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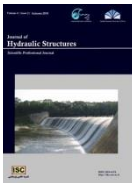

Laboratory investigation of the removal pattern of salinity from the base of coastal reservoirs during the first water impounding

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Abstract

Coastal reservoirs, located near the shores of either seas or oceans, play a crucial role in storing fresh water for residents in coastal regions. Enclosed by concrete walls to prevent seawater intrusion, these reservoirs face challenges due to porous ground layers and direct connections to the sea. This laboratory study delves into the initial stages of optimizing coastal reservoirs, with a specific focus on desalination during the initial water intake process. The investigation highlights that salt removal primarily occurs in the ecotone bed during the initial bed scouring process. After bed leaching in this section and its extension to a specified depth, leaching initiates from beneath the main reservoir area, connecting to the ecotone scouring area. Examination of the shape and pattern of the washed area reveals that the depth of the scouring area surpasses its length along the bed. This study contributes valuable insights into the desalination potential of coastal reservoirs, particularly during the critical phase of water intake, offering a foundation for further research and development in sustainable water supply practices for coastal communities.

Keywords: Coastal Reservoirs, Leaching, Laboratory Model, Ecotone Zone.

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1. Introduction

In recent years, rapid economic development has exacerbated the water scarcity problem, especially in coastal plains [1], where meeting the demand for freshwater can be challenging [2]. This situation becomes more complex with the irregular spatial and temporal distribution of freshwater resources in these areas. The flow rate (or flood) in coastal plains is usually high, but the river network has limited capacity to retain this freshwater resource [3].

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A Coastal Reservoir (CR) is a unique structure constructed at an estuary, bay, inlet, or sea (where a river joins the sea) to store a portion of excess water during floods [4]. The first coastal reservoir still in operation was built approximately 1185 years ago in China [5]. A more precise definition of coastal reservoirs could be as follows: a reservoir within a large aquatic zone stores a liquid that differs in physical, chemical, and biological characteristics from external water and is intended for a specific purpose. For example, storing fresh water in a sea reservoir implies a difference in salinity between the water inside the reservoir and the seawater [6] such as land ownership or submergence of forests [4].

For an inland reservoir, the most critical criteria are the selection of the dam site and the dam height, as these determine storage capacity, total cost, etc. Other factors such as spillways, shipping routes, and hydroelectric stations have less significance. The key considerations for CR design include the following: Firstly, the CR inlet should be ideally located to facilitate the sustainable and high-quality conveyance of water with minimal salinity in dry years. Secondly, in selecting the CR site, the overall construction cost and the confined volume of the body of water should consider the maximum flow rate and minimum cost. For an offshore CR on a flat seabed, a circular embankment with the minimum dike length is required, and the length of the dike should be determined at the minimum cost [6].

In coastal reservoirs, salt transfer processes vary throughout the different operational stages over the reservoir's lifespan. Generally, there are two major stages: in the initial stage after construction, desalination is predominant, and in the operational phase, seawater intrusion becomes a serious threat. Both desalination and the intrusion of seawater, if not properly addressed, can significantly impact the performance of coastal reservoirs [7].

Yang and Lin patented coastal reservoirs using soft dams to separate, prevent, and protect against external pollution. They concluded that the use of coastal reservoirs could significantly increase river runoff and water supply in these two areas, improving water quality. This is because the patented technology utilizes natural resources in an environmentally sustainable manner for ecosystem use [8]. Liu and colleagues examined the integrated functions of coastal reservoirs and found that water-pumping pipelines in upstream of dams or storage reservoirs could be installed simultaneously with downstream pipelines, which is much more convenient than internal reservoirs. Additionally, coastal reservoirs can be located away from environmentally sensitive areas, contributing to environmental protection. For a more rational use of water, coastal reservoirs may offer a cheaper and more sustainable option in future planning [9]. Hong and colleagues analyzed the efficiency of water quality improvement by constructing constructed wetlands (CW) to prevent pollution entry into the Hwaseong coastal reservoir. They correlated the input and output flow rates with required chemical oxygen demand (COD) and total nitrogen (TN) loads. The flow volume to CW during non-rainy days was less than the output flow, indicating that CW effectively reduces runoff volume [10].

