

Stochastic Simulation of Saline Intrusion in the Coastal Aquifer of Saloum, Senegal

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Abstract

In the Saloum region of central-western Senegal, water needs are essentially met by tapping an underground aquifer associated with the sandy-clay formations of the Continental Terminal, in contact with both the ocean to the west and the highly saline waters of the Saloum River to the north. In this estuarine and deltaic zone with its very low relief, the hydraulic loads in the water tables are generally close to zero or even negative, creating a reversal of the natural flow and encouraging saline intrusion into this system, which makes it very vulnerable. This study concerns the implementation of a numerical model of saline intrusion to provide a better understanding of the vulnerability of the water table by analyzing the variability of the freshwater/saltwater interface. The Modflow-2005 code is used to simulate saline intrusion using the SWI2 module, coupled with the GRASS (Geographic Resources Analysis Support System) software under the Linux operating system with the steep interface approach. The probable expansion of the wedge is studied in three scenarios, taking into account its position relative to the bedrock at 1 m, 5 m and 10 m. Simulations carried out under imposed potential and river conditions, based on variations in groundwater reserves using two effective porosity values, 10^{-1} and 10^{-2} , show that the water table is highly vulnerable in the northwest sector. The probable expansion of the wedge increases as the storage coefficient decreases and is more marked with river conditions in the areas surrounding the Saloum River, reaching 6 km with a probability of 1. The probability of the wedge reaching a certain degree of expansion decreases from 1 to 0.5, and then cancels out as it moves inland. The probable position of the wedge is limited to 500 m or even 1 km depending on the corner around the coast to the southwest and in the southern zone. This modelling, carried out under natural conditions, will be

developed further, taking into account climatic parameters and pumping from wells and boreholes.

Keywords

Saline Intrusion, Stochastic Modelling, Modflow, SWI2, Grass GIS, Aquifer, Saloum, Senegal

1. Introduction

Coastal aquifers constitute the main source of renewable freshwater in many arid and semi-arid regions around the globe. Seawater intrusion is already a major concern in many coastal aquifers because of the contamination of groundwater resources [1]. The fresh groundwater resources become unsuitable for human consumption with a mixture of 2% - 3% salinity and become unsuitable over 5% for any other use [2]. Density differences between freshwater and seawater together with intense pumping cause seawater to intrude inland along the aquifer bottom. Saltwater intrusion in coastal aquifers depends also on the distribution of hydraulic properties and on climate [2] [3] [4]. The problem is especially severe in arid and semi-arid zones where alternative water resources are scarce [4]. Seawater intrusion, hence, reduces the freshwater storage in coastal aquifers and in extreme cases can result in the abandonment of freshwater supply wells. Remediation of groundwater could be very costly and could take a long time depending on the source and level of salinization. Essink [5] quotes that almost 50% of the world's population lives within 60 km of the shoreline. The above fact enhances the necessity of integrated groundwater resources management in coastal aquifers, as the phenomenon of seawater intrusion poses serious social as well as economic threats to the 0 of coastal zones. In the Saloum region, salinization is one of the most serious long-term environmental problems. It mainly affects the shallow groundwater resources, large areas of arable land with the formation of saline barren soils in the vicinity of the estuary system and the economically valuable mangrove ecosystem, which plays a vital role to the majority of this rural population [6]. As a result, groundwater resources should be protected from saltwater intrusion, using suitable measures. Seawater intrusion models are very efficient tools for coastal aquifer management and protection [7]. This paper discusses a numerical study of seawater intrusion in the Saloum unconfined aquifer (mid-west of Senegal), where groundwater stored in the Continental Terminal (CT) formations is the only source of freshwater for domestic and pastoral water supply. It is essential to model the extent of seawater intrusion and to locate the saltwater interface taking into account heterogeneity and parameter uncertainty. The seawater intrusion problem has been investigated by many researchers (a recent series of works highlighted in a special issue of Hydrogeology Journal: Saltwater and freshwater interactions in coastal aquifers, 2010, Vol 18, No 1) using various approaches and different methods. Two general approaches, *i.e.* the sharp interface approach and the transition zone (dis-

