most of the cases studied. In addition, the steady-state sharp interface estimates of toe shift span 40%–250% of the toe shifts obtained from the 100-year dispersive interface simulations. This large range indicates that steady-state sharp interface estimates are at best only crude initial estimates of 100-year "planning time frame".

2.3. Saltwater intrusion due to tidal effects

Tidal oscillations influence the groundwater behavior; however, their effect is not well understood. The beach hydraulics is non-linear even in the absence of waves on beaches. Seepage face location [76], water flow in the unsaturated zone, and the dependence of water density on salt concentration [77] add non-linearity to the beach hydraulics. Tides create an enhanced mixing of fresh and saline groundwater thereby creating complex flow patterns that result in the variability of discharge fluxes [78]. Tidal fluctuation can speed up the seawater intrusion into aquifers, and has a great influence on the groundwater dynamics, such as groundwater discharge to the sea and the groundwater table fluctuations [45]. Tidal fluctuations generally have profound influence on saltwater intrusion processes in coastal aquifers. For example, the saltwater begins to intrude landward through estuarine circulation during neap tide. Saltwater further intrudes via Lagrangian and tidal pumping transport during the transition period between the neap tide and the following spring tide. During the spring tide and the subsequent middle tide, saltwater intrusion process retreats [79]. In the intertidal zone below the beach surface on a sloping beach, a relatively rapid circulation of saltwater occurs due to tidal oscillations [80,81]. Moreover, the location of the seepage face is unknown a priori because the location and area of the seepage face depend on both the sea level and the groundwater level. When the seawater head is lower than the groundwater head at the beach, the seepage face at the beach develops. In this situation, groundwater moves from the aquifer to the land surface through this seepage face. During tide cycles, the seepage face area reaches its maximum at low tide, and is considered as zero at high tide [46].

Two saline recirculation zones exist in an unconfined coastal aquifer and the discharge of fresh groundwater to the sea is often bounded by these two zones. The lower one is the deep saltwater wedge, and the upper one is a tidally driven recirculation cell called intertidal saltwater [47]. The deep saltwater wedge develops in both the confined and unconfined coastal aquifers due to the stable density stratification with discharging freshwater lying above the denser saltwater. Deep saltwater infiltration (DSI) of the ocean water and deep saltwater discharge (DSD) are the two fluxes associated with the deep saltwater wedge. At steady state, the value of DSI and DSD are equal [82,83], however, the value of these two fluxes may increase because of tidal oscillations [84–86].

The intertidal saltwater cell (ISC) exists between the intertidal zone and the discharging freshwater in unconfined aquifers. During high tides, this ISC is filled by the intertidal seawater infiltration. Saltwater discharges back to the ocean during low tides. Tidal amplitude, the magnitude of fresh groundwater flow toward the ocean, and the beach slope largely determines the dimensions of an ISC [80,87]. Changes in the amplitudes of spring and neap tides causes a change in the dimensions of the ISC [88]. ISC is not a constant feature of the coastal aquifer; instead it can appear and disappear with the lunar cycle and tidal variability affects the ISC size and development [47].

Tides induce a wider seawater–freshwater interface across the intertidal zone in unconfined shallow aquifers that causes seawater to intrude further [41,89]. Also, based on their numerical simulation results, Werner and Lockington [90] reported no significant changes in the landward movement of seawater as a result of tidal fluctuations though they found a wider seawater–freshwater interface. Groundwater head fluctuates when tidal oscillations propagate in coastal aquifers and this fluctuation of head is significant near the shore [91]. Freshwater–seawater interface in the subsurface of the intertidal zone is continuously changing as a result of the periodic tidal fluctuations in the intertidal zone. Dynamic freshwater and seawater fingering as a result of the density differences may be observed at the saltwater–freshwater interface [92]. Based on the numerical simulation results, Ataie-Ashtiani et al. [41] demonstrated that tidal activity in the intertidal zone lead to the landward migration of saltwater–freshwater interface. Size of the mixing zone is controlled by short-term tidal fluctuations and their amplitude [93]. However, when the effects of tidal oscillations are combined with the effects of kinetic mass transfer, the width of the mixing zone can significantly be increased [94,95].

Possible gross overestimation of the freshwater resources may result from neglecting the enhanced transition zone induced by the oscillating flow velocities in tidal cycles. However, the majority of the simulation models rarely incorporates the effect of tidal oscillations, or provides evaluation of its water quality impacts in long-term management of groundwater resources in coastal aquifers [43]. Tidal fluctuations generate seawater pumping into an unconfined aquifer. A part of this water returns to the sea driven by the mean water table gradient, while the other part leaks into the confined aquifer through the semi-permeable layer and afterward returns to the sea through the confined aquifer driven by the mean head gradient. This seawater–groundwater cycle has significant influence on the submarine groundwater discharge and exchange of various chemicals in coastal areas. If the enhancing processes of sea tide on the mean groundwater levels are not considered for the estimation of the net inland recharge, one may get an overestimation of net inland recharge [96]. Kuan et al. [91] showed that tidal oscillations significantly reduce the overall extent of seawater intrusion compared with the non-tidal (static) case. They concluded that tidal oscillations in the intertidal zone could cause a significant reduction of seawater intrusion in an unconfined coastal aquifer system because of an increase in the total discharge from the aquifer to the sea. In an unconfined aquifer, tide-induced circulation across the seaward boundary restricts the density-driven circulation and subsequently restricts the seawater intrusion in the aquifer.

The first analytical solution incorporating a vertical seaside boundary and one-dimensional (1D) flow in a confined aquifer was derived by Jacob [97] to describe groundwater response to tides. Lu et al. [31] reported tidal effect as the main factor triggering seawater intrusion in the coastal aquifer of Shenzhen city, China. Abarca et al. [47] found that high-tide elevation largely controls recharge to the intertidal saline cell. On the other hand, more freshwater discharges and less DSDs occur when the low-tide elevation is relatively high. In contrast, when low tides are very low, less amount of freshwater discharges and deeper saltwater discharges occurs. Inouchi et al. [98] demonstrated that during the ebb tide stage when sea level reaches the mean sea level, the transition zone between freshwater and seawater becomes widest and saltwater intrudes further inland. However, they also noted that tidal oscillation leads to saltwater intrusion only to the area near the coast, and that seawater intrusion is mainly influenced by groundwater pumping in areas further inland. Incorporation of tidal activities in simulating the flow and transport processes for a two-layered (high and low permeability) heterogeneous aquifer of a beach in Alaska was demonstrated by Li and Boufadel [99]. Narayan et al. [42] showed that the effect of tidal fluctuations on groundwater levels is limited to the areas close to the coast, and therefore, tidal influence on saltwater intrusion can be neglected when compared with the effects due to groundwater pumping.

Pool et al. [43] quantified the effects of tidal fluctuations on solute mixing and spreading in seawater intrusion problems for an idealized homogeneous coastal aquifer of finite areal extent. They demonstrated, based on their parametric analysis, that tidal mixing behavior is controlled by a dimensionless parameter called tidal mixing number. Tides have significant impact on the shape and location of the freshwater–saltwater interface when the tidal mixing number is ≤600. This tidal mixing number depends on the tidal amplitude, the period, and the hydraulic diffusivity. Later, Pool et al. [44] investigated the combined effects of tidal oscillations and heterogeneity in the hydraulic conductivity field on 3D dynamics of seawater intrusion in coastal aquifers. Results revealed that heterogeneity of the aquifer produces a significant widening of the transition zone and an inland movement of the toe location. They found that when tidal oscillations are included, the combined effect of tidal oscillations and heterogeneity on mixing and spreading of the interface reduces as the degree of heterogeneity increases. Contrary to homogeneous case, mixing behavior in heterogeneous coastal aquifers is controlled by the effective tidal mixing number. In this case, the effective tidal mixing number depends on the tidal amplitude, the period and the hydraulic diffusivity, and the effective horizontal permeability.

The slope of the beach is an important factor to be considered in investigating the effects of tidal fluctuations on saltwater intrusion in coastal aquifers. Tide-induced seawater–groundwater circulation in shallow beach aquifer was investigated using a dimensionless tidal period and a dimensionless beach slope of 10% [46]. Numerical simulation result suggests that the major portion of the seaward groundwater seepage usually occurs in the shallow part of the submerged beach and that the maximum Darcy velocity always occurs at the intersection of the water table and the beach surface. Liu et al. [45] investigated the tide-induced groundwater flow dynamics under different beach slopes and demonstrated that fluctuation of groundwater decayed exponentially with the distance to the beach and that the effects of tide on a milder beach is much greater than on a vertical beach. Seawater infiltration into the intertidal zone in a tide cycle increases with the beach permeability and decreases with an increase in inland recharge. In the intertidal zone of the beach, a larger saltwater plume develops when the beach slope and inland freshwater recharges are small and the beach permeability is high [46].

2.4. Saltwater intrusion due to other reasons

Besides the factors discussed in sections 2.1, 2.2, and 2.3, there are other factors reported to be responsible for the salinization of the aquifer. Aquifer salinization can occur from the karst structures developed as a result of bacterial reduction of the dissolved sulfate. A good example of this type of aquifer salinization was reported in the Guanahacabibes Peninsula of Pinar del Rio Province, western Cuba [48]. Orientation of fractures in a krastified coastal aquifer and fluid density was also reported to be the drivers of seawater intrusion in a krastified coastal aquifer in Crete, Greece [49]. The other reported causes of seawater intrusion includes unregulated beach placer mining in the aquifer of the south west coast of Kanyakumari district in Tamil Nadu, India [50], extensive agricultural land drainage systems in the Pleistocene Crag aquifer in the Thurne catchment in northeast Norfolk, UK [5], leakage during drilling works [57], groundwater fluxes due to changes in rainfall patterns [100], etc. In some aquifers, several processes occur simultaneously and all or some of the processes are responsible for aquifer salinization. For instance, aquifer salinization in the irrigated coastal shallow aquifers of Aousja-Ghar El Melh and Kalâat el Andalous, northeastern of Tunisia were reported to be caused by the combined effect of water–rock interaction, evapotranspiration, irrigation return flow, sea aerosol spray, and agricultural fertilizers [51]. They also noted that carbonate and sulfate precipitation occurs as a result of increasing concentrations of solutes in groundwater due to evaporation.