Since the deployment of coastal reservoirs has recently gained more attention, existing works predominantly feature general recommendations and justifications for constructing these reservoirs. Consequently, details such as the salt displacement in these reservoirs from the sea and river sides have not been thoroughly investigated in past studies. Therefore, the current research focuses on laboratory experiments to examine the leaching pattern and movement of salts from the bottom and bed of the coastal reservoir after the initial water intake. The analysis will specifically address how the salts are displaced from the reservoir bottom towards the sea.

2. Materials and Methods

2.1. Laboratory model

To investigate salinity changes in the bed material of coastal reservoirs during initial water impoundment, we designed and constructed an experimental setup. The system consisted of a Plexiglas sandbox measuring 150 by 60 by 10 centimeters. This setup was partitioned into three sections: a 70-centimeter section for seawater, a 50-centimeter section for freshwater, and a 30-centimeter Ecotone reservoir serving as a barrier between saltwater and freshwater. To mimic a porous environment, we utilized standard glass beads with particle sizes ranging from 500 to 710 micrometers.

To maintain a constant discharge of freshwater and saltwater into the respective reservoirs, dedicated tanks were positioned 0.5 meters above the top of the model. Saltwater, prepared in the main ground tank to achieve the desired concentration, was pumped into the top tank. The installation of a spillway around the top tank enabled the maintenance of a constant head in the relevant tank. Similarly, freshwater was introduced into another top tank. Consequently, salt and freshwater were supplied to their designated sections within the experimental setup.

To explore the influence of water levels in individual sections of the Coastal Reservoir (CR) system on salinity variations in the base material, a series of experiments was devised. Various water levels were selected for each partition. Saltwater or freshwater was discharged from the corresponding top tank, and upon reaching a specific level, any excess water was discharged through an adjustable weir. Subsequently, the water levels in each section were stabilized at the desired levels, allowing water seepage to flow from higher-level partitions to lower ones. As a result, the seepage flow-induced changes in the salinity of the base materials over time. To mitigate seepage volume between the freshwater reservoir and seawater, and vice versa, two cutoff walls were installed beneath the boundaries of the Ecotone. The details of the constructed laboratory model are shown in Figure 1.