persion) approach, have been used to analyze seawater intrusion in coastal aquifers. The authors [8] and [9] introduced the sharp interface approach. The freshwater and saltwater are considered immiscible. This simplification allows for the treatment of the problem numerically [10] in a very efficient way. Albitar [11] also used a sharp interface model to investigate on a 2D horizontal section the impact of multi-Gaussian heterogeneity on Seawater Intrusion. The sharp interface approach is based on the simplification of the thin transition zone relative to the dimension of the aquifer. The disperse interface approach explicitly represents a transition zone or a mixing zone of the freshwater and saltwater within an aquifer due to the effects of hydrodynamic dispersion [7] [12]-[15]. Two-dimensional and 3D models have been developed in both approaches to simulate the steady-state or unsteady-state problem of seawater intrusion [12] [16]-[20]. We choose here the vertically integrated sharp interface approach, with two immiscible fluid regions (freshwater and seawater). This type of approach facilitates regional-scale studies of coastal areas. Although it does not provide information about the nature of the transition zone, the sharp interface simulator captures the regional flow dynamics and predicts the response of the freshwater/saltwater interface to applied stresses [10]. We use this model to analyze the effects of aquifer variability on the saltwater wedge in the plan view, based on large numerical simulations of 2D seawater intrusion in randomly heterogeneous unconfined aquifers.

2. Study Area

The coastal aquifer studied is the Saloum aquifer, located in the central-western region of Senegal, which supplies most of the population's water needs. The study area covers approximately 5000 km² (Figure 1). The region is bounded by the Atlantic Ocean on the west side. The hypersaline Saloum River forms its northern boundary and the Gambia River its southern boundary via its tributaries, the Djikoye and Baobolon Rivers. The main cause of the hyper-salinization of the Saloum River and the accumulation of halite crusts in the flat-lying alluvial deposits within the drainage basin is the intense evaporation of surface water.

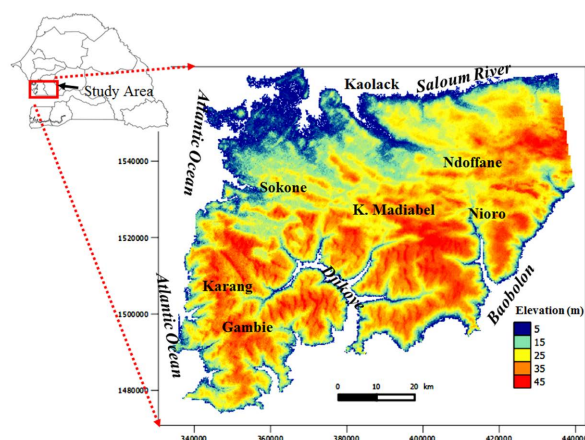


Figure 1. Location map of the study area.

