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# Seawater Intrusion in Coastal Aquifers: A Systematic Literature Review of Modeling and Management Contributions from African

**Ibtissam Medarhri**

*MMCS Research Team, LMAID Laboratory, MINES, Rabat.*

***Abstract:*** *Coastal aquifers are a critical source of freshwater for drinking supply, agricultural irrigation, industrial development, and tourism, particularly in arid and semi-arid regions. However, they are increasingly threatened by seawater intrusion (SWI), which is aggravated by overexploitation, anthropogenic pressures, and the combined impacts of climate change, such as sea-level rise and reduced recharge. This study aims to examine the scientific contributions of African- affiliated institutions to the modeling and control of SWI in coastal aquifers. A systematic literature review was conducted by querying the Scopus database using predefined search string to identify studies that employed numerical, analytical, or experimental modelling approaches to SWI. The selection was restricted to peer-reviewed scientific articles published between 2016 and 2024, written in English, and involving at least one institutional affiliation located in Africa, regardless of the geographical location of the case study. A total of 33 articles meeting these criteria were retained. Each publication was then analyzed based on a structured research framework focusing on the geographic distribution of African affiliations, the mitigation strategies addressed, the role of climatic and anthropogenic pressures, the modeling and validation approaches applied, and the sustainable management strategies proposed. This study provides a comprehensive methodological basis for assessing African research dynamics and guiding future decision-making in coastal aquifer resilience.*

***Keywords:*** *Seawater Intrusion; Coastal Aquifers; Numerical Modeling; African Research Contributions; Mitigation and Management Strategies.*

## I. Introduction

Coastal zones currently host nearly 40% of the global population and represent strategic areas from economic, social, and environmental perspectives. In Africa, many major cities such as Casablanca, Dakar, Alexandria, Tunis, Lagos, and Cape Town rely heavily on coastal aquifers for drinking water supply, agricultural irrigation, industrial activities, and tourism. These hydrogeological systems play a vital role, particularly in semi-arid and arid regions where groundwater often represents the main, if not the only, available resource[1]. However, these aquifers are increasingly subject to multiple natural and anthropogenic pressures, which lead to their gradual degradation. Among the major threats they face, seawater intrusion (SWI) is one of the most critical phenomena [2].

SWI occurs when the marine hydraulic pressure exceeds that of continental freshwater, resulting in the inland migration of the saline wedge. This hydrodynamic imbalance typically arises when natural recharge decreases or when intensive groundwater pumping inverts the natural hydraulic gradient. Once salinized, groundwater becomes difficult to exploit without costly desalination processes, endangering water security, agricultural viability, and the socio- economic resilience of coastal regions[3], [4].



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Climate change is a major driver in the intensification of seawater intrusion. Processes such as sea level rise, decreased precipitation, diminished groundwater recharge, and the increasing frequency and duration of drought events collectively enhance the landward progression of the saline front. Concurrently, anthropogenic pressures, particularly groundwater over-extraction, accelerated urban expansion, the intensification of irrigated agriculture, and the development of hydraulic infrastructures, further destabilize coastal aquifer systems. The combined influence of these climatic and human-induced stressors generates critical intrusion conditions, resulting in significant freshwater depletion and posing a high risk of persistent or potentially irreversible aquifer salinization [5][6].

Given these challenges, the identification, understanding, and control of seawater intrusion mechanisms have emerged as key scientific and strategic priorities. Addressing this issue requires not only a thorough assessment of the underlying hydrodynamic processes but also the selection of appropriate control and mitigation strategies tailored to local aquifer characteristics, including depth, permeability, heterogeneity, gradient, pumping regime, and proximity to the shoreline. A wide range of techniques has been proposed in the literature, spanning physical barriers (e.g., cutoff walls, subsurface dams, coastal land reclamation), hydraulic interventions (e.g., pumping/injection schemes, artificial recharge, optimized discharge regulation), and more advanced integrated systems such as ADCI (Abstraction– Desalination–Cooling–Injection). However, the performance of these strategies is highly dependent on site-specific conditions, underscoring the need for comparative evaluations supported by robust and context-appropriate modeling frameworks [7], [8].