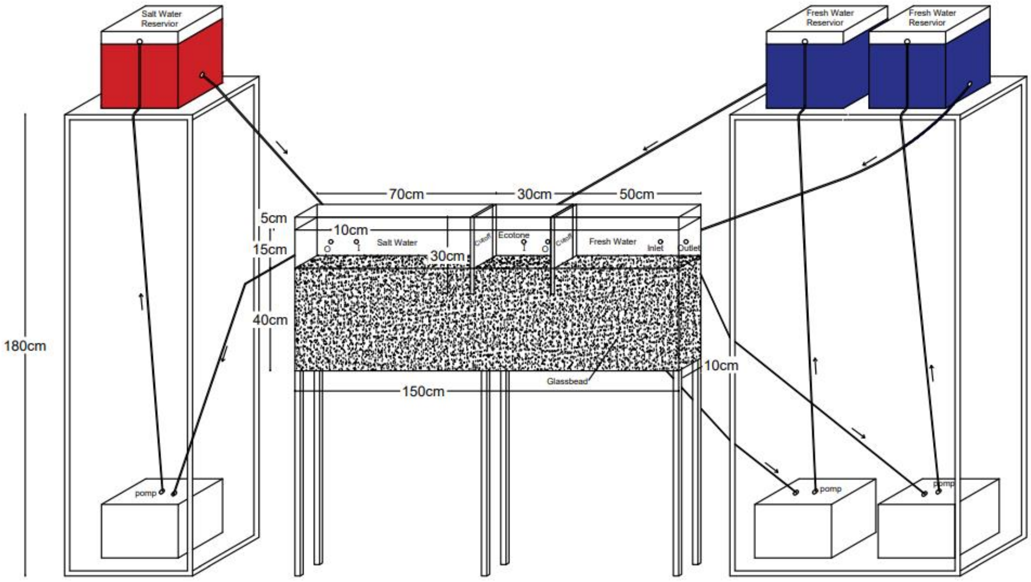

Figure 1. Geometry of the laboratory model

The glass beads were pre-washed with deionized water to eliminate any contamination thoroughly. The geotechnical parameters of the glass beads are presented in Table 1.

Table 1. physical properties of glass beads used as bedding material on the bottom of the reservoir

Physical Properties	
Hardness	6-7 Mohs
Grain Shape	round
Melting Point	730 ˚C
Specific Gravity	2.5 g/cm^3
Apparent Density	1.6 g/cm^3
Porosity	0.558
Void Ratio	35.8%
Density of Solid Grains	2.5
Saturated Humidity	0.22
Specific Gravity of Saturation	1.96
Specific Dry Weight	1.603
Specific Weight for Immersion	0.962
Dimensions	500-710 µm

After adding the required amount of glass beads into the sandboxes and homogenizing them, the environment under study was saturated with saltwater at a specific concentration. The salinity concentration used for the seawater reservoir was equivalent to the salinity of open seas, approximately 35 grams per liter. The freshwater reservoir and the ecotone reservoir were filled with tap water. Considering the salt concentration used for seawater, its density was 1.024 grams per liter. To maintain a constant water head in the air chambers, fixed overflow outlets were incorporated, and water with a constant flow rate was pumped into the lower reservoirs. This way, excess water was discharged through the overflows from the air chambers, and the water level remained constant. This technique was employed to establish a stable flow from the air tanks to different sections of the laboratory system. A yellow food dye was used to trace the seawater. Salinity measurements were taken throughout the experiment to ensure a constant salt concentration in the seawater reservoir, and changes in the density of the ecotone and coastal reservoir were recorded. A water head of 15 centimeters was considered in the coastal reservoir and ecotone reservoirs, and for the specified range of seawater, 14 centimeters were considered. Discharge valves installed at specific levels maintained a constant water head in these areas.

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2.2. Numerical Model

In this study, the SEEP/W and CTRAN/w a module of GeoStudio-2022 software was used for numerical simulation. SEEP/W is an advanced computational tool based on the finite element method, which is employed for modeling seepage and distribution of pore water pressure in porous media such as soil and rock. This software enables the modeling of both simple and complex problems through specialized formulations and complex algorithms. By utilizing numerical methods, SEEP/W can accurately simulate the flow of water among soil particles and analyze the physical process [11]. Based on the model properties and problem circumstances free convection solute effect, solute transfer advection-dispersion with water transfer Were selected to investigate the mass of solute transportation in the model. The method of selecting the model inputs was based on the physical properties of the glass beads selected in the laboratory model, as shown in Table 1.

The boundary conditions are determined based on laboratory conditions, and their details are provided in Table 2.

Table 2. Assumptions for the boundary conditions in the numerical model

Boundary Conditions	CR	Ecotone	Saltwater	
Category: Contaminant	0 kg/m³	0 kg/m³	35 kg/m³	Solute Concentration
Color	Green	Orange	Red	
Category: Hydraulic	0.55 m	0.55 m	0.54 m	Water Total Head
Color	Blue Navy	Sky Blue	Red	

Also, Figure 2-a shows the image of the model after applying the hydraulic head boundary condition, and Figure 2-b shows the model after applying the contaminant (salinity) condition.