The study area has an altitude of between 0m and 40 m. It has a tropical climate with annual rainfall varying between 400 and 800 mm and potential evapotranspiration from 1900 - 2400 mm/year. The average ground temperature varies between 25°C and 30°C. The geology of the study area, like that of the rest of the basin, describes a relatively simple overall pattern defined by a vast west-dipping monoclinical structure with fracturing that can be very significant in some places [19]. The formations encountered in the oil and water drilling carried out in the study area show that the geology comprises, from bottom to top: the Maastrichtian, Paleocene and Eocene formations and finally the Oligocene and Mio-Pliocene formations known as the Continental Terminal (CT) and covered by Quaternary dune sands. The geological formations studied here are those of the CT. The Terminal Continental is represented in the Saloum by terrains ranging from the Oligo-Miocene to the Pliocene. It is generally unconformable with the oldest formations and is often covered by the Quaternary. These formations show the marks of intense ferralitic alteration, the clearest expression of which is the presence, in addition to concretions and ferruginous cuirasses, of the kaolinite formation [21]. This forms the boundary between the CT and Quaternary periods, which are generally made up of sandy clays [22]. Lateral and vertical variations in facies are frequent. There is a transition from more or less clayey sandstone formations to more permeable lateritic levels [23]. In some areas, particularly to the west and southwest, compact clays sometimes overlie the bedrock. These clays are probably Miocene in age as they are unconformable with the nummulite limestones near Sokone to the west of the area [24]. Examination of the drilling logs reveals an irregular and discontinuous alternation of several models of detrital sediments ranging from coarse to fine sand, clayey sand and sandy clay interspersed with discontinuous levels of clay; a batch of clayey sandstone, clay and ferruginous sands. This ensemble is surmounted by a highly indurated cuirass horizon and an indurated gravelly ferruginous horizon. Beige sands with a low clay content from the Quaternary are encountered almost constantly at the top. These CT formations contain a water table fed mainly by rainwater from the surface. Various structures (wells, boreholes) are used to tap the water at varying depths of between 5 and 45 meters. The permeability coefficient (K) of the aquifer varies widely between 0.2×10^{-4} and 3.2×10^{-2} m·s⁻¹. The lowest hydraulic conductivity values are found in the north and north-west of the zone, and the highest in the south and center of the system. This spatial variability in hydraulic conductivity values is due to the heterogeneity of the facies and above all to the lateral and vertical variations in facies [23] that characterize the aquifer system. In fact, the southern and central part of the system is characterized by sandy facies (coarse to medium sand) with sandstone channels, while in the northern to north-western and southern zones fine to clayey sands dominate. The storage coefficient (S) values obtained from the test pumping are few and varied, ranging from 3.2×10^{-4} to 4.0×10^{-1} . The morphology of the piezometry has remained the same since 2002 and is characterized by two main elements: a groundwater mound-oriented NNE-SSW (head > 20 m) located in the plateau area and a groundwater trench that collects part of the flow derived from the ground-

water mound and the flow from the Saloum River. In the southern part of the system, groundwater flow is divergent and discharges respectively to the Bandiala towards the sea and to the Djikoye (a tributary of the Gambia River).