Within this framework, numerical models (e.g., MODFLOW, SEAWAT, MT3DMS), analytical solutions (e.g., Henry and Ghyben–Herzberg formulations), and controlled laboratory experiments serve as essential tools for simulating the evolution of the saline wedge, evaluating the sensitivity of system responses to key parameters (e.g., permeability, dispersivity, recharge rate, pumping depth), and exploring potential management strategies. Nevertheless, the reliability of these models depends on rigorous calibration and validation procedures, which require high-quality datasets and well-defined methodological protocols [6], [10]. Furthermore, meaningful comparisons among different modeling approaches necessitate the use of standardized performance metrics, such as saline intrusion extent, freshwater loss volume, repulsion efficiency, and energy or economic effectiveness [11], [12].

Furthermore, under conditions of increasing water scarcity and rising demand, the development of optimal groundwater management strategies becomes essential. These strategies must not only control seawater intrusion but also ensure the sustainable exploitation of groundwater resources while remaining economically viable. Achieving this objective requires an integrated approach that incorporates hydrological, technical, economic, and socio- environmental dimensions to design adaptive allocation plans consistent with climate constraints and projected demand scenarios [13].

In this context, the present study investigates seawater intrusion in coastal aquifers through five interrelated research questions. First, it identifies which African countries contribute most significantly to the advancement of knowledge, modeling practices, and practical implementation of seawater intrusion control solutions. Second, it evaluates the relative effectiveness of different control and mitigation strategies across varying hydrogeological settings and determines the conditions that optimize their performance. Third, it assesses the influence of climate change and anthropogenic pressures on seawater intrusion dynamics and associated freshwater losses. Fourth, it examines how numerical, analytical, and experimental models can be calibrated, validated, and compared, while identifying the parameters exerting the greatest control over the intrusion process. Finally, it explores which management and allocation strategies are most effective in limiting seawater intrusion under long-term water demand scenarios while ensuring resource sustainability.

Through the exploration of these research questions, this study establishes a comprehensive scientific framework aimed at developing an integrated understanding of seawater intrusion mechanisms, critically evaluating existing mitigation strategies, and generating context-specific recommendations applicable to both African and global coastal aquifer systems increasingly subjected to environmental stressors and anthropogenic pressures.

The remainder of this paper is organized as follows: Section 2 presents the materials and methods of this review, detailing the adopted review protocol. Section 3 reports and discusses the results. Section 4 provides the conclusions and outlines potential directions for future work.

## II. Materials and Methods

This section presents the study selection process and outlines the research questions addressed in this review. The paper follows a systematic literature review approach based on the guidelines proposed by Petersen et al. [14]. This protocol has been widely applied in previous studies [15], [16], demonstrating its suitability for conducting systematic literature reviews.

### 1.1. Data Source and Search Strategy

The candidate papers for this study were retrieved from the Scopus digital library, one of the most comprehensive peer-reviewed scientific databases, including those covering environmental sciences and hydrogeology. To identify research addressing SWI in coastal aquifers using quantitative modelling approaches, the following search string was applied to the title, abstract, and keyword fields:

**("seawater intrusion" OR "saltwater intrusion" OR "saline intrusion") AND ("numerical model" OR "mathematical model")**

The search was designed to identify studies focusing on modeling-based approaches to seawater intrusion. To ensure relevance and quality, the results were limited to peer-reviewed journal articles published between 2016 and 2024, and written in English.

### 1.2. Inclusion and Exclusion Criteria

To align the analysis with the objective of evaluating African contributions to SWI modeling and mitigation strategies, the retrieved articles were further filtered based on the geographical affiliation of the authors. Only studies that included at least one author affiliated with an African institution were retained.