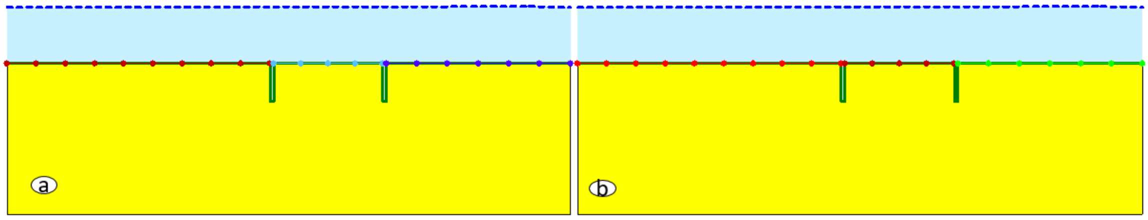

Figure 2. Apply the boundary condition: a (hydraulic BC), b (contaminant BC)

3. Results and Discussion

Freshwater and seawater are two distinct water bodies with different physical and chemical properties. However, in coastal reservoirs, with the creation of a height difference, freshwater can move from the porous bed towards the seawater. When freshwater is positioned at a higher elevation than the seawater in the sea, the movement of freshwater towards seawater occurs due to the energy difference, resulting in a gravity flow. In the current experiment, with a bed fully saturated with saltwater, the difference in water level between the freshwater reservoirs (ecotone and CR) and the seawater creates a hydraulic gradient. Since in both modeled areas for ecotone and the coastal reservoir, freshwater is positioned 1 cm higher than seawater ($h_{CR}=h_{eco}>h_{sw}$), the hydraulic pressure designed in ecotone and CR is greater than that of the seawater reservoir. The average gradient of the flow created from the freshwater reservoirs towards the seawater was calculated using Darcy's law. The gradient values for each of the reservoirs are presented in

Table 3. Accordingly, freshwater flow from the ecotone and the freshwater reservoir occurs as leakage from the bed. Due to the proximity of the ecotone area to seawater, initially, the flow occurs from this area towards seawater. As shown in Figure 3-a, bed leaching in the ecotone area has occurred due to this flow. Subsequently, the infiltrated freshwater flow from the bed of the freshwater reservoir joins the flow from the ecotone and reaches the washed area in the bed of these two sections, as shown in Figure 3-b.

Table 3. hydraulic parametric of Freshwater, Seawater, and Ecotone Reservoir

Water Level (cm)			Hydraulic Head (cm)			Hydraulic Gradient	
Coastal Reservoir	Ecotone	Seawater Reservoir	Coastal Reservoir	Ecotone	Seawater Reservoir	Seawater Reservoir/ Coastal Reservoir	Seawater Reservoir/ Ecotone
15	15	14	15	15	15.174	59	25.33

After completely leaching the ecotone bed from seawater, the downward movement of the infiltrated flow from the CR zone is stopped. After passing around the wall of the water barrier, it enters the seawater reservoir from the nearest distance, as shown in Figure 3-c. Meanwhile, the infiltrated flow from the bed of the freshwater reservoir continues to join the inflow from the ecotone, increasing the intensity of the leakage flow from freshwater to seawater. Due to the limited cross-sectional flow area behind the second water barrier (near the seawater reservoir), the leakage flow is diverted downwards and causes the expansion of the washed area, as shown in Figure 3-d. Eventually, after sufficient space for the passage of the leakage flow is created behind the second water barrier, the downward movement of the infiltrated freshwater from the freshwater reservoir and ecotone is stopped. With the passage of time, no significant change in the washed area of the bed is observed, as shown in Figure 3-e.