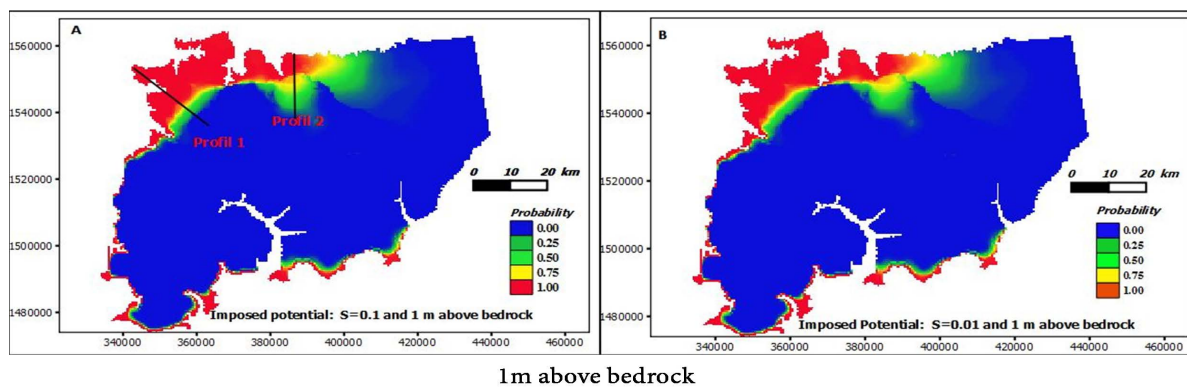
3. Materials and Methods

The problems associated with marine intrusion into coastal aquifers are not new. Numerous codes are used to model saline intrusion into coastal aquifers [25] [26] [27]. In this work, the Modflow-2005 code is used to simulate saline intrusion using the SWI2 module [28] under Grass (Geographic Resources Analysis Support System) with the steep interface approach. The Sea Water Intrusion Module (SWI2) vertically integrates three-dimensional variable-density groundwater flow and salt-water intrusion in coastal multilayer aquifer systems under MODFLOW-2005 [29] [28]. The approach is based on the Dupuits approximation in which the aquifer is vertically discretized into zones of different densities, separated from each other by defined surfaces representing interfaces or iso-surfaces [30]. The main advantage of using the SWI2 module is that fewer cells are required for the simulations as each aquifer can be represented by a single layer of cells. This reduction in the number of model cells and the elimination of the need to solve the advection-dispersion transport equation [28] [30] provides significant time savings for model execution. This makes the SWI2 module very suitable for stochastic modeling. The simulation of the variation of the density (salinity) distribution is always done in transient [28] [31]. The structural basis used in this simulation is based on the results of the steady-state model [32]. In this model, the study domain is discretized by a regular 500 m square mesh with 63648 meshes distributed over 204 rows and 148 columns. The vertical discretization is based on a monolayer bounded by the natural terrain at the top and the impermeable clay layer at the base obtained with the work of [24] and [33]. Thus, the various K values obtained are in phase with the predominantly sandy and sandy-clay facies of the different soils and oscillate between 10^{-2} and 10^{-5} $\text{m}\cdot\text{s}^{-1}$ and that of conductance between 10^{-3} and 10^{-7} $\text{m}^2\cdot\text{s}^{-1}$ [32]. The storage coefficient values required for transient calculations were also implemented. Given the limited information available on this parameter, an average value of 10^{-2} was applied. The duration of the simulation chosen to study the transient regime is 300 years. This simulation was carried out over such a long period to allow the model to stabilize properly before comparing the measured data with the simulated data. The main input to the SWI2 module is the initial position of the Zéta surface (interface surface) referring to the bedrock [28]. In order to reduce calculation times, this surface is smoothed, bearing in mind that a discontinuous surface cannot undergo abrupt changes in gradient. Simulations are carried out under imposed potential and river conditions, in an attempt to determine the vulnerability of the aquifer to saline intrusion. The probable expansion of the wedge is studied in three scenarios, taking into account its position relative to the bedrock at 1 m, 5 m and 10 m. The sensitivity of saline intrusion to effective porosity is also tested using two values, 10^{-1} and 10^{-2} .

4. Results and Discussions

4.1. Results

The maps of the probability of expansion of the salt wedge obtained (Figure 2 and Figure 3) show that, whatever the type of boundary and the value of the effective porosity, the aquifer is more vulnerable in its northwestern part. The probable expansion of the salt wedge increases as the storage coefficient decreases and is more marked by river conditions in the areas surrounding the Saloum River. The expansion of the wedge varies according to its position in relation to the bedrock. The probability of the wedge reaching a certain degree of expansion decreases from 1 to 0.5, and then disappears as it moves inland. The probable position of the wedge is limited to 500 m or even 1 km depending on the corner around the coast to the southwest and in the southern zone. The wedge does not appear in river conditions at Djikoye and Baobolon (Figure 3). The analysis of the probable intrusion maps with the imposed potentials shows that the area affected by salt intrusion in the northwest corner with a probability of 1 is almost identical for a storage coefficient of 10^{-1} (Figure 2(A), Figure 2(C) & Figure 2(E)). The salt front can be found up to 12 km inland. When the effective porosity decreases, the probable position of the wedge in imposed potential is approximately 13.41 km, decreasing as a function of the position of the wedge in relation to the bedrock to reach 12.24 km (Table 1). In this northwestern sector, the progress of the wedge can reach 17.90 km at 1 m above the bedrock with a probability of 0.75 and 19.20 km with a probability of 0.5. In the vicinity of the Saloum, still under imposed potential conditions (Figure 3(A1), Figure 3(C1) & Figure 3(E1)), the salt wedge appears at a maximum of 3 km with a storage coefficient of 10^{-1} and 3.13 km with 10^{-2} at 1 m above bedrock. This expansion can become significant, reaching 8.00 or even 8.66 km, but with a probability of 0.50 (Table 2). Under river conditions, although the degree of expansion is similar to that of the potential case imposed at $S = 10^{-1}$, the expansion is very great inland, with a storage coefficient of 10^{-2} reaching 5.64 km and with a probability of 0.5, a distance of 16.31 km inland (Table 2). In the northwest sector, under river conditions (Figure 3(B1), Figure 3(D1) & Figure 3(F1)), the wedge is more advanced than under imposed potential, with an average increase of 3 km (Table 1).