Vegetation dynamics is also an important parameter to be considered for groundwater study, and neglecting the uptake of groundwater by vegetation might result in an overestimation of both the amount and quality of freshwater resources, and would lead to an unrealistic and unsustainable groundwater management strategy [52]. They simulated the evolution of groundwater salinity in Grande Glorieuse, a low-lying coral island in the Western Indian Ocean. Their results revealed that the combined effect of sea-level rise and climate change (rainfall and evapotranspiration) would result in an average increase in salinity of 140% (+8 kg/m^3) whereas the increase in salinity could reach up to 300% (+10 kg/m^3) in low-lying area with high vegetation density.

3. Approaches for prediction and management of saltwater intrusion in coastal aquifers

Saltwater intrusion modelling approaches can be classified into two broad categories: sharp-interface and diffuse-interface models. Sharp-interface models comprise analytical solutions and numerical models, while diffuse-interface models are usually based on numerical models. Fig. 1 illustrates the flow chart of the common approaches utilized for prediction and management of saltwater intrusion processes in coastal aquifers.

In the sharp-interface modelling approach, a sharp interface is assumed between the fresh and saline groundwater. However, in reality a diffuse interface exists between them. In this diffuse interface, the density of water gradually decreases from the seawater side to the freshwater side.

3.1. Analytical solutions

Analytical solutions provide a relatively simple and clear concept of a problem. They are often used as benchmarks for numerical solutions. Analytical solutions are physically based approach and computationally less intensive compared with a non-physically based approach [72].

3.1.1. Sharp-interface analytical solutions

The first analytical solution of saltwater intrusion problem is given by the Ghyben–Herzberg relationship [101]. It is based on the assumption of hydrostatic conditions in a homogeneous unconfined coastal aquifer. The modified Ghyben–Herzberg relation uses observed piezometric head in the saltwater zone. The Ghyben–Herzberg relation can be used primarily to locate the saltwater–freshwater interface.

Strack [102] developed a 2D analytical solution to locate the position of the saltwater–freshwater interface in coastal aquifers. Strack's solution assumes a homogeneous and isotropic aquifer with sharp interface between freshwater and saltwater. It also assumes pumping wells to be fully penetrating into the aquifer and intersects the lower boundary of the aquifer. This assumption is typically wrong in real situation and, therefore, Beebe et al. [103] recommended that Strack's solution is not suitable to predict saltwater intrusion in pumping wells. Bower et al. [104] developed an analytical model for predicting the extent of saltwater upconing in a leaky confined aquifer using sharp-interface assumption.

3.1.2. Diffuse-interface analytical solutions

Benchmarking the performance of a numerical code against standard analytical solutions is necessarily the first step in testing the accuracy of the numerical approximations [105]. Henry and Elder problems, commonly used for the benchmark test, are associated with variable density flow in a variably saturated porous medium.

3.2. Numerical modelling

Models describe conceptual frameworks or approximations of the physical processes by using mathematical equations, and are generally the simplified representation of complex physical systems. Models are incorporated to predict, test, and compare reasonable alternative scenarios by mathematically representing a simplified version of a hydrological system. The reliability and applicability of a model depends largely on how accurately it approximates the physical system being modelled. Modelling of any system or process generally begins with a conceptual understanding of the problem domain being modelled followed by the representation of the physical system into mathematical terms [106]. Groundwater modelling starts with defining the problem and the purpose of the modelling followed by collecting, reviewing, and interpreting all available data. The next steps are to implement the model, modify and verify the solution results, model calibration, sensitivity analysis of the model parameters, and model verification. The implemented model will then be ready for prediction. At the final stage, post-audit will be required after analyzing the uncertainty of model prediction. A flow chart summarizing the detailed modelling steps can be found in Hardyanto [107]. However, models alone are not sufficient for a complete solution of the saltwater intrusion problems in coastal aquifers. For example, Hillier [108] demonstrated that engineering works in combination with management using predictive groundwater models can reduce saltwater intrusion and can provide high sustainable yields from coastal aquifers.

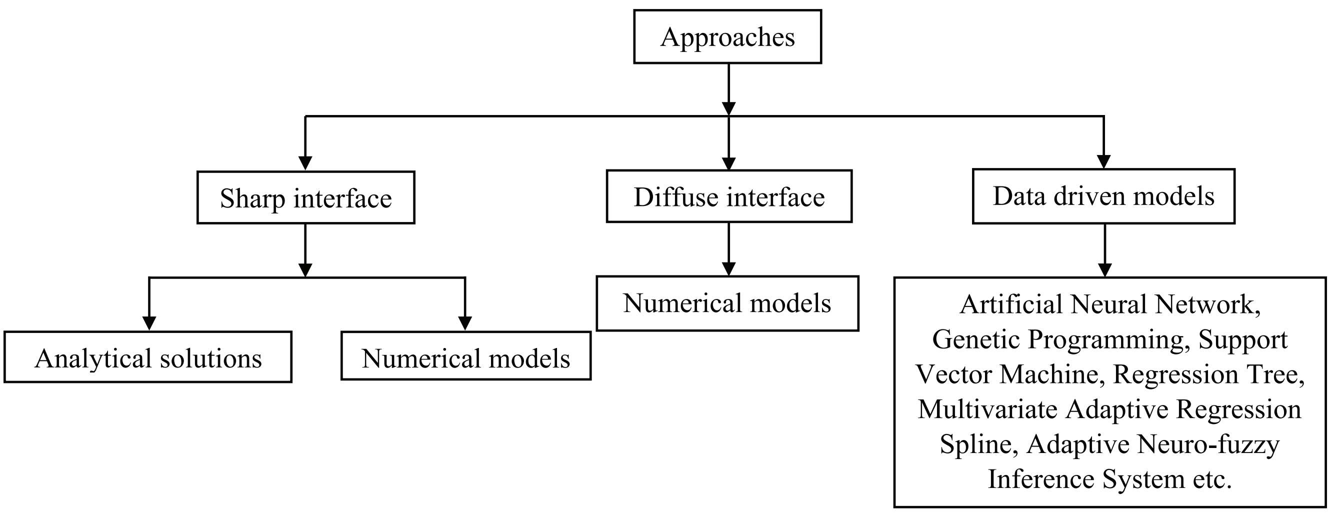

Fig. 1. Modelling approaches used to predict and manage saltwater intrusion.

3.2.1. Numerical models based on sharp-interface modelling approach

Several saltwater intrusion models were developed based on sharp-interface assumption. Sbai et al. [109] used sharp-interface assumption to simulate saltwater intrusion under steady state and transient conditions using finite element method. The interface between saltwater and freshwater was simplified to a line to develop methodologies for simulation of time-dependent behavior in coastal aquifers [110]. They developed SIM_COAST model to simulate coastal aquifer system's behavior and verified the developed model by comparing the results obtained from analytical solutions. Marin et al. [111] assumed sharp interface to develop a quasi-3D finite-difference model to simulate groundwater flow in Karstic aquifer of northwestern Yucatan, Mexico. The critical rise in the interface as influenced by groundwater pumping was presented by a sharp-interface-based numerical modelling and comparing the results with those obtained by analytical solutions [112]. Based on sharp-interface assumption, Fleet and Baird [113] developed a 2D model to predict saltwater intrusion due to over extraction from the coastal aquifer in Tripoli, Libya.

To reduce the computational burden in saltwater intrusion problems, Llopis-Albert and Pulido-Velazquez [114] proposed a transient sharp-interface model that does not require calibration process and implementation of a density-dependent model. Their results revealed that sharp-interface approach provides a good agreement in terms of piezometric heads regarding the density-dependent transport model. This was confirmed by conducting a numerical experiment in a 3D unconfined synthetic aquifer with spatial and temporal distribution of recharge and pumping wells. Overall conclusion is that the sharp-interface approach when applied to transient problems provides a considerable accurate result as well as improves the steady-state results. Therefore, they concluded that this approach could replace the application of computationally intensive density-dependent models by reducing the computational cost.

3.2.2. Numerical models based on diffuse-interface modelling approach

Freshwater and saltwater mixes as a result of hydrodynamic dispersion and diffusion, and consequently develops a transition zone in coastal aquifers. The thickness of the transition zone depends on structure of the aquifer, extraction from the aquifer, variability of recharge, tides and climate change, and could range from a few meters to several kilometers in over-pumped aquifers [115]. For the simulation of the physical processes in coastal aquifers, an accurate and realistic modelling approach is the density-dependent miscible flow and transport simulation modelling.

Tsai and Kou [116] considered 2D section of a coastal aquifer system to evaluate the saltwater intrusion processes using a density-dependent flow and salt transport model. For saturated and unsaturated soils, Cheng et al. [117] developed a 2D density-dependent flow and solute transport model. Sakr [118] investigated the limitation of sharp-interface approach by presenting a finite element density-dependent solute transport model. Bear et al. [119] developed a 3D finite-element variable density model to simulate saltwater intrusion due to over extraction in the upper section of the coastal aquifer in Israel. A numerical model to study density-dependent groundwater flow and solute transport in unsaturated soil was developed by Jung et al. [120]. Hamza [121] presented a numerical model considering the dispersion zone to predict the effect of saltwater upconing on the salinity of pumped water considering the velocity-dependent, hydrodynamic dispersion, and density-dependent flow. Lakfifi et al. [122] developed a numerical model using SEAWAT to study groundwater flow and saltwater intrusion in the coastal aquifer of Chaouia, Morocco. Advective and dispersive transport of saltwater below a partially penetrating pumping well was presented by a numerical model [123]. A 3D variable density flow model considering the development of a transition zone was developed and applied to a heterogeneous coastal aquifer to investigate the pumped water quality degradation as a result of pumping rate, the salinity of freshwater inflow and the thickness of the aquifer [124]. The developed model was verified against Henry seawater intrusion problem, Elder salt convection problem, and experimental results of the 3D saltpool problem. Results demonstrated that concentration of salts in the pumped water increased with the increase in aquifer thickness regardless of the aquifer transmissivity.