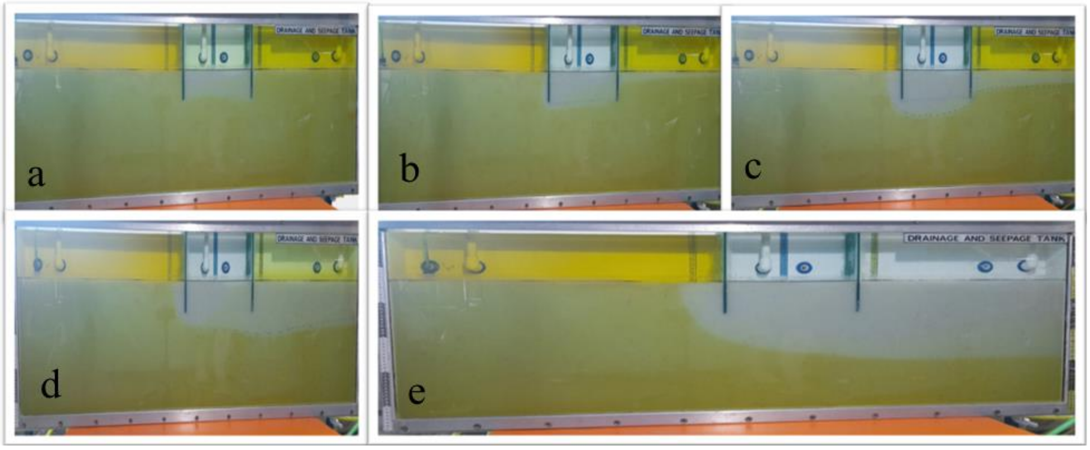

Figure 3. Different stages of movement of fresh water to salt water, respectively from a to e

In this way, the depth of the washed area is limited to 23 centimeters, which is about 1.5 times the height of the water inside the reservoir. It is evident that the depth of the washed area depends on various factors, including the height difference, water temperature, and water density, and it is recommended to investigate these factors as parametric parameters. Moreover, the results presented in Figure 3 and the comparison of images of the washed area and its expansion show that the depth of the washed area under the freshwater reservoir and the ecotone reservoir is significantly greater than the washed area behind the second water barrier. The depth ratio of the washed area under the freshwater reservoir and the ecotone reservoir to the length of the washed area behind the second water barrier in the modeled system is 2.5.

3.1. Simulation Results in SEEP/W Model

To assess the accuracy and precision of the laboratory experiment, the experiment conditions were defined in the Geo-Studio2022 software, specifically in the Seep/w module of this software. According to the laboratory conditions and to calibrate the freshwater head for the region, a constant head of 15 cm and a seawater head at an elevation of 14 cm were set. The results of this modeling are presented in Figure 4.

Based on the vectors of saltwater (Green vectors that represent solute mass flux) and freshwater (black vectors that represent water flux) flow extracted from the software image, it can be concluded that the presence of two cut-off walls (forming the Ecotone area) and the 1cm difference in head between saltwater and freshwater prevent saltwater leakage into the Ecotone and CR reservoirs. The vectors of saltwater flow indicate that saltwater did not pass through the cut-off walls and even freshwater entered the saltwater area during the final hours of the experiment and ultimately ceased to advance at the boundary where the energy of saltwater and freshwater is equal.

Observations showed that the vectors of saltwater in the CR region changed direction over time from a predominantly vertical state to a relatively horizontal one, moving towards the saltwater area. Additionally, the mentioned vectors in the saltwater region indicated that the saltwater mass in the modeled area is circulating in the sea and the intrusion has ceased at the beginning of it.

The reason for not completely freshwater intrusion in the area intended for the sea near the first cut-off wall is the diffusion phenomenon and the low speed of the flow, which means that part of the layer always remains salty.

The designed model in the laboratory exhibits good agreement with the numerical model. As observed, the depth of the saltwater intrusion after the cessation of freshwater intrusion in the SEEP/W model was also 23 cm, similar to the laboratory model.