The following criteria were applied:

- **Time period**: 2016–2024, to ensure recent and relevant studies.
- **Document type:** Articles, to guarantee peer-reviewed quality.
- **Language:** English, to ensure consistency of analysis.
- **Geographic relevance:** African institutional affiliation, to highlight African contributions.
- **Thematic scope:** SWI + modeling, numerical, analytical, or experimental.

Following this two-step screening process, a total of 33 articles were retained for full analysis.

### 1.3. Research Question

Each selected article was examined with reference to the five research questions (RQs) guiding this study. Table 1 outlines these RQs together with their underlying motivations.

**Table 1 Research Questions and their Motivations.**

| Id | RQs | Motivations |
|---|---|---|
| RQ1 | Which African countries contribute mos to advancing SWI research and practica implementation? | To map geographic leadership, capacity, and knowledge gaps in Africa, enabling targeted collaboration, funding, anc technology transfer where research and on-the-ground implementation are underrepresented. |
| RQ2 | RQ2: What are the most effective contro and mitigation strategies against SWI? | To identify strategies with the highest demonstrated efficacy and scalability across hydrogeological settings, guiding cost effective, context-appropriate interventions and avoiding trial-and-error deployments. |
| RQ3 | RQ3: How do climate change anc anthropogenic pressures influence SW dynamics? | To quantify the relative and combined impacts of sea-level rise recharge shifts, drought, pumping, and land-use change or intrusion progression, informing robust, forward-looking adaptation pathways. |
| RQ4 | RQ4: How are models calibrated validated, and compared, and whicl parameters exert the greatest control? | To standardize modeling practice (calibration/validation metrics) and identify dominant controls (e.g., K, αL/T recharge, pumping configuration), improving reproducibility, transferability, and decision confidence. |
| RQ5 | RQ5: What management and allocatior strategies can limit SWI while meeting long-term water demand? | To integrate hydrological, operational, and economi considerations into adaptive allocation schemes that simultaneously constrain intrusion risk and satisfy future water needs under uncertainty. |

## III. Results and Discussion

This section presents the results derived from the analysis of the 33 selected papers and discusses them in relation to the five RQs outlined in Table 1.

### 1.4. RQ1: African Contributions to Seawater Intrusion Research and Implementation

The reviewed literature comprises 33 peer-reviewed publications produced between 2019 and 2024, all authored by researchers affiliated with African institutions. As illustrated in Figure 1, Egypt consistently dominates scientific production over the entire period, reaching a peak of six publications in both 2020 and 2021, and accounting for approximately 60.6% of total contributions (20 articles). Tunisia follows with a moderate yet relatively steady output of six articles (≈18.2%), while Algeria and Morocco each contribute three publications (≈9.1%), reflecting more sporadic engagement. Sub-Saharan countries such as Mozambique, Congo, and Kenya appear only marginally, with a single publication each (≈3.0%). These trends are further confirmed in Table 2, which also highlights the limited extent of intra-African collaboration: while Tunisia, Algeria, Congo, and Kenya are involved in at least one regional co-authorship effort, Egypt, the most productive country, shows no collaborative links with other African partners. Considering these findings, the spatial distribution of contributions indicates a concentration of research activity in North Africa, coupled with weak South–South scientific integration. Nonetheless, the collaborative role of Tunisia suggests early signs of emerging regional connectivity.

These findings underscore the need to foster stronger continental research networks to enhance knowledge sharing and strengthen Africa's collective capacity to address seawater intrusion challenges in coastal aquifers.