Das and Datta [15] developed a large-scale non-linear optimization-based methodology to obtain solution of the discretized density dependent, 3D transient saltwater intrusion process in coastal aquifers. The discretized governing equations were specified as binding constraints in the non-linear optimization model with the objective of satisfying these equations. The solution results were validated using benchmark saltwater intrusion problems.

Simulation models currently used for simulating density-dependent groundwater flow are SUTRA [125], MOCDENS-3D [126], FEMWATER [127], CODESA-3D [128], SEAWAT [129], HST3D [130,131], FEFLOW [132], OpenGeoSys [133], HydroGeoSphere [134], MARUN (2D variable density and saturation simulations for salinity and nutrients) [135–137]. OpenGeoSys was used previously for the simulation of several density-driven applications [92,138,139]. Previous studies of HydroGeoSphere were carried out by Yang et al. [40,140] and Christelis and Mantoglou [141]. Some recent examples for the use of numerical model, SEAWAT to solve density-dependent flow, and transport equations in coastal aquifers include Herckenrath et al. [142], Ding et al. [143], Gopinath et al. [144], and Surinaidu et al. [145].

Fig. 2 illustrates the 3D mesh and model boundaries of saltwater intrusion modelling by numerical simulation model FEMWATER for a typical location utilizing water abstraction from a set of production bores and barrier wells [146]. In this figure, PWs and BWs represent production and barrier wells, respectively. Resulting saltwater concentration is monitored at different locations denoted by MPs. Fig. 3 is an example of the resulting saltwater concentration (a) and head distribution (b) contours after the simulation period of 5 years as a result of combined operation of production bores and barrier wells from the same study area depicted in Fig. 2.

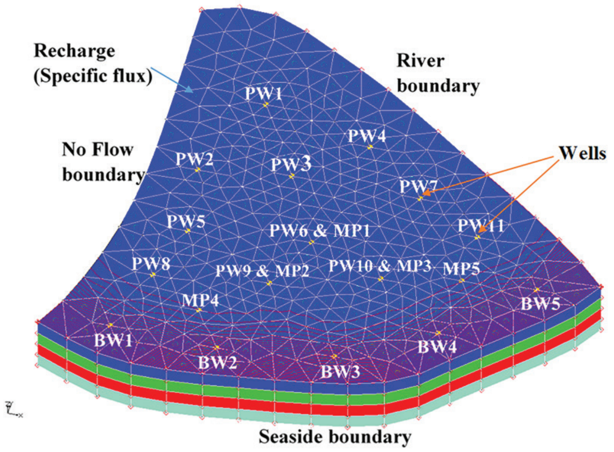

Fig. 2. Three-dimensional mesh and model boundaries.

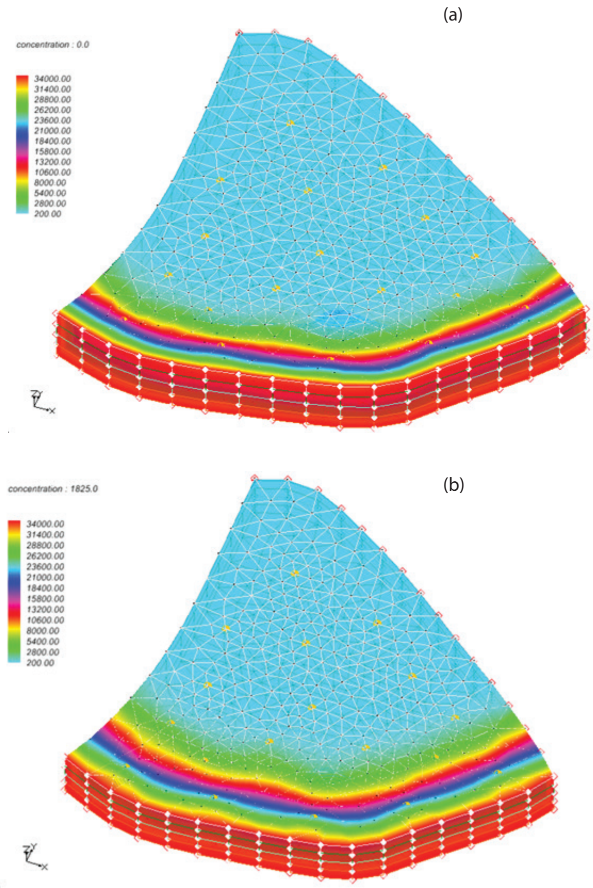

Fig. 3. Concentration contours resulting from simulation modelling: (a) at the beginning of the simulation period and (b) at the end of the simulation period.

3.2.3. *Effect of boundary conditions on saltwater intrusion modelling*

Solutions of conceptual models are greatly influenced by seaward and landward-boundary conditions. Constant hydraulic head and constant recharge rate boundary conditions are common in the landward side [71]. On the other hand, constant hydraulic heads are usually imposed in the seaward boundary [94,101,147]. However, a constant hydraulic-head boundary often results in larger estimations of the maximum pumping rate compared with the solution for a constant recharge rate boundary [148]. Generally, in miscible-flow models, the flow fields are not affected by landward-boundary condition because of a sufficiently large model domain is used to simulate the aquifer processes [148]. A general-head inland boundary condition instead of assuming constant-head or constant-flux boundary condition is needed for the proper characterization of the hydraulic response of model boundaries [74]. Zhang et al. [149] emphasized the choice of appropriate seaward-boundary conditions to develop management strategies for controlling saltwater intrusion in coastal aquifers using numerical modelling. Seaward-boundary conditions in numerical modelling are important as they influence the manner in which salt is transported into the aquifers. Wrong boundary conditions in the seaward boundary may lead to errors in saltwater intrusion prediction. The seaside-boundary condition depends on permanent factors such as heterogeneity of the aquifer and topography of the land surface; and transient factors such as hydraulic gradient in the aquifer, tidal variations, and storm surge events.

Tidal fluctuation necessitates a time variable and complex seaside-boundary condition. A periodically submerged beach zone (Dirichlet type) and non-submerged beach zone (Neumann type) is developed as a result of the seawater level fluctuation due to tidal activity [46]. Yang et al. [140] applied tide and storm surge-induced time variant head to the nodes of the surface domain. In their approach, they used hydraulic coupling between the surface and subsurface domain that makes it unnecessary to re-assign seaside-boundary conditions and to re-calculate the seepage face position and the area. Selection of appropriate seaside-boundary conditions and proper handling of these boundary conditions at the intertidal zone is necessary for the simulation of this dynamic system. An improper seaside-boundary condition in the advection dominant intertidal zone may lead to the accumulation of saltwater mass (artificial fingering) beneath this boundary. In these situations, an adaptable free exit boundary condition introduced by Frind [150] is the proper boundary condition [92].

On the ocean face, an advective outflux of the mixed fluid to the ocean occurred from the top 20% of the aquifer; therefore, solute concentration gradient normal to the ocean face can be set to zero in this portion of the ocean face. The remaining 80% of the ocean face allows influx of seawater into the aquifer, and therefore, solute concentration in this portion is equal to the maximum salt concentration of the seawater [11]. Hugman et al. [23] used two extreme boundary condition conceptualization: constant head equal to elevation along lower effluent reaches, and constant head equal to elevation along the entire stream. They found a larger impact of seasonality compared with boundary condition conceptualization on discharge rates.

Table 2 shows the overview of different modelling approaches utilized by different researchers.

Table 2
Overview of different saltwater intrusion modelling approaches by different researchers

Modelling approaches	References	Methods/data used/techniques followed	Place of study	Major findings
Numerical and analytical modelling approaches	[104]	Prediction of saltwater upconing in a leaky confined aquifer using sharp-interface assumption	Analytical solution	Critical rise of the interface at the bottom of the pumped well was calculated to be 0.712 and the critical pumping rate was calculated to be 3.72×10^4 m^3/d
	[110]	Numerical modelling approach compared with the analytical solutions	Two cases in the Middle East: an aquifer that discharges from springs at the coast, as well as in submarine springs, and the recharge effect of a dam across a Wadi	Even if this program is based on the relatively simple concept of a sharp-interface, water balances and time-dependent evolution of specific saltwater/freshwater systems can be simulated very well
	[112]	Numerical model based on sharp-interface assumption	Conceptual model	Critical rise in saltwater interface due to pumping was analyzed and critical pumping rate was calculated
	[113]	2D-twolayer sharp-interface model	Gefara Plain, Tripoli, Libya	The vertical position of the salinity interface is sensitive to the extent of abstraction. When the abstraction has reduced or stopped, considerable time needed for the aquifer to recover to original condition
	[26]	Several recharge and infiltration scenarios from heterogeneous coastal aquifer systems	Korba plain, Eastern Cap Bon, Tunisia	Groundwater pumping is the cause of salt contamination in the soils and subsurface water in the study area
	[151]	Different scenarios of recharge and sea-level rise for a heterogeneous coastal aquifer system	Belgian western coastal plain, Belgium	Groundwater flow, recharge and discharge pattern, hydraulic heads, and water quality distributions would be seriously altered as a result of expected increase in recharge and sea-level rise
	[152]	Effect of geologic heterogeneity on saltwater intrusion using laboratory experiment and numerical modelling approach	Laboratory experiment	Macroscale heterogeneity has a potential influence on the migration patterns and flushing times of diffuse saltwater contamination
	[153]	Investigation of local hydrogeological conditions for recharge and saltwater intrusion in a highly heterogeneous coastal groundwater system	Gio Linh coastal plain, North Central Coast of Vietnam	Provides information on which coastal aquifers are vulnerable to saltwater intrusion, and an explanation of why groundwater system in the study area is slightly influenced by saltwater intrusion compared with other coastal aquifers of Vietnam
	[40]	Sea-level rise and storm surge effects on saltwater intrusion in a heterogeneous coastal aquifer	Northern Germany	Hydraulic conductivity of the subsurface largely affects the fate of the salt plumes
Numerical and analytical modelling approaches	[154]	Stochastic simulation-based methodology to investigate the effect of heterogeneity on seawater intrusion modelling	Thiruvanmiyur–Injambakkam aquifer, South Chennai, India	Provides a better understanding of the transport mechanism in heterogeneous formation of coastal aquifers

(*Continued*)

Table 2 (*Continued*)