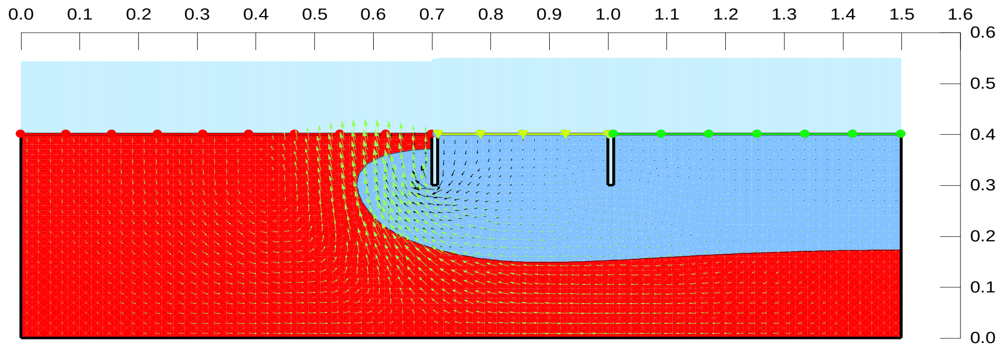

Figure 4. The progress of freshwater and solute mass flux vectors at the end of the experiment

In Figure 5 from a to e, the process of washing the saline bed by freshwater intrusion from the inlets of the CR and the ecotone zone is shown during the time. The relatively complete agreement of the numerical model with the laboratory model (figure 3) can be seen.

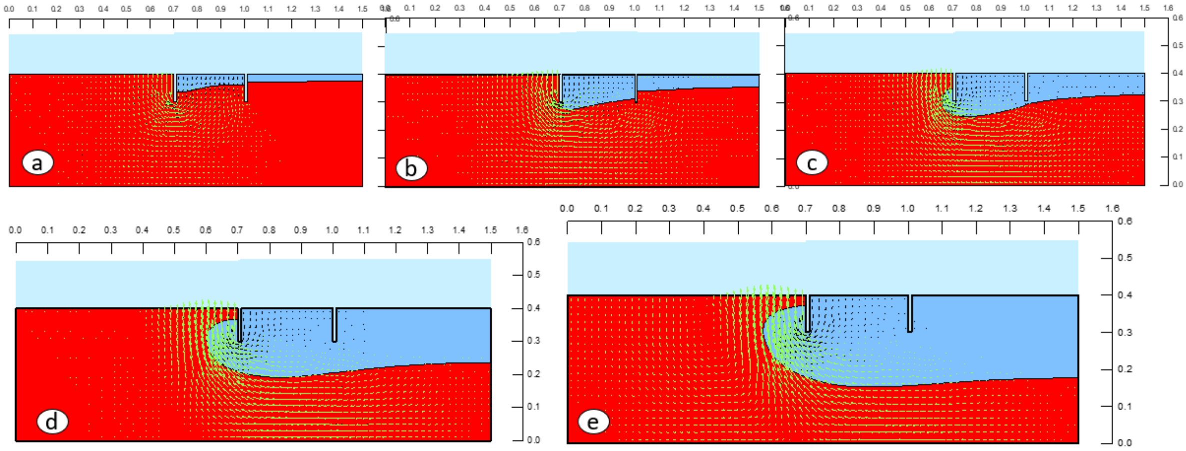

Figure 5. Different stages of movement of fresh water to salt water in GeoStudio, respectively from a to e

Also, according to Figure 6, the amount of mass flux in terms of time, which is extracted from the software based on meshing, can be seen in the first cut-off wall, which is designed on the saltwater side of the sea, the amount of mass flux of salt with time Dropped. This indicates the entry and intrusion of freshwater from the side of the coastal reservoir and the ecotone area.