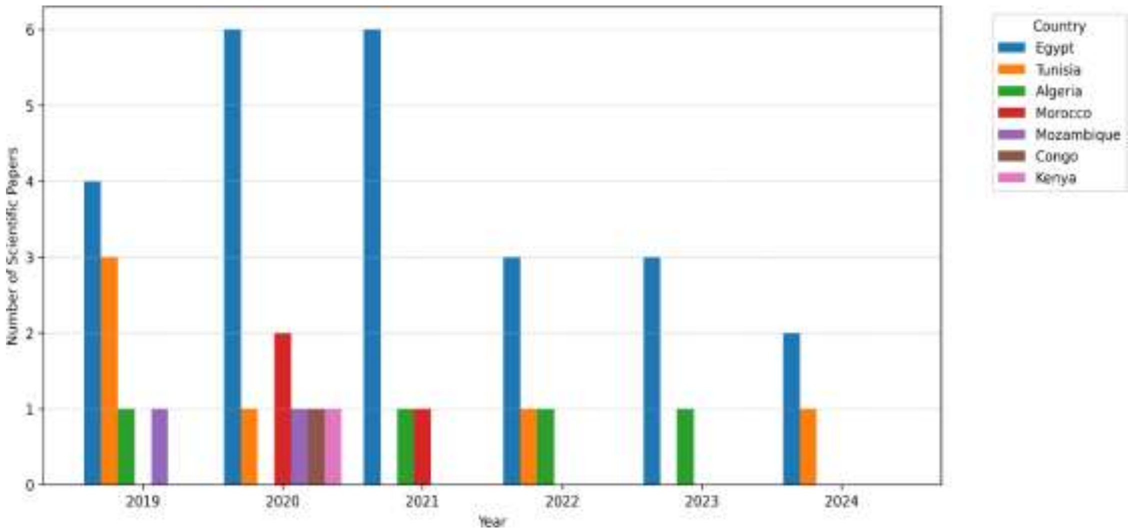


**Figure 1 Temporal evolution of SWI-related research output per African country between 2019 and 2024.**

**Table 2 African Contributions and Collaboration Patterns in SWI Research.**

| African Country | Number of Contributions | Number of Africans Collaborations |
|---|---|---|
| **Egypt** | 20 | 0 |
| **Tunisia** | 6 | 1 |
| **Algeria** | 3 | 1 |
| **Morocco** | 3 | 0 |
| **Mozambique** | 1 | 0 |
| **Congo** | 1 | 1 |
| **Kenya** | 1 | 1 |

### 1.5. RQ2: Control and Mitigation Strategies for Seawater Intrusion

Control and mitigation strategies against SWI in coastal aquifers vary in effectiveness depending on hydrogeological conditions, pumping intensity, aquifer depth, and physical parameters such as permeability and hydraulic gradient. Among proven methods, physical subsurface barriers such as cutoff walls (CW) and subsurface dams (SD) play a key role in blocking or slowing the advancement of the saltwater wedge, especially when installed near the shoreline with deep anchorage and low permeability; in these conditions, seawater repulsion rates can reach up to 72% in conceptual models, with CWs outperforming SDs in most cases [17]. Similar findings are confirmed in sloping aquifers where a penetration depth ratio greater than 0.4 combined with proximity to the coast maximizes intrusion reduction, particularly under high hydraulic gradients and moderate permeability conditions [18]. In shallow aquifers, as demonstrated in a comparative study between Gaza and the Nile Delta, physical barriers, especially subsurface dams proved far more effective than hydraulic methods by significantly reducing saline mass and pushing back the 35,000- ppm front, whereas in deep aquifers hydraulic techniques combining pumping and recharge dominate in efficiency [16]. Coastal land reclamation (CLR) or earth-fill barriers constitute another effective surface-based physical intervention, particularly when a wide, low-permeability embankment with zero slope is positioned along the shoreline and coupled with natural or artificial recharge, resulting in a substantial increase in freshwater storage and a marked retreat of the saline wedge [5]. This efficiency persists even under sea-level rise (SLR) conditions, where progressively wider fills can reduce intrusion by more than 60% in real-case applications such as the Biscayne aquifer [20]. Hydraulic strategies based on regulating pumping and managing the hydraulic gradient are especially relevant in deep aquifers or under strong anthropogenic stress, such as during the filling of the GERD reservoir, where controlled pumping reduction helps preserve the freshwater zone, although it remains insufficient to completely stabilize deep saline fronts [13]. Similarly, in overexploited aquifers such as Skhira (Tunisia), reducing groundwater abstraction and restoring recharge enables recovery of a seaward-directed gradient, limiting intrusion [21]. Optimized well management strategies combining reduced abstraction rates, deeper screened intervals, and appropriately spaced wells in semi-confined aquifers also prove effective for minimizing intrusion while supporting long-term resource sustainability [22]. When combined with artificial recharge, especially through infiltration basins, the effectiveness of controlled pumping is substantially enhanced, particularly when supported by a deep vertical barrier [10], a trend further validated in coastal regions where recharge through retention dams and efficient irrigation systems induces piezometric recovery and saltwater retreat [23]. However, structural–hydraulic combinations remain the most efficient strategies overall: deep cutoff walls coupled with freshwater injection near the saline wedge toe significantly outperform isolated measures, particularly when the wall is installed close to the shoreline and injection is sustained [24]. Mixed physical barriers (MPB), combining a cutoff wall with a semi-permeable subsurface dam, have demonstrated high effectiveness of up to 71% regardless of stratification, exploiting a hydraulic lifting mechanism that pushes back saline water, making them particularly suitable for stratified heterogeneous aquifers subjected to pumping stress or sea-level rise [25]. This efficiency is further confirmed in optimized configurations where a permeable wall placed above an impermeable dam (MPB-3) achieves more than 60% reduction in both homogeneous and heterogeneous conditions [26]. Innovative integrated approaches such as the ADCI method combining abstraction, desalination, cooling, and reinjection of freshwater offer promising results under SLR and pumping pressure conditions, with better performance achieved with colder injected water, although requiring economic feasibility assessments [27]. Moreover, desalination-based management systems demonstrate that adjusting feedwater salinity and optimizing extraction and reinjection depths can drastically reduce stored saline mass [28]. In conclusion, the most effective solutions are those that integrate deep physical barriers with targeted recharge or injection systems, tailored to the geological and hydrodynamic characteristics of the aquifer, while physical structures alone dominate in shallow aquifers, and hydraulic or innovative methods prevail in deep or heavily stressed systems.