Modelling approaches	References	Methods/data used/techniques followed	Place of study	Major findings
	[114]	Transient sharp-interface model that does not require calibration process and implementation of a density-dependent model	Numerical experiment in a 3D unconfined synthetic aquifer with spatial and temporal distribution of recharge and pumping wells	Sharp-interface approach when applied to transient problems provides a considerable accurate result as well as to improves the steady-state results. This approach could replace the application of a computationally intensive density-dependent models by reducing the computational cost
	[119]	A computer program, FEASi-SWIT to simulate saltwater intrusion due to over extraction from the transition zone in a phreatic coastal aquifer	Upper section of the coastal aquifer in Israel	The well can pump essentially freshwater when the pumping rate is relatively small. For larger pumping rates, the salinity of the pumped water will reach the limiting value of 2% after a certain period of pumping
	[122]	Mathematical model to simulate different management scenarios in the transient conditions	Chaouia coastal aquifer, Casablanca city, Morocco	Surface water is required to protect the irrigated area and to restore the abandoned exploitation. Need to improve water quality in the area which is already contaminated by seawater intrusion
	[123]	Water withdrawal from a partially penetrating well tapping the fresh-water zone of a confined aquifer. Numerical model developed and validated against two analytical solutions and a set of published field data	Conceptual model	The developed model can be employed to determine the permissible discharge and pumping schedules for wells underlain by saltwater
	[124]	3D numerical model applied to a heterogeneous coastal aquifer. Developed model verified against Henry seawater intrusion problem, Elder salt convection problem, and an experimental results of the 3D saltpool problem	Conceptual model	Concentration of salts in the pumped water increased with the increase in aquifer thickness regardless of the aquifer transmissivity
Management models	[11]	Embedding technique for the development of multi-objective coastal aquifer management models	Conceptual model, unconfined coastal aquifer system	A spatially and temporally varying planned pumping strategy, obtained as solutions of an embedded optimization model, is a possible management method for beneficial exploitation and salinity control of a coastal aquifer
	[12]	Single objective management model by externally linking ANN model to a GA-based optimization model	Conceptual model using an illustrative study area	GA–ANN based linked simulation–optimization approach can be applied for the optimal management of coastal aquifers

(*Continued*)

Table 2 (*Continued*)

Modelling approaches	References	Methods/data used/techniques followed	Place of study	Major findings
Management models	[13]	Multi-objective management model. External linking and comparison of solution results with those obtained from embedded technique and classical non-linear optimization technique	Conceptual model using an illustrative study area	External linking performed better compared with the embedding technique
	[14]	Multi-objective management model using three different modelling scenarios	Conceptual model using an illustrative study area	The developed methodologies are applicable for multi-objective management of saltwater intrusion in coastal aquifers
	[155]	Saltwater intrusion management model	Gaza strip coastal aquifer, Palestine	The developed optimal scheme significantly lowered the salt concentration of the extracted water by 23% while keeping the overall extraction close to the user defined total amount
	[156]	Management model combining abstraction of water from the aquifer and recharge to the aquifer using desalinated water	Biscayne aquifer, Florida, USA	The proposed methodology performs significantly better than using abstraction or recharge wells alone as it gives the least cost and least salt concentration in the aquifer
	[157]	Different management scenarios with a view to minimize the cost of management process	Conceptual model verified with Henry's saltwater intrusion problem	Treated wastewater is the most cost-effective option of recharging the aquifer and the use of desalinated water should be restricted to domestic use only
	[158]	Management model incorporating different combinations of recharge and abstraction scenarios	The developed models were verified against a parametric study considering a 30 m deep pumping well	The application of treated wastewater and/or storm water, coupled with continuous abstraction of brackish water and its desalination and use was found to be the most cost-effective alternatives to control seawater intrusion
	[159]	Pumping management methodology based on desalination of pumped brackish water and on recharging the aquifer with treated wastewater	Island of Santorini	An increase in the economic and environmental cost as groundwater recharge reduces due to climate change
	[160]	An integrated approach coupling groundwater–agricultural hydrosystems under uncertainty. Two contradictory management objectives such as sustainable aquifer management and profitable agricultural production	Al-Batinah coastal agricultural region, Oman	Several policy combinations enables decision makers to assess the risks associated with implementing alternative management strategies

(*Continued*)

Table 2 (*Continued*)

Modelling approaches	References	Methods/data used/techniques followed	Place of study	Major findings
	[161]	Conjunctive use of surface water and groundwater resources with an aim to maximize the supply for irrigation and public supplies	Chou-Shui alluvial fan system, central Taiwan	When the drawdown is limited to 1 m/year, the water shortage can be increased by an average of 25.2 million m^3/year
Management models	[138]	A regional scale model utilizing a scenario simulation	Southern Al-Batinah region at the northern coast of Oman	Modelling and visualization results give information on the time scale for remediation activities
	[7]	Multi-objective management model incorporating GP and modular neural network as surrogate models	Conceptual model using a hypothetical illustrative study area	GP model performed well compared with modular neural network model on the basis of uncertainty measures
	[8]	Multi-objective management model incorporating GP and ANN as surrogate models and their comparison	Conceptual model using a hypothetical illustrative study area	The performance of GP model is better compared with ANN model
	[9]	Multi-objective management model for optimal combined operation of production and barrier wells	Conceptual model using a hypothetical illustrative study area	The developed methodology is suitable for finding optimal and sustainable pumping strategies for coastal aquifers
	[16]	Genetic programming-based ensemble surrogate models and multiple-realization optimization	Conceptual model using a hypothetical illustrative study area	Ensemble-based GP models provide reliable solutions for coastal aquifer management
Monitoring network design	[162]	Robust compliance moni-toring network design for a multi-objective saltwater intrusion management problem	Conceptual model using a hypothetical illustrative study area	Field application of prescribed management strategy can be facilitated by a robust optimal solution with some allowed deviations within some bounds
	[163]	Fuzzy logic-based framework incorporating fuzzy mass estimation error and spatial coverage of the designed network	Conceptual model using a hypothetical illustrative study area	The proposed methodology is applicable under uncertain system conditions
	[22]	An adaptive management approach to develop compliance monitoring design	Rita island in the Burdekin region of Queensland, Australia	Sequential modification of the strategies was found to help in better compliance, while optimally satisfying the salinity requirements

3.3. Management models in saltwater intrusion problems

The management models for managing the saltwater intrusion processes in coastal aquifers require development of regional-scale management strategies. These management models for prescribing spatially and temporally varying large-scale management strategies are generally based on different optimization algorithms, and often integrating an optimization model with simulation models to simulate accurately the flow and transport processes in an aquifer.

Willis and Finney [164] were the first to develop a planning model for the control of seawater intrusion in regional groundwater systems. Later, Finney et al. [165] proposed another optimization model for the control of saltwater intrusion. The optimization technique was further implemented in the development of coastal aquifer management strategy based on optimized pumping [8,9,11–15,166,167]. Accuracy of management strategy depends on the level of approximation and the way in which they are incorporated. To develop saltwater intrusion management models, the simulation models are combined with the management models either by using the governing equations as binding constraints in the optimization model or by using a response matrix or an external simulation model. The simulation model component of the management model is generally based on the finite-difference or finite-element approximations of the partial differential equations of groundwater flow and solute transport [11].

The coupled simulation optimization technique (linking groundwater simulation models with optimization techniques in a single framework) is the more efficient approach for determining optimum management strategies of coastal aquifers [29]. This coupling of simulation and optimization models can be developed by embedding technique (binding the discretized governing equations into the constraints of the optimization model) [11], response matrix [168–171], or by external linking [166]. The commonly used techniques to incorporate the simulation model within the management model are embedding technique and response matrix approach [170].

Das and Datta [11] demonstrated the potential feasibility of the embedding technique for the development of multi-objective coastal aquifer management models. In this principle, the finite-difference form of density-dependent coupled flow and transport equations are embedded as constraints, and constraint method is used to obtain the Pareto-optimal or non-inferior set of solutions for the multiple-objective models. Later, Das and Datta [15] proposed a non-linear optimization method to solve the embedded governing equations for the simulation of seawater intrusion in coastal aquifers. They used gradient search process to solve the discretized flow and transport equations simultaneously. They compared the results of the proposed methodology with those of the other researchers and found a good agreement of the results with the known solutions. However, embedding technique is computationally inefficient for a large-scale heterogeneous aquifer system, and has several limitations when used for saltwater intrusion management model in a large-scale aquifer system [10,11,164]. Moreover, in the embedding technique approach, a large number of decision variables need to be used in the optimization model [13]. On the other hand, response matrix approach, based on the principle of superposition and linearity, is unsatisfactory for highly non-linear systems [172]. Response matrix approach is applicable when the system is linear or approximately linear and the boundary conditions are homogeneous. Any change in boundary condition, location of the source/sink, and observation wells requires several simulations to generate the responses and also requires recalculation of the response matrix [15].

However, for highly complex and non-linear 3D numerical models, a management tool based on external linking of the simulation model with an optimization framework is more feasible [12,29,173]. For the saltwater intrusion management models, a linked simulation–optimization approach was proposed as an alternative to embedding technique and response matrix approach [170,174]. Several authors incorporated external linking technique to develop saltwater intrusion management models by externally linking coastal aquifer simulation models with an optimization model [7–9,12,13,16,22,175]. In a linked simulation–optimization technique, the simulation model provides necessary information to the optimization model at every stage of iteration to reach an optimal solution [8].

Bhattacharjya and Datta [12] developed a single-objective management model by externally linking a properly trained and tested ANN as an approximate simulator with the GA-based optimization model in a linked simulation–optimization framework to develop a saltwater intrusion management model. The developed methodology was evaluated using an illustrative study area, and the evaluation result suggests that GA–ANN based linked simulation–optimization approach can be applied for the optimal management of coastal aquifers. However, the management of groundwater resources in coastal regions usually involves several contradictory objectives affecting each other adversely. Some examples of these objectives include maximizing pumping from the production wells for the beneficial use while maintaining the salinity level in the pumped water within a permissible limit, minimizing pumping from the barrier wells, maximizing profit from the pumped water, minimizing the cost of pumping, etc.