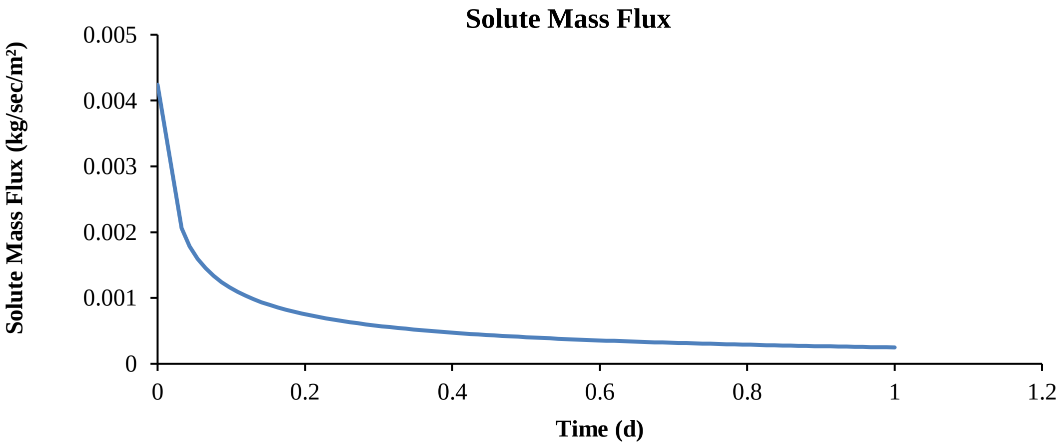

Figure 6. The amount of mass flux in terms of time at the boundary of the first cut-off wall

Based on the obtained results, the graph related to the second cut-off wall, which is designed on the side of the coastal reservoir, was also drawn, figure 7. In this graph, it was observed that the salt in the water was completely washed away. This result indicates the complete desalination of water in the coastal reservoir and ecotone zone. According to the complete agreement of the graphs obtained from the observations in the laboratory, it can be concluded that the designed cut-off walls have worked well and have been able to separate fresh water from salt water.

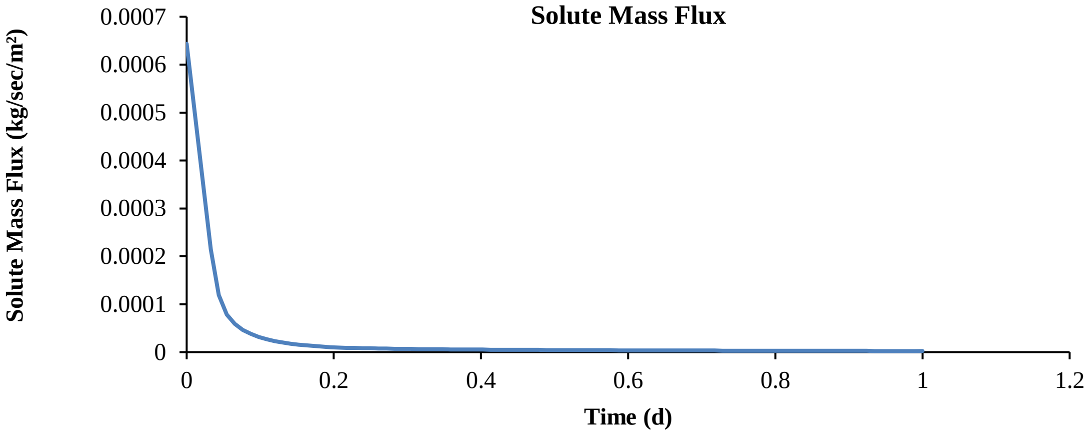

Figure 7. The amount of mass flux in terms of time at the border of the second cut-off wall

4. Conclusion

In the present study, the washing pattern of the bed of a coastal reservoir was investigated using a laboratory model during the initial water intake. In the examined model, the level of freshwater and the ecotone reservoir were set equal to and higher than the level of the seawater surface. The results of this investigation showed that due to the higher level of the freshwater surface in the respective reservoirs and, consequently, the movement of infiltrated water from the freshwater towards the seawater reservoir occurs. Notably, the bed washing of the salt crystals initially takes place from the ecotone and its bed, and then the washed area expands and develops under the seawater reservoir.

In this current investigation, the study also derived general equations for calculating energy loss under threshold conditions. The accuracy of these equations was rigorously assessed using various statistical indices, including Relative Error, Root Mean Square Error, and Kling Gupta Efficiency. The results affirm the high precision of the presented equation, endorsing its utility in predicting relative energy loss with confidence.

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