### 1.6. RQ3: Impact of Climate Change and Anthropogenic Pressures on SWI Dynamics

Climate change and anthropogenic pressures exert a major influence on the dynamics of saltwater intrusion in coastal aquifers, leading to significant losses of freshwater resources. SLR a direct consequence of global warming, increases hydraulic head on the coastal boundary, pushing the freshwater-saltwater interface landward and intensifying the saline wedge, with estimated freshwater losses of more than 41,162 m³ per kilometer of aquifer for an 84.86 cm sea level rise projected by 2060 [5], while experimental and numerical studies confirm that incremental increases in sea level from 10–40% or 5–10 cm cause substantial advancement of the 0.5 isohaline, sometimes exceeding 130 cm in Henry-type models or reaching up to 506 m in the Biscayne aquifer, demonstrating a nonlinear elongation of the saline wedge and increasing freshwater depletion [6], [17], [20], [27], [26]. At the same time, recharge reduction often caused by declining rainfall due to climate change or hydrologic alterations such as dam construction decreases continental freshwater pressure and favors the lateral penetration of seawater; for instance, the filling of the GERD dam reduces Nile recharge and leads to the landward advancement of the 35,000 ppm isohaline by more than 70 km, reflecting a drastic reduction in exploitable freshwater volume [13], an effect also confirmed by scenarios where a 10–30% reduction in freshwater inflow causes more than 110 cm advancement of the saline front [17], [30]. In semi-arid or arid regions such as Morocco, Algeria, or Qatar, prolonged precipitation decline combined with more frequent droughts limits natural aquifer replenishment and structurally weakens the hydraulic barrier, promoting progressive salinization and the inland migration of the saline wedge [7], [31], [32]. These dynamics are further exacerbated by direct anthropogenic pressures, primarily groundwater over pumping, which constitutes one of the most critical factors altering the hydraulic gradient and aggravating freshwater losses; indeed, excessive pumping induces piezometric drawdown that inverts the natural hydraulic gradient and draws saltwater toward pumping wells, as seen in the Korba aquifer where the drawdown cone reaches 12 m below sea level, leading to an additional 5.15 $Mm^3$/year of seawater inflow [33], or in the Moghra aquifer where a fivefold increase in extraction results in a salinity rise of up to +26.8% and a drawdown of 162 m [34], a phenomenon similarly observed in the Nile Delta and Port Said where salinity levels may reach 40,000 mg/L under intensive pumping conditions [22], [28]. In some cases, the interaction of over pumping with anthropogenic brine disposal further exacerbates salt accumulation in aquifers, as demonstrated in the Nile Delta where a salinity increase of +4.38% per year is recorded due to combined extraction and deep brine injection [28], while in coastal or karstic aquifers such as El Negila or Jijel, increased pumping combined with reduced recharge leads to saline intrusion advances of up to 2 km, or even 4 km when marine pressure rises [23], [35].When climatic pressures (SLR and reduced recharge) and anthropogenic pressures (over pumping) act simultaneously, they produce synergistic effects that generate the most critical scenarios of saline intrusion and freshwater loss; for instance, in the Middle Nile Delta, the combined effect of SLR, recharge reduction, and intensified pumping may push the saline front to 131 km, indicating a drastic reduction in freshwater availability [36], while in the Nile Delta, combined scenarios show an increase in saline mass by nearly 13%, an extension of intrusion up to 66.80 km, and a decrease in freshwater discharge to the sea by more than 61% by 2070 [8]. In areas such as Greater Maputo or Skhira, even when current recharge exceeds demand, future increases in groundwater abstraction along with SLR accelerates intrusion and promote salinity buildup, threatening long-term water resource sustainability [21], [37]. Finally, several studies emphasize the need for integrated management strategies to counter these pressures, such as artificial recharge, optimized pumping regimes, physical barriers, or freshwater reinjection, demonstrating that only adaptive strategies can restore hydrodynamic balance and reduce freshwater losses under the combined impacts of climate change and human activities [10].