Multi-objective optimization of coupled simulation and optimization models can address these trade-offs between the contradictory objectives [7,9,11,12,29,175,176]. A multi-objective optimization technique for a coastal aquifer management problem generates a large number of so-called Pareto-optimal solutions posing a significant challenge for interpreting and communicating those solutions to decision makers [160]. Therefore, post-Pareto-optimality analysis is necessary to communicate the Pareto-optimal solutions form the multi-objective decision-making problems [160,177,178].

To solve multi-objective saltwater intrusion management problems, Bhattacharjya and Datta [13] utilized an ANN-based surrogate model externally linked with an optimization model. The results obtained from this linked simulation–optimization framework were compared with those obtained from embedded technique and classical non-linear optimization technique. They concluded that the optimization model needs to handle only few variables and explicit constraints in a linked simulation–optimization technique, and therefore, this technique performed better than the embedding technique. Dhar and Datta [14] evaluated the computational efficiency of the developed multi-objective management model by using three different modelling scenarios: direct linking of the numerical model with the optimization model, ANN-based surrogate model as a replacement of the numerical simulation model, and use of a partially trained surrogate model. The performance evaluation of the developed methodologies was carried out in an illustrative coastal aquifer system indicating that the developed methodologies were applicable for multi-objective management of saltwater intrusion in coastal aquifers. Sreekanth and Datta [8] evaluated the performance of an ANN- and a GP-based LSOM by using an illustrative coastal aquifer system to determine the optimal groundwater extraction strategies from coastal aquifers. Sreekanth and Datta [9] proposed another optimal pumping management strategy by externally linking a properly trained and tested ANN model with a multi-objective optimization algorithm. Recently, Dentoni et al. [155] developed a saltwater intrusion management model for the Gaza strip coastal aquifer, Palestine using a linked simulation–optimization technique. They showed that the developed optimal scheme significantly lowered the salt concentration of the extracted water by 23% while keeping the overall extraction close to the user defined total amount. Moreover, they reported an average increase of groundwater heads by 4.5% and a decrease of seawater intrusion affected area by 5% with the optimized solution.

To develop saltwater intrusion management models, Abd-Elhamid and Javadi [156] proposed a methodology combining abstraction of water from the aquifer and recharge to the aquifer using desalinated water. Later, Javadi et al. [157] modified this methodology by using treated wastewater as a source of water for aquifer recharge. Javadi et al. [157] considered different management scenarios to find the best management practices to control seawater intrusion in coastal aquifers with a view to minimize the cost of management process while minimizing the total salinity in the aquifer. A multi-objective optimization formulation was utilized to search optimal solutions for each scenario of the saltwater intrusion management problem. Results indicated that the proposed methodology maximizes the impedance of freshwater–saline water interface, and induces the seaward movement of the seawater body while providing the least cost and least salt concentration in the aquifer. They also claimed that their methodology requires less volume of water for aquifer recharge to control seawater intrusion. They concluded that treated wastewater is the most cost-effective option of recharging the aquifer and the use of desalinated water should be restricted to domestic use only. Different combinations of recharge and abstraction were also considered in developing saltwater management models by Hussain et al. [158]. Minimizing the cost of management approaches and the salinity level in the aquifer was chosen as the objective function to evaluate the efficiency of each management scenario. Among the management alternatives, the application of treated wastewater and/or storm water, coupled with continuous abstraction of brackish water and its desalination and use was found to be the most cost-effective alternatives to control seawater intrusion.

A management plan for simultaneous minimization of economic and environmental costs was proposed for the island of Santorini by utilizing the formulation of a multi-objective optimization framework [159]. Subagadis et al. [160] presented an integrated approach to support management decisions of coupled groundwater–agricultural hydrosystems under uncertainty. They also demonstrated the functionality of the proposed methodology to find the appropriate management interventions for the saltwater intruded Al-Batinah coastal agricultural region in Oman addressing two contradictory management objectives such as sustainable aquifer management and profitable agricultural production. Chen et al. [161] developed a management model for the large-scale conjunctive use of surface water and groundwater resources with an aim to maximize the supply for irrigation and for public supplies by imposing the constraints of groundwater level drawdown for the Chou-Shui alluvial fan system, central Taiwan. They showed that if the drawdown is limited to 1 m/year, the water shortage could be increased by an average of 25.2 million m^3/year for the Chou-Shui alluvial fan. A regional-scale model utilizing a scenario simulation using the numerical model OpenGeoSys was developed for the southern Al-Batinah region at the northern coast of Oman to assess the development of the groundwater levels and salinity intrusion in the past and to project a future scenario [138].

3.3.1. Surrogate models used in simulation–optimization framework

Sanford and Pope [56] emphasized the challenges of models to forecast seawater intrusion and suggested that accurate simulation of regional-scale (many km) saltwater intrusion and accurate forecasting even for a single well is computationally prohibitive even with an infinitely powerful computer. In simulation, sensitivities are approximated by calculating the ratios of the resulting marginal (incremental) changes in the output variables to the changes in the input variables that caused them [179]. Therefore, simulation part of the simulation–optimization framework has a relatively high computational cost. Moreover, to get an optimum solution in the irregularly shaped feasible regions of the problems, the simulations must be performed many hundred or, even thousand times in a typical optimization problem. Runtime of the optimization can be reduced by introducing parallel or distributed algorithms on the simulation level such as domain decomposition [180] or on the optimization level such as parallel direct search [181]. Another way of reducing the computational effort is to apply approximation techniques to reduce the number of simulations [182]. Sufficiently accurate and computationally less intensive approximate solution of the flow and transport processes in coastal aquifer may be useful [12].

To obtain optimal management strategy, density-dependent flow and transport simulation models need to be coupled with a suitable optimization algorithm. External linking of the simulation model with the optimization-based management model is a probable solution of coupling which is very complex and difficult. Moreover, this technique demands a considerable computational time because large number of iterations between the optimization and simulation model is required to obtain an optimal management strategy [8]. This modelling bottleneck can be solved either by using parallel algorithm and better computer configurations [183,184], or by using an approximate simulator called meta-model or surrogate model.

To achieve computational efficiency, simulation models can be replaced by a properly trained and tested surrogate model or meta-model in the simulation–optimization framework. The concept of meta-modelling approach in optimization processes to reduce the computational time was proposed by Blanning [179]. A meta-model can be used as a surrogate to calculate fitness values, which are normally based on time-consuming simulations. Such a meta-model can be effectively integrated into the search process to gradually substitute the large portion of simulation [185]. Hemker et al. [186] showed that the surrogate approaches can locate design points better than the other approaches while improving the computational efficiency to a great extent. However, surrogate models should preserve the size and scope of the problem domain, and should reflect the empirical relationships between decision variables and selected model outcomes [187]. The use of surrogate models in a simulation–optimization framework requires an additional calibration effort in order for the surrogate models to represent the system and produce good predictions. Surrogate models require small execution time to produce model predictions in spite of the extra computational time required for the surrogate model calibration [188].

Surrogate models should be trained with the representative input–output patterns from the entire decision space [8]. Dividing the dataset into two mutually exclusive subsets (training set and the validation set), called holdout method [189], is commonly used during the model validation and selection process. A part of the data is usually used to train the surrogate model while the rest of the data is used to validate the surrogate model [190], resulting in the overfitting of the training data and under fitting of the validation data [191]. The holdout method can be improved by a method called cross-validation, where both the training and validation data are used. However, cross-validation method is rarely used in the field of groundwater optimization field for the estimation of the surrogate model accuracy [192].

Comprehensive review of meta-model-based optimization approaches in general can be found in Jin [193], and in Jin and Branke [194]. Polynomial regression (PR), ANN, kriging, support vector machine, and multivariate adaptive regression spline, are common methods to build surrogate models that can be used to substitute the complex numerical models [191].

Earlier attempts of surrogate modelling were confined to 1D or 2D flow and transport processes [12]. For example, Alley [195] developed regression equations for 2D transport processes in an aquifer. Lefkoff and Gorelick [196] presented an approximation model using multiple-linear regression to predict the change in groundwater salinity resulting from the hydrologic conditions and water use decisions. For the prediction of total solute mass removal for treatment, Rogers and Dowla [197] linked ANN with an optimization model. An ANN model was presented by Morshed and Kaluarachchi [198] to approximate concentration break-through curves for 1D unsaturated flow and transport.

Surrogate models are used as computationally cheaper substitute for complex numerical models to solve complex problems [7,179,188,199]. In recent years, surrogate models have been used as approximation of the computationally intensive simulation models to improve the efficiency of computation for simulation–optimization framework in groundwater remediation in coastal aquifers. The commonly used surrogate models in groundwater simulation–optimization fields are linear regression [187], PR [158,200–203], second-order polynomial [204], radial basis functions [204–208], ANNs [8,29,185,187,198,209–215], modular neural networks [213], and kriging method [186].

Among several meta-modelling techniques available, response surface methodology and ANN methods are two well-known approaches to construct simple and fast approximations of complex computer codes [199]. The most widely used approximate surrogate models are based on ANNs. Rogers et al. [209] introduced ANN as a potential surrogate model in LSOMs for solving groundwater management problems. ANN surrogate models were developed to approximate density-dependent saltwater intrusion process in coastal aquifers for developing saltwater management models by different authors [12–14,162,216]. On the other hand, adaptive neural network model [217] and modular neural networks [213] were also used to solve salinity intrusion management problems.

Since ANN model can handle partial information, noisy data do not have a significant influence on the performance of the approximate simulation model [17]. Bhattacharjya et al. [17] evaluated the performance of an ANN surrogate model as a replacement of a numerical simulation model to simulate 3D flow and transport processes in coastal aquifers. The performance of the developed surrogate model was justified for an illustrative study area. Nikolos et al. [212] also assessed the performance of ANN–differential evolution algorithm based surrogate modelling approach to replace the classical finite-element simulation model for the productive pumping wells in the northern part of the island of Rhodes, Greece. Johnson and Rogers [187] investigated the accuracy of ANN approximators by comparing the results of an ANN-based simulation–optimization model with those obtained from numerical simulation model-based simulation–optimization technique.