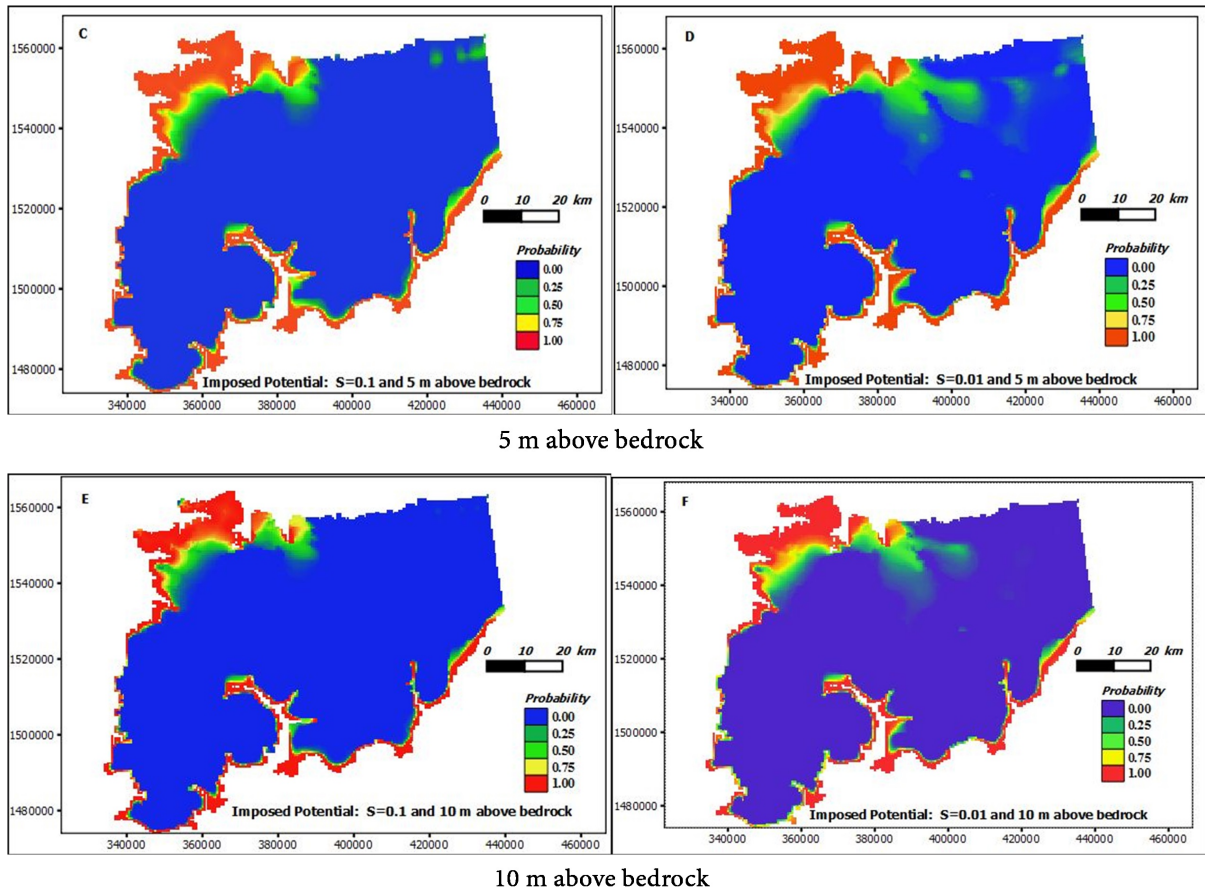
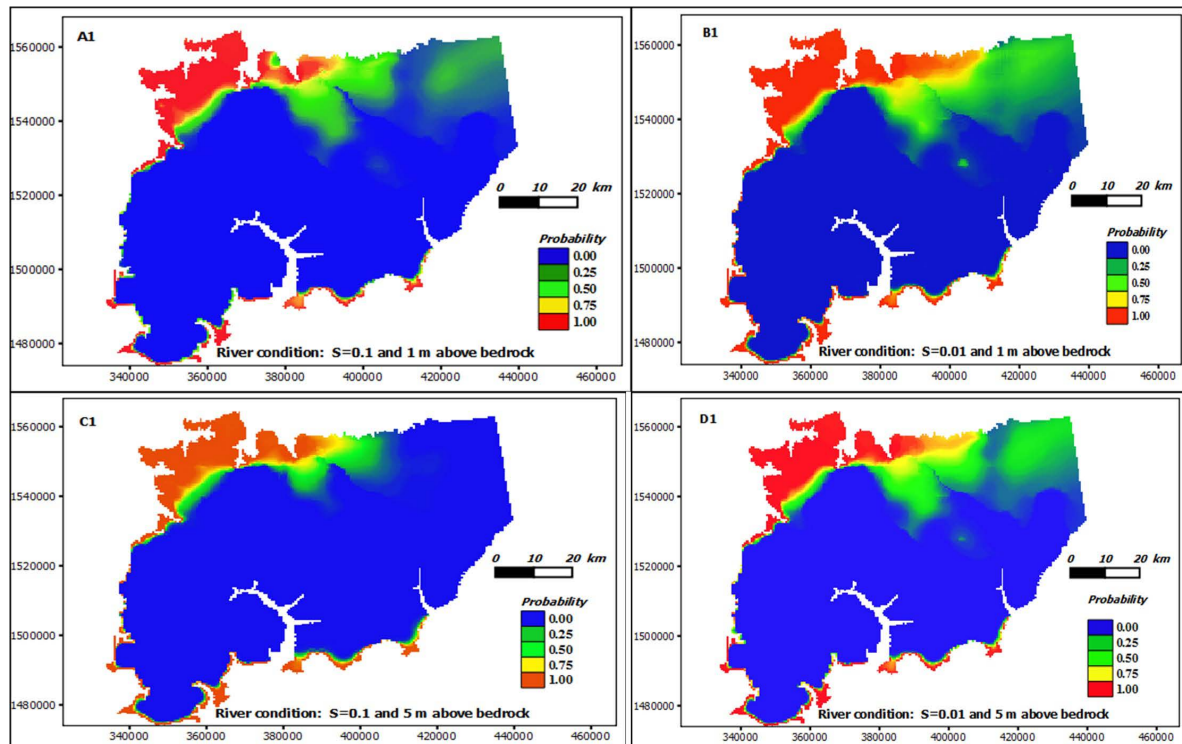