### 1.7. RQ4: Calibration, Validation, and Parameter Sensitivity in SWI Modeling

The answer to the question "How can models (numerical/analytical/experimental) be calibrated/validated and compared, and which parameters exert the greatest control over saline intrusion?" relies on an integrated three-step approach: (i) iterative and/or assisted calibration of flow and transport models until key observations are reproduced,
(ii) cross-validation using analytical reference solutions, experimental setups, and independent field datasets, and (iii) multi-criteria comparison of management scenarios and governing parameters. In practice, the calibration of density- dependent models (MODFLOW–MT3DMS/SEAWAT) is most frequently conducted through progressive "trial-and- error" adjustments and, where available, automated optimization (PEST) of hydraulic (K, transmissivity, storage) and transport (dispersivity) parameters, first under steady-state conditions and later under multi-year transient regimes, with explicit fitness metrics (RMSE, $R^2$) based on piezometric levels, TDS, and isochlore positions anchoring parameter credibility prior to scenario testing [5], [16], [32], [33], [37]. Validation, an essential second stage, is typically conducted using canonical analytical benchmarks (e.g., Henry problem), where the accurate reproduction of the 0.5 isochlore confirms numerical robustness, followed by confrontation with independent time-series data (piezometer levels, salinity profiles, intrusion lengths) to demonstrate model transferability to real sites [17], [18], [20], [38]. This methodological foundation is reinforced through strong integration with laboratory experiments, which help identify sensitive parameters (dispersivity, porosity, K) and verify transient behavior (intrusion/retraction, pumping-induced upconing) across stress intensities before transferring the same evaluation framework to natural systems [6], [26], [26], [36]. Scenario comparison gains objectivity when based on physically meaningful, standardized indicators such as intrusion length (toe length, 0.5 or 35,000 ppm isochlores), stored saline mass, repulsion rate, water balance metrics, and, depending on the strategy, energy or operational performance indices (e.g. pumping–injection efficiency), which enable clear ranking of control actions such as cut-off walls, mixed barriers, coastal filling, artificial recharge, or targeted pumping [10], [25],