An approximation precision of at least 99% with a reduction of computation time of at least 60% can be achieved by utilizing ANN to approximate a finite element-based simulation system [210]. Behzadian et al. [185] also demonstrated a significant computational savings by replacing a full fitness model with adaptive neural networks meta-model in a multi-objective genetic algorithm adaptive neural networks framework. The developed methodology was applied to a real case study and was found 25 times faster than the full fitness model without significant decrease in the accuracy of the final solution. A distinction between neural network and GP-based surrogate modelling approaches was presented in Sreekanth and Datta [8]. They found several advantages of GP over ANN, for example, the model structure of the GP-based surrogate modelling need not be fixed prior to model development. Instead, the self-organizing ability of the GP algorithm makes it possible to evolve the optimum model structure. GP-based surrogate modelling also requires fewer model parameters compared with weights of neural network models. Moreover, the neural network model structure will be very complex for systems having quite a large number of decision variables. In such cases, it might be faster to use the original numerical model.

An alternative approach bypasses network training prior to optimization and trains the network adaptively during optimization [213]. Later, Kourakos and Mantoglou [188] combined modular neural network-based surrogate models with a GA-based optimization algorithm to develop a multi-objective optimization algorithm to minimize economic and environmental costs while satisfying the water demand. Modular neural networks consist of a series of simple neural subnetworks. Each subnetwork within a modular neural network serves as a module, operates on separate inputs and is meant to accomplish some subtask [218]. Training becomes more effective and significantly faster in modular neural networks as each module needs to learn simpler and smaller subtasks. While in one large global neural network, the number of parameters depends on the size of the decision variable space and the number of parameters increases quadratically as the number of the decision variables increases [219].

The performance of Evolutionary Polynomial Regression (EPR) as a meta-model to examine the efficiency of different arrangement of hydraulic barriers in controlling seawater intrusion was tested in an unconfined coastal aquifer system [158]. The results obtained from this simulation–optimization technique were also compared with the results obtained from the direct linking of a numerical model, SUTRA with the multi-objective optimization tool (GA). The results indicated that EPR–GA based surrogate modelling approach could replace the computationally intensive SUTRA–GA based simulation–optimization modelling approach. Mugunthan and Shoemaker [206] performed automatic calibration and parameter uncertainty analysis of groundwater models using radial basis functions as meta-models and Gaussian random sampler as search algorithm. They claimed an achievement of computational saving of more than 87% in terms of the number of full evaluations. Lall et al. [220] used a locally weighted PR surrogate to approximate the arbitrary non-linear relationship between inputs and outputs.

Christelis and Mantoglou [141] employed cubic radial basis functions as computationally efficient substitute of computationally expensive variable-density model, HydroGeoSphere for a pumping optimization problem of coastal aquifers. Adaptive–recursive and meta-model embedded evolution strategy was employed as two meta-modelling frameworks. Optimization problem was solved by combining evolutionary annealing simplex and the original simulation model. Optimization was also performed using meta-models instead of original simulation model. Results indicate that the meta-model embedded evolution framework outperformed the adaptive–recursive approach in terms of computational efficiency. Furthermore, with the meta-model embedded evolution strategy the computational time of the variable-density-based optimization was reduced by 96%.

Comparative evaluation of different meta-modelling approaches to achieve accuracy and computational efficiency in modelling is also found in literature. Jin et al. [199] investigated the advantages and disadvantages of four meta-modelling techniques such as PR, multivariate adaptive regression splines, radial basis functions, and kriging on the basis of multiple criteria and multiple test problems. In terms of accuracy and robustness, radial basis function was found to be the best of all the meta-modelling techniques used. For the most difficult problems such as large scale and high order non-linear problems, the average accuracy of multivariate adaptive regression splines is the best while its performance deteriorates when small or scarce sample sets are used. PR performs best in case of the problem with noise and kriging is very sensitive to noise because it interpolates the sample data. Radial basis functions meta-modelling approach was found to be the best in most situations and in terms of accuracy and robustness. Luo and Lu [191] compared three types of surrogate models for optimum groundwater remediation strategy identification. Among them radial basis function ANN and kriging methods had acceptable approximation accuracy and had similar computational burden. However, the approximation accuracy of kriging method was slightly higher than the radial basis function ANN while PR-based surrogate model demonstrated poor and unacceptable approximation accuracy.

Uncertainty in surrogate model simulations limits the practical usefulness of surrogate-based simulation–optimization methodology though they have the advantage of reducing the computational time [16]. Most of the surrogate modelling approaches in the literature optimizes the parameters of the surrogate models to obtain the best fit between the explanatory and response variables assuming a fixed surrogate model structure. The optimality of the solution of the coupled simulation–optimization model is affected by the uncertainties in the surrogate model predictions. Moreover, surrogate models add errors in the output response of the optimization procedure as a result of their approximate and imprecise predictions. Surrogate model errors can be handled using an ensemble of surrogate model realizations [16] or by introducing an error adjustment method [221]. Later technique uses an adjustment of the objective function values of the offspring predicted by the surrogate model is carried out based on the error of their parents. The feasibility of the ensemble-based GP framework to quantify the uncertainty in hydrological prediction is documented in the work of Parasuraman and Elshorbagy [222]. Sreekanth and Datta [16] evaluated ensemble of surrogate models using GP to tackle the uncertainties of surrogate modelling in saltwater intrusion management problems. The ensemble of surrogate models was coupled with stochastic-optimization models to derive optimal extraction strategies. The results of the ensemble-based approach was compared with those obtained using a chance-constrained optimization formulation and single-surrogate-based model. The ensemble-based approach was found to provide reliable results while retaining the advantages of reducing computational burden. Ensemble of surrogate models was constructed by using non-parametric bootstrap method together with GP.

3.3.2. Overview of optimization techniques in saltwater intrusion modelling

The efficient search of global optimal solutions is the most important part of the simulation–optimization process, and different optimization processes have been proposed by researchers to achieve this goal [223]. The commonly used meta-heuristic search algorithms are simulated annealing (SA) [224,225], Tabu search [226,227], GAs [228,229], etc.

Among different optimization methods that have been used to tackle the search process in different ways, the gradient-based methods are known to be the fastest optimization method. However, these methods require several starting points to perform the global search and the final optimal solution depends on these starting points [230]. The classical optimization techniques used for groundwater management models are based on gradient search techniques, for instance, linear and non-linear programming, mixed integer programming, etc. are extensively used. These gradients are calculated numerically leading to large errors. Moreover, the numerical estimation of gradient is computationally intensive. When the response surface is highly irregular, these gradient search techniques often obtain only local optimum solutions. In such a situation, the possibility of obtaining a local optimal solution is more. Furthermore, Pareto-optimal solutions of a multiple-objective optimization problem can be achieved after several runs of the classical optimization techniques [17]. Point-to-point search, necessity of initial guesses, deterministic transition rule, assumption of unimodality, etc., are some of the other disadvantages of classical optimization techniques [231].

GA [228,229] and SA [224] are the two commonly used non-gradient-based heuristic search techniques used in the simulation–optimization framework [12]. GA [228,229], particle swarm optimization [232], and SA [224] optimization methods are computationally expensive in spite of the capability of finding global optima [230]. To improve the convergence rate of the search process, Ingber [233] proposed an adaptive SA by modifying the existing conventional SA algorithm. However, there is no guarantee that global optimal solution be found using these two search techniques though they can achieve nearly optimal solutions at a reasonable computational cost [234]. Heuristic techniques have the ability to locate solutions with greater efficiency in combinatorial optimization problems. On the other hand, branch-and-bound techniques are implicit enumeration techniques that have less efficiency compared with heuristic techniques [235]. They have also advantages over the gradient-based techniques because heuristic techniques can handle the discontinuities and non-linearities of the real-world problems [236,237]. However, the number of times the objective function must be calculated is still very high in heuristic search techniques. For example, to complete a single search, GA required 1,250 evaluations of the objective function [235] whereas 2,344 evaluations of the objective functions were required by SA algorithm [238].

Different types of search algorithms have been used to find the optimal solution of groundwater remediation problems. The most commonly used optimization algorithms by different researchers are SA [187], GA [158,217], (μ,λ)-evolution strategy [204], Gaussian random sampler [205,206], Gaussian and uniform random samples [207,208], evolutionary annealing simplex scheme [213], covariance matrix adaptation-evolution strategy [30]. Different stochastic optimization techniques have been found in the literature for the optimal decision-making under uncertainty [239–241]. Chance-constrained programming [239,242–244] and multiple-realization approach [242,243,245,246] are commonly used as stochastic simulation optimization in groundwater management problems. In multiple-realization approach, several realizations of the uncertain model parameters are considered simultaneously in an optimization framework [16].

Fen et al. [203] demonstrated that response surface-based optimization approach gave better optimal solution while required less computation time compared with simulation/optimization approach. Goel and Stander [230] compared three different optimization algorithms (leap-frog algorithm for constrained optimization, GA, and adaptive SA) using two analytical examples (Schwefel function and Rastrigin function) as well as two engineering problems (crash optimization and multi-disciplinary reliability based design optimization). Adaptive SA optimization algorithm performed better than others for all test problems. GA has the similar accuracy with adaptive SA for their test cases and they concluded that GA could be a good alternative to adaptive simulated annealing with slightly higher computational expense. Hemker et al. [186] compared the performance of three different modelling approaches for a mixed-integer non-linear optimization problem. They showed that branch-and-bound approach (surrogate approach) can significantly reduce the computational burden and at the same time can provide a comparable and even better location of the design point than the other approaches (GA and the implicit filtering algorithm). Dual response surface optimization in combination with subsurface modelling was used to develop an integrated simulation–optimization approach for real-time dynamic modelling and process control of surfactant enhanced remediation at petroleum contaminated sites [200]. Johnson and Rogers [187] used SA in the search process for two different groundwater remediation problems in an optimization framework that uses ANN and linear approximators as a replacement of SUTRA. An adaptive optimization algorithm based on an evolutionary annealing simplex scheme (EASS) was used by Kourakos and Mantoglou [213] in a simulation–optimization framework to optimize pumping in coastal aquifers. EASS is a probabilistic heuristic global optimization algorithm, where a generalized downhill simplex methodology is coupled with an SA procedure. The algorithm combines the robustness of SA with the efficiency of hill-climbing methods in simple search spaces [213].