Figure 2. Probable expansion of the salt wedge under imposed potential.



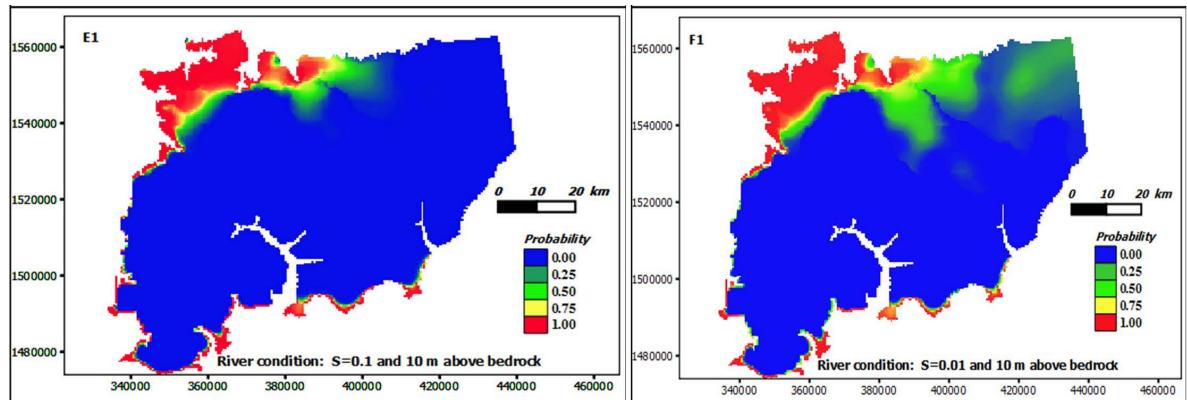


Figure 3. Probable expansion of the salt wedge in river conditions.