[27], [28]. Combined pressures sea-level rise reduced freshwater recharge, and intensified pumping significantly modulate saline wedge dynamics: rising sea level shifts the freshwater–saltwater equilibrium, declining continental head reduces inland resistance, and increased abstraction steepens hydraulic gradients, collectively driving deeper and faster intrusion migration, especially under adverse hydrological or aggressive extraction conditions [8], [13], [36]. At this scale, dispersion representation is critical: incorporating distance-dependent dispersivities reshapes parameter dominance (with transverse dispersivity αT governing the 0.5 isochlore location and $\ell_0$ controlling total intruding saline mass), leading to more realistic predictions than models using constant dispersivity formulations, emphasizing the need for scale-specific calibration of mixing laws [40]. Heterogeneity and stratified layering further amplify these effects: vertical K distribution and effective porosity control upconing and lateral migration, requiring 3D modeling and structured sensitivity analyses to evaluate the influence of well depth, spatial configuration, and hydraulic connectivity between layers [34], [35]. In systems tightly coupled to estuarine or marine environments, coastal engineering and local hydrodynamics (channel geometry, current velocity, tides, wind forcing) shape intrusion patterns, while empirically calibrated nonlinear regression models proved reliable for rapid intrusion estimation when validated through numerical simulations and field observations [41], [42]. From an exploitation standpoint, optimally selecting pumping rates, depths, spacing, and well locations (favoring deeper screens and wider spacing) effectively limits TDS rise, particularly when decisions are assessed over multi-decadal horizons and paired with managed recharge strategies [22], [23].Finally, the most effective adaptive management approaches combine hydraulic interventions (well-located artificial recharge) with thermal engineering innovations (injection of cooled freshwater), which increase density/viscosity and enhance saltwater repulsion when supported by thermo-hydrodynamic calibration and cost-benefit assessment[7]. In systems facing long-term anthropogenic stress, increased pumping intensity and reduced recharge progressively lower the inland hydraulic head, submerge the freshwater level below sea level, and promote wedge advancement, thus emphasizing the importance of realistic restrictive pumping scenarios and increased recharge strategies to ensure long-term aquifer stabilization [21].

### 1.8. RQ5: Long-Term Management and Water Allocation Strategies to Limit SWI

To limit seawater intrusion while meeting water demand, the literature emphasizes a multi-layered strategy combining demand control, supply enhancement, and physical/hydraulic protection, guided by modelling and economic optimization. Among infrastructural approaches, coastal landfill embankments (PSB/CLR) with large widths (~615 m), low permeability (<100 m/day), and flat seaward slopes demonstrate strong effectiveness by displacing the saline interface offshore while increasing freshwater storage and generating economic co-benefits in agriculture and tourism [5]. In parallel, decision-support systems based on multi-criteria analysis identify combined solutions such as surface recharge paired with vertical barriers positioned at mid-aquifer length, maximizing saline wedge repulsion under cost- efficient recharge volumes [10]. For highly stressed regions, ADCI (Abstraction–Desalination–Cooling–Injection) systems that reinject desalinated brackish water at lower temperatures (e.g., 5°C) show high technical adaptability under sea-level rise scenarios by improving interface stability and hydraulic balance [27]. These physical interventions are supported by modelling frameworks (e.g., MODFLOW/SEAWAT) that guide adaptive calibration of recharge volumes, hydraulic gradients, and structural permeability in alignment with local hydrogeological conditions [22].

On the supply enhancement side, managed aquifer recharge (MAR) emerges as a core pillar, particularly when spatial prioritization is performed. In arid regions, transforming floodwaters into recharge through technologies such as infiltration basins, injection wells, and agricultural Flood-MAR improves hydraulic heads and reduces reliance on desalination [7]. In semi-arid coastal systems, integrating small retention dams with infiltration facilities and modern irrigation practices helps reestablish positive aquifer balances and slow intrusion under drought conditions [23]. Where recharge availability is limited, optimized pumping configurations including carefully selected abstraction depths, well spacing, and moderate discharge levels allow for controlled extraction while preventing harmful drawdown and saline field expansion, particularly when targeting semi-confined aquifers as resilient abstraction zones [22]. Additionally, hybrid systems that combine embankment structures with multi-source recharge using stormwater, treated wastewater, or brackish desalinated water further enhance resilience by covering peak demands without reigniting intrusion pressures. Multi-criteria evaluation frameworks contribute to investment efficiency by ranking the most viable spatial targets for intervention and avoiding over-designed hydraulic systems.