3.3.3. Robust optimization

In saltwater intrusion management problems, simulation models are usually associated with uncertain model parameters such as variation in hydraulic conductivity field, aquifer recharge, etc. These uncertain model parameters add certain degree of uncertainty in the simulation–optimization process. Therefore, an efficient methodology is required to account for these uncertainties to obtain reliable and robust solutions. Robust solutions of a problem are solutions which are not affected by perturbation in the variables that constitute objective function and constraints of the system being modelled [247]. On the other hand, reliability is thought of as the probability of meeting the criteria to satisfy the constraints [248].

Robust optimization is an innovative and rapidly growing methodology incorporating in optimization problems to handle non-stochastic "uncertain-but-bounded" data [249]. Although both stochastic and robust optimization techniques are used in models where exact data are unknown, the later approach is additionally bounded by a set of possible realizations. In addition, a given probability distribution cannot be assumed for all the possible realizations of the uncertain data. Data are assumed stochastic in nature with known distributions when dealing with data uncertainty in stochastic programming. In contrast, data are presumed to be varied within a given uncertainty set rather than to be stochastic in robust optimization. In stochastic programming, the aim is to obtain a solution result that simultaneously satisfies the constraints and minimizes the objective function value over a range of candidate solutions. On the other hand, robust optimization finds the best solution from a set of solutions that remains feasible for all realizations of the data taken from an uncertainty set [249].

However, Iancu and Trichakis [250] illustrated the potential drawback of classical robust optimization and proposed the concept of "Pareto Robustly Optimal (PRO)" solutions which are not associated with suboptimal solutions. Numerical experiments on three separate application areas suggested a better performance of the PRO against classical robust optimization. To tackle uncertainties in water quality management problems and to facilitate formulation of the non-linear optimization problems, Xu et al. [251] developed a hybrid-interval robust optimization (HIRO) by coupling stochastic robust optimization and interval linear programming. Results demonstrated that the proposed optimization model could effectively communicate uncertainties into the optimization process. They also pointed out that HIRO could be integrated into other uncertain handling techniques such as fuzzy programming to solve more complex real-world practical problems. To attain robustness of the solutions, Salomon et al. [252] suggested the concept of active robust optimization, a concept that combines robust optimization with dynamic optimization in order to evaluate the performance of a candidate solution. The key novelty of this methodology is the "adaptation" that reduces the loss in performance as a result of environmental changes, demonstrating the superiority of the suggested approach over a non-adaptive approach.

Ndambuki et al. [168] developed a robust optimal strategy for multi-objective groundwater management problems considering uncertainty in hydraulic conductivity field. Three conflicting objectives were used in the optimization formulation to evaluate the trade-offs among them, and the applicability of the developed methodology was evaluated using a hypothetical illustrative study area. The robustness of the model was also evaluated by conducting a post-optimality Monte Carlo analysis. Results demonstrated the usefulness of the robust optimization to develop a management strategy under uncertain model parameters. Sreekanth et al. [253] presented the implementation of robust optimization in a groundwater management problem for an injection bore design problem in a stochastic multi-objective optimization framework. The developed methodology is efficient in handling uncertainty in hydraulic conductivity field, and is able to provide reliable and robust solutions. Sreekanth and Datta [175] presented a methodology that couples ensemble surrogate models with multiple-realization optimization to address uncertainty in hydraulic conductivity and aquifer recharge in a multi-objective and multiple-realization optimization problem of a coastal aquifer management problem in Lower Burdekin area in Australia. Maximize the pumping from production wells and minimize the pumping from the barrier wells were the two conflicting objectives of their robust optimization formulation. They noted that the Monte Carlo simulations are well suited for comprehensive characterization of uncertainty. However, their proposed methodology is beneficial in terms of saving computation time where Monte Carlo simulations are infeasible due to computational burden.

4. Saltwater intrusion models incorporating aquifer heterogeneity

Most of the previous and some recent studies of saltwater intrusion modelling were based on the assumption of aquifer homogeneity. However, to study seawater intrusion in coastal aquifers, the key importance is to consider aquifer heterogeneity. The role of aquifer heterogeneity on coastal aquifer flow dynamics has been considered more recently. The following paragraphs will discuss saltwater intrusion modelling studies incorporating aquifer heterogeneity.

Hydrogeological heterogeneity of the subsurface plays an important role in the saltwater intrusion processes of coastal aquifers. Geological heterogeneity at various scales strongly influences the groundwater flow and transport in aquifers, and therefore, homogeneous assumption can sometimes lead to serious error [154]. In the transport process through a heterogeneous medium, fluid needs to be moved through a complex path making the process more complex. Spatial and temporal extent of aquifer salinization by seawater intrusion and storm surge largely influenced by aquifer heterogeneity [40]. The fate and migration of inundating saltwater and recovery time of groundwater quality is also dependent on the aquifer heterogeneity [152]. The effect of heterogeneity in the Henry problem investigated by researchers revealed that a seaward migration of the freshwater–seawater interface occurs due to a strong heterogeneity of the conductivity field in 2D isotropic problems [44]. Although climate change-induced sea-level rise and excessive groundwater pumping are the two main drivers of seawater intrusion in coastal aquifers around the globe, hydrogeological heterogeneity of the subsurface also influences the recharge patterns and the saltwater intrusion as well [153]. The complexities arising from the heterogeneity of the aquifer coupled with the non-linear nature of the flow system make proper explanation of the seawater intrusion process a challenging task [44].

For application in seawater intrusion scenarios, Held et al. [254] examined the Henry problem for a stochastic heterogeneous aquifer considering a stable density configuration for density-dependent flow and transport in coastal aquifers. Their numerical results suggests that while steady-state saltwater distribution is less affected by spatially varying permeabilities and longitudinal dispersion, transient saltwater intrusion is primarily affected by heterogeneous permeability fields.

Ababou and Al-Bitar [255] presented numerical experiments of saltwater intrusion in randomly heterogeneous aquifers based on unconditional simulations of random permeability fields by implementing a numerical finite volume scheme using modified version of the BIGFLOW code

(BF2000) for simplified sharp-interface problems. They qualitatively studied the effect of heterogeneity on the extent and shape of the salt wedge. Results revealed that saltwater wedge migrates tens of meters further toward the aquifer due mainly to aquifer heterogeneity, for instance, 50 m further compared with homogeneous aquifer when heterogeneity is represented by $\sigma_{\ln K} = 1$. They also observed a sudden movement of the substratum saltwater interface toward inland direction because of the increase in heterogeneity from $\sigma_{\ln K} = \sqrt{2}$ to $\sigma_{\ln K} = \ln 10$.

Hydrodynamic dispersion plays the key role to control solute transport in a heterogeneous porous media. Beaudoin and de Dreuzy [256] determined the longitudinal and transverse dispersivities as functions of heterogeneity and dimensionality by using classical Gaussian correlated permeability fields with a lognormal distribution of variance. They showed that transverse macrodispersion that increases steeply with the proposed permeability field is at least two orders of magnitude smaller compared with longitudinal macrodispersion, which increases even more steeper than transverse macrodispersion. On the other hand, transverse dispersion also converges much faster to its asymptotic regime compared with longitudinal dispersion. Therefore, high longitudinal macrodispersions are not attributable to braiding (a mechanism specific to 3D systems) alone, strong velocity correlations in 3D than in 2D also responsible for this. This fact is evidenced by five times greater longitudinal macrodispersion values obtained in 3D than in 2D systems.

In a layered heterogeneous aquifer of Hawaii, Voss and Souza [257] simulated the groundwater flow of a mixture of freshwater and saltwater using a 2D numerical model and observed the presence of a narrow freshwater–saltwater transition zone. Dagan and Zeitoun [258] addressed the effect of heterogeneity in coastal aquifers using theoretical analysis based on the sharp-interface assumption. In a stratified aquifer of random permeability distribution, they presented an exact closed form solution for the statistical moments of the interface. Abarca [259], based on 2D analysis, found that a seaward displacement of the saltwater wedge as well as the widening of the mixing zone is produced by the aquifer heterogeneity. A 2D numerical modelling study was also employed to investigate the effects of anthropogenic activities and sea-level rise on seawater intrusion in a heterogeneous coastal aquifer [66]. Another simulation study considering a 2D cross-sectional heterogeneous aquifer of a beach in Alaska indicated that low-permeability layer of the aquifer resulted in a longer residence time of groundwater impacting the bioremediation potential of Exxon Valdez accident oil spills due to loss of dissolved oxygen [260]. They also simulated the fate of the tracer in response to tidal activities in the same heterogeneous aquifer to the fate of injected nutrients used for accelerating bioremediation.

A 3D model for the saltwater intrusion in heterogeneous coastal aquifer was developed to simulate several recharge and infiltration scenarios to understand the interactions between the scenarios and saltwater–freshwater interface [26]. Bray et al. [261] considered aquifer heterogeneity using the pointwise hydraulic conductivity data to develop a confined–unconfined density-dependent flow and transport model for Alamitos saltwater intrusion barrier in Southern California. They considered nine different layers of aquifers. A two-phase calibration procedure was employed to calibrate the hydraulic conductivity and dispersivities in the flow and transport model. The variation of hydraulic conductivity was also used to represent aquifer heterogeneity to develop saltwater intrusion model in heterogeneous confined aquifers using lattice Boltzmann method [262]. They claimed that the model results were in good agreement with that obtained by several numerical examples and modified Henry problems that consider heterogeneous hydraulic conductivity and velocity-dependent dispersion. In another 3D model for the coastal aquifer of low-lying Dutch delta region, heterogeneity of the aquifer was incorporated by considering layered zones of different permeability [33]. The spatial variation of the aquifer hydraulic conductivity was between 0.1 and 40 m/d. To deal with the complex geology in the subsoil as well as the complex distribution of fresh, brackish and saline groundwater, they used 40 model layers in the vertical direction. Based on the analysis from a single 3D permeability realization and considering small-scale heterogeneity, Kerrou and Renard [263] concluded that the seawater–freshwater interface migrates seaward in a 2D modelling approach and it migrates landward while considering 3D modelling approach as the degree of aquifer heterogeneity increases.