Table 1. Probable distance (in km) of penetration of the wedge in relation to the sea from northwest to southeast. (See profile 2 in Figure 2)

Above bedrock position (m)	Constant Head					River Condition							
	1	5	10	1	5	10	1	5	10	1	5	10	
Storage coefficient	0.1	0.01	0.1	0.01	0.1	0.01	0.1	0.01	0.1	0.01	0.1	0.01	
Probability	1.00	12.00	13.41	12.00	12.93	12.00	12.24	15.97	18.20	15.46	17.70	14.01	13.38
	0.75	15.20	17.90	15.00	16.80	14.98	16.30	18.93	20.50	18.30	19.88	18.24	18.55
	0.50	17.10	19.20	17.00	18.46	17.00	17.80	19.92	21.39	19.02	20.70	19.01	19.91

Table 2. Probable distance (in km) of penetration of the wedge in relation to the Saloum River from north to south. (See profile 1 in Figure 2)

Above bedrock position (m)	Constant Head					River Condition							
	1	5	10	1	5	10	1	5	10	1	5	10	
Storage coefficient	0.1	0.01	0.1	0.01	0.1	0.01	0.1	0.01	0.1	0.01	0.1	0.01	
Probability	1.00	3.00	3.13	2.60	1.24	1.02	0.97	5.00	5.64	3.82	3.92	1.80	2.73
	0.75	6.00	6.30	5.08	5.90	4.25	4.90	8.90	9.32	6.98	7.40	5.08	5.48
	0.50	8.00	8.66	7.50	8.11	5.20	6.79	12.50	16.31	10.83	12.60	8.87	10.04

4.2. Discussions

The modelling of the abrupt interface is being developed to identify the expansion of the salt wedge. The northwestern part is the most vulnerable, whatever the boundary conditions applied. The significant loss of water through evaporation due to the shallowness of the water table, combined with the inflow of water into this sector, maybe at the origin of this phenomenon. With the very low relief, the hydraulic loads are generally close to zero or even negative, creating a reversal of the natural flow, resulting in a manifestation of saline intrusion on the coastal fringe in this sector. The decrease in effective porosity resulting from a reduction in reserves can lead to a breakdown in the balance between fresh and salt water, resulting in the advance of the salt wedge. The piezometry shows a connection between the aquifer and the Saloum River [34] and the conductance applied is at the origin of the significant expansion of the salt wedge. Inflows are

greater as the freshwater reserve decreases. In the Djikoye and Baobolon rivers to the south, the absence of saltwater wedge expansion can be explained by the conductance values but also by the draining effect of these two effluents on the water table. In the northwest zone, the greater expansion of the wedge under river conditions is based on a balancing effect with the water outflows noted to the south. In the rest of the zone, as we are in natural conditions, the contribution of the marine intrusion remains moderate. This position of the wedge could be affected if pumping is applied.

5. Conclusion

This work made it possible to implement the stochastic model simulating the vulnerability of the Saloum aquifer on the basis of probabilistic distributions of the abrupt interface. Simulation of salt intrusion has identified the likely expansion of the salt wedge. The expansion of the wedge varies according to its position in relation to the bedrock and can reach varying degrees of expansion depending on the different sectors. The probable position of the wedge is limited to 500 m or even 1 km depending on the corner around the coast to the southwest and in the southern zone. Modelling has shown that the northwestern part is the most vulnerable, whatever the boundary conditions applied, with a probable position of the salt wedge that could exceed 12 km. At the current stage of research, this work represents a starting point for the study of saline intrusion in this sector. This modelling needs to be developed further, taking into account more detailed parameters and variables (climate and pumping).

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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