From the perspective of demand management, controlled reductions in groundwater abstraction prove essential when external constraints reduce natural recharge. During the filling of large upstream reservoirs such as the GERD, proportional reductions in abstraction, accompanied by economic prioritization of domestic over agricultural uses and modernization of irrigation systems, help preserve freshwater cores in coastal aquifers at lower costs than purely structural solutions [13].

Similarly, long-term simulations in North African coastal aquifers show that unregulated pumping intensifies drawdown and reverses hydraulic gradients, while planned extraction reductions restore hydrodynamic equilibrium under adaptive, recharge-aligned allocation schemes [21]. Accordingly, the optimal solution is not a single intervention but a synthesized portfolio incorporating: (i) strategically positioned hydraulic barriers and targeted MAR to elevate hydraulic heads ; (ii) optimized abstraction schemes minimizing drawdown risks
[22]; and (iii) temporally managed demand reductions that align extraction with recharge capacity under climatic constraints, Underpinned by modelling and economic decision tools, this integrated strategy represents the most cost-effective route to simultaneously control seawater intrusion and ensure long-term water supply sustainability across diverse coastal settings.

## IV. Conclusion and Future work

This study provides a systematic evaluation of African scientific contributions to seawater intrusion (SWI) modeling, mitigation, and groundwater management in coastal aquifers. The analysis of 33 peer-reviewed publications (2016– 2024) reveals that research efforts are predominantly concentrated in North Africa, particularly in Egypt and Tunisia, while sub-Saharan participation remains limited. Intra-African collaboration is generally weak, although emerging regional links around Tunisia suggest growing potential for continental research integration. Such disparities indicate the need to enhance transboundary collaboration, promote cross-country capacity building, and extend research efforts to underrepresented regions.

Mitigation strategies reviewed under RQ2 indicate that their effectiveness is highly dependent on hydrogeological heterogeneity, hydraulic stress, and aquifer depth. Structural interventions such as cutoff walls and mixed physical barriers perform best in shallow or stratified systems, whereas hydraulic and hybrid strategies, including managed aquifer recharge and multi-stage systems like ADCI, show promise under deep or heavily stressed conditions and projected sea-level rise. The influence of climate change and anthropogenic activities, as explored in RQ3, demonstrates that sea-level rise, reduced recharge, recurrent drought, and excessive pumping act synergistically to accelerate saline intrusion, often in nonlinear and potentially irreversible ways. These findings underscore the urgency of integrating climate-informed and demand-responsive groundwater governance.

Regarding modeling practices (RQ4), numerical approaches dominate literature, with calibration frequently conducted through trial-and-error rather than automated sensitivity-based optimization. While analytical and experimental validations are occasionally incorporated, standardized cross-validation and uncertainty quantification remain underutilized. Long-term management strategies assessed in RQ5 emphasize the importance of combining structural defenses, hydraulic regulation, managed recharge, and demand control within decision-support frameworks; however, economic viability, energy efficiency, and social acceptability require greater consideration.

In future work, we will focus on three main directions. First, we will conduct a deeper comparative assessment of the most widely used SWI models to evaluate their computational efficiency, sensitivity to parameter uncertainty, and suitability across different African hydrogeological settings. Second, we will explore advanced calibration and optimization techniques, including high-performance computing frameworks, to improve model convergence and reduce simulation time under complex climate and pumping scenarios. Third, we plan to investigate the applicability of artificial intelligence and machine learning techniques for intrusion forecasting, parameter estimation, and early- warning detection, particularly in data-scarce coastal regions.

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