Recently, Tam et al. [153] investigated local hydrogeological conditions for recharge and saltwater intrusion in a highly heterogeneous coastal groundwater system in Vietnam. They explained why some aquifers in the world are susceptible to saltwater intrusion while the others are almost unaffected by saltwater intrusion. Pramada and Mohan [154] developed a methodology based on stochastic simulation of the system to investigate the effect of heterogeneity on seawater intrusion modelling. The developed methodology provides a better understanding of the transport mechanism in heterogeneous formation in coastal aquifers. The heterogeneity has been modelled by coupling Monte Carlo simulation to a seawater intrusion model SEAWAT, and the developed methodology was illustrated by a case study using Thiruvanmiyur–Injambakkam aquifer system of South Chennai, India. Doulgeris and Zissis [124] developed a 3D variable density seawater intrusion simulation model and applied it to a heterogeneous coastal aquifer system (two zones of hydraulic conductivity). They considered pumping rate, the salinity of freshwater inflow, and the thickness of the aquifer to predict the salinity concentration in the pumped water through well in certain location. Aquifer heterogeneity was considered for modelling the effect of global change on the heterogeneous aquifer in the Belgian western coastal plain [151]. They simulated the model using the effects of 15% recharge increase and 0.4 m of sea-level rise in the next 100 years. Their result suggested that groundwater flow, the recharge and discharge pattern, hydraulic heads, and water quality distributions would be seriously altered as a result of expected increase in recharge and sea-level rise. They emphasized the need of including the aquifer heterogeneity as much as possible in groundwater flow models.

Vithanage et al. [152] experimentally and numerically investigated the effect of geologic heterogeneity on the groundwater salinization and flush-out times. They concluded that macroscale heterogeneity has a potential influence on the migration patterns and flushing times of diffuse saltwater contamination. Walther et al. [138] evaluated the remediation potential of a salinized 3D, heterogeneous coastal aquifer system in the southern Al-Batinah region at the northern coast of Oman. Aquifer heterogeneity was also considered to simulate the effects of sea-level rise and storm surge on saltwater intrusion in a heterogeneous coastal aquifer in northern Germany [40]. They investigated the migration of salt plumes as influenced by aquifer heterogeneity in a 2D cross-section of an aquifer at the North German coast. Their result suggested that hydraulic conductivity of the subsurface largely affects the fate of the salt plumes.

5. Implementation of monitoring network design in saltwater intrusion modelling

Field response to the developed optimal management strategies might deviate from the prescribed values by linked simulation–optimization based groundwater management solutions due to the uncertainties resulting from the poor characterization of the groundwater system and field-scale implementation deviation. Therefore, for any groundwater management strategy to be effective, a properly designed groundwater quality monitoring network is essential to evaluate the field-level compliance of the prescribed groundwater management strategy. Sreekanth and Datta [22] proposed an adaptive management approach where sequential revision of optimal management strategies by incorporating field level compliance monitoring information from a designed monitoring network was performed. Simulation–optimization technique, design of optimal monitoring network, and incorporating feedback information to the original simulation model are the three major components of their developed methodology. Sequential modification of the strategies was found to help in better compliance, while optimally satisfying the salinity requirements. Monitoring locations were chosen in locations where uncertainty in the salinity concentration value is highest and correlation between the concentrations of the monitored locations is lowest to minimize the redundancy in monitoring data. Monitoring information from a large number of monitoring points ensures better characterization of the system and thereby accurate solutions for groundwater management by reducing the uncertainty. However, this is not practically possible to install large number of monitoring wells due to budgetary constraints. Compliance monitoring at the field level is associated with collection of relevant data that are time consuming and costly. Therefore, field-scale implementation of the proper monitoring strategy is always constrained by the availability of funds [163].

Previous literature of monitoring network design was based on different issues such as addressing multiple time steps [167,264–266], minimization in redundancy [267–269], multi-objective formulations [22,270–275], uncertainty [276–277], optimal location of monitoring wells [280], vulnerability mapping and geostatistics [281], etc. Different objectives for the design of an optimal monitoring network design can be found in literature, for instance, cost minimization [268,275,282–284], parameter identification [285,286], detection of contaminant [167,276,287–289], minimization of the variance of pollutant prediction [167,244,265,268–270,273,279,290,291], minimization of the salt concentration in pumping wells [22,162], etc. Earlier studies on monitoring network design in groundwater contamination emphasized on minimum well density [292], initial detection of contamination [293], cost-effective groundwater monitoring design [282], and optimal groundwater-quality monitoring networks [294]. However, in problems related to contamination plume movement, most of the optimization techniques for monitoring network design were based on an implicit objective of minimizing the monitoring cost [274].

Robust management strategies and field-scale monitoring of their impacts in terms of compliance with management goals should be the basis of the management of saltwater intrusion in coastal aquifers. Due to uncertainties involved, optimal monitoring network for compliance also requires robust optimal design. Dhar and Datta [162] claimed that their developed compliance monitoring network design is robust for a multi-objective saltwater intrusion management problem. In their study, a robust monitoring network was designed for an illustrative study area to determine the field-level compliance of implementing an optimal pumping strategy for saltwater intrusion management. They concluded that field application of prescribed management strategy can be facilitated by a robust optimal solution with some allowed deviations within some bounds.

The appropriate monitoring network for optimized pumping is designed at the end of the management time span. After correct identification and implementation of the system parameters, implementation of the prescribed management strategy is only associated with the operation uncertainty. Uncertainty can be categorized into two basic types: aleatory uncertainty and epistemic uncertainty. It is impossible to reduce the aleatory uncertainty with higher amount of information. However, reduction is possible in case of epistemic uncertainty. Monitoring network design can be classified as an approach for reducing epistemic uncertainty about the subsurface system. To handle uncertainty, Dhar and Patil [163] proposed a fuzzy-logic-based framework incorporating fuzzy mass estimation error and spatial coverage of the designed network for optimal design of groundwater quality monitoring networks. In multi-objective decision model formulation, concentration estimation algorithm based on fuzzy kriging was incorporated and spatiotemporal concentration values were considered as fuzzy numbers. They demonstrated the potential applicability of the proposed methodology under uncertain system conditions as evidenced from a performance evaluation for a hypothetical illustrative system. Fuzzy spatial interpolation and optimization model was used in combination with groundwater flow and transport simulation model in the proposed monitoring network design framework. Fuzzy kriging algorithm was used as a logical external module to the optimization algorithm. Instead of using binary decision variables, they used real coded version of NSGA-II for faster convergence.

6. Conclusions and recommendation for future scope of work

Seawater intrusion and subsequent deterioration of groundwater quality in coastal aquifers usually result from over extraction of groundwater resources. Different factors affecting saltwater intrusion processes in coastal aquifers have been identified in recent literature. Some of these factors and the associated consequences as addressed in the existing literature are discussed. Overexploitation of groundwater for domestic usages, sea-level rise due to climate change, tidal waves, and infiltration of salt due to inundations caused by storm surges are the main causes of salinity intrusion in coastal aquifers. Literature regarding the effects of tidal fluctuations on saltwater intrusion is divergent in view. While one group of researchers proved that tidal oscillations significantly reduce the overall extent of seawater intrusion compared with the non-tidal (static) case, others reported tidal effect as one of the main factors inducing seawater intrusion in the coastal aquifer system.

Mathematical models ranging from simple (steady flow) analytical solutions to complex numerical solutions used to describe or simulate relevant processes of saltwater intrusion have been reviewed. Existing literature on the development of optimal saltwater intrusion management approaches developed using a combination of simulation and optimization methodology is reviewed. Surrogate models are usually introduced in a linked simulation–optimization methodology to reduce the computational burden and to improve the feasibility of developing optimal regional-scale management strategies using LSOMs. Different surrogate modelling approaches are also highlighted in this review. Both adaptive and modular GP-based surrogate models have been successfully used as an approximate simulator of density-dependent 3D advective–dispersive processes in coastal aquifers affected by saltwater intrusion due to overexploitation. The ensemble GP models, essentially serving the role of ensemble surrogate models are potentially useful for quantifying the reliability of successfully implementing a coastal aquifer management strategy under parameter uncertainties. Ensemble surrogate models could be utilized to incorporate the uncertainties in parameter estimates as well as in simulation modelling.

Most of the previous and some recent studies of saltwater intrusion modelling are based on the assumption of aquifer homogeneity. Only a limited number of studies incorporate heterogeneity of aquifers and density dependence of both the flow and transport processes to represent complex flow and salt transport processes in coastal aquifers. Future researchers can focus on developing saltwater intrusion management models for heterogeneous coastal aquifers and extend the management modelling approaches to more complex saltwater intrusion scenarios.

Another relevant issue expected to draw greater future attention is the development of optimal management strategies robust in nature, based on robust optimization models. These robust optimization models are relatively less affected due to actual deviations from prescribed management strategies at implementation stage, as well as owing to difference between predicted management outcomes and actual outcome due to uncertainties in the hydrogeological parameters. Therefore, ensuring the robustness of the optimal solution remains an important issue [175].

Another critical issue being addressed and requiring further attention is the practical need for continued monitoring of the prescribed management strategy implementation in terms of compliance. The other issue highlighted is the temporal deviations between the expected outcomes and actual impacts of an implemented management strategy that need to be monitored utilizing a designed optimal monitoring network [19]. Any management policy needs proper implementation, and therefore, requires compliance monitoring. Appropriate design of the monitoring scheme needs an additional mechanism of feeding back compliance information and information on deviations between planned and actual impacts of a management strategy. Hence, a sequential design and feedback-based methodology consisting of a time varying monitoring network design [22] is a logical option for effective management of coastal aquifers.

6.1. Recommendations

Numerical simulation models should incorporate aquifer heterogeneity, seasonal and transient fluctuation in water bodies, climate change-induced sea-level rise, and tidal fluctuations for better representation of the real-world coastal aquifers. Future research should focus on achieving computational efficiency in coupled simulation–optimization model for coastal groundwater management strategy. For this, accurate and robust surrogate models, properly trained and validated using numerical models, can be utilized to replace computationally intensive numerical simulation models in the management model. In addition, management models can exploit the capability of parallel processing. Moreover, future coastal aquifer management models should address multiple conflicting objectives. For finding optimal solution for management models, more efficient and robust optimization techniques should be explored so that any deviation from the optimal solution can have minimal impact.

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