

SEAWATER INTRUSION IN COASTAL AQUIFERS

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**DEPARTMENT OF CIVIL ENGINEERING
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SEAWATER INTRUSION IN COASTAL AQUIFERS

By

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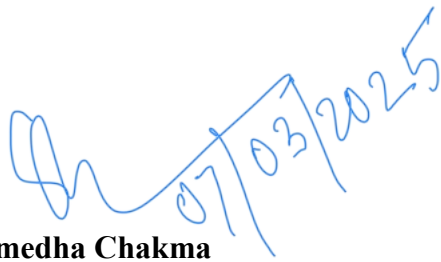
I dedicate this dissertation to my father

Ashok Sharma

CERTIFICATE

This is to certify that the thesis entitled “**Seawater intrusion in coastal aquifers**” being submitted by **Mr. Vikas Sharma** to the **Indian Institute of Technology Delhi**, for the award of the **degree of Doctor of Philosophy** is a record of the original bonafide research work carried by him under my guidance and supervision. The thesis work, in my opinion, has reached the requisite standards fulfilling the requirement for the **Degree of Doctor of Philosophy**.

The results contained in this thesis have not been submitted part or full to any other University or Institute for the award of any degree or diploma.



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Vikas Sharma

ABSTRACT

Seawater intrusion (SWI) is an ongoing issue exacerbated internationally by the growing need for freshwater along coastlines, which is affected by rising sea levels and changing climates, challenging sustainable management. Rising sea levels exacerbate SWI, diminishing freshwater availability, disrupting groundwater recharge, amplifying tidal influence, inducing land subsidence, degrading agriculture, damaging coastal ecosystems, and complicating remediation methods such as managed aquifer recharge and physical barrier installation. This research focuses on finding intrusion behavior under the different layering and packing of formation material. The more realistic and conventional remediation techniques are tested for their efficiency under the influence of inclined ocean-aquifer boundary. A laboratory-scale glass box apparatus of dimension $100 \times 50 \times 10 \text{ cm}^3$ was used to experiment with a 70° inclined interface. Individual material with different permeability was used to form the stratified formations. High-resolution images were taken at defined intervals and enhanced for clear intrusion visuals. The thesis documents the importance of an inclined ocean aquifer boundary in stratified layers aquifer formation with static sea level and sea level rise and accessed the efficiency of subsurface barrier and mixed barrier. Additionally, a novel physical barrier has been tested for efficiency and proven to be more effective than existing physical barriers.

The first phase started with determining the intrusion behavior within a sloping boundary in a heterogeneous aquifer and assessing the efficiency of subsurface barriers. Comparing the results of the heterogeneous base case and barrier installed condition, a huge quantity of about 38.93% of groundwater was conserved from contamination. Homogeneous media shows a faster rate of intrusion with a progressive rate of contamination, while heterogeneous media, without barriers, shows slower rates of intrusion due to reduced permeability. Analysis of the toe length using sensitivity analysis in the heterogeneous case shows a range of 24.82 cm to 75 cm before barrier installation and a range of 13.05 cm to 65.24 cm after installation of a barrier.

For the second phase, stratified media was prepared, and the performance of a new kind of novel under-surface barrier system for stratified layers with different permeability under the influence of an inclined ocean-aquifer interface was tested. Results show that the under-surface barrier is much more successful in stopping intrusion when materials with monotonically increasing permeability are considered, as the toe length increases with increasing permeability. For perpendicular stratification, using a conventional barrier is much less efficient than an under-surface barrier as the ratio of toe length to height decreases. The height of intrusion after using an under-surface barrier in different layers decreases subsequently as compared to without the barrier. Results also exhibit that using an under-surface barrier starting from the point where the equilibrium of water has reached and extending towards the impermeable strata is the most efficient approach to follow.

For the third phase, the behavior of intrusion under layering of material in monotonic increasing permeability of the material from bottom to top in parallel stratification and from fresh groundwater side to ocean side. The intrusion was recorded in 2-layer, 3-layer, and 4-layer formations. The height of the intrusion ranged from 28.3 to 32.2 cm. The intrusion was fast and accurate due to the higher permeability of the material. It was concluded that the toe length-to-height ratio varies from 0.43 to 7.0. This ratio is small for materials with lower permeability because the intrusion is slow but steady in both directions; however, for materials with higher permeability, this ratio corresponds to a higher value. The intrusion is restricted to the individual layer until it encounters an impervious layer and follows a proportional pattern with an increasing intrusion area as the opening area increases.

For the fourth phase, the efficiency of the mixed barrier was tested, and the extent of intrusion was analyzed in stratified layers under the influence of an inclined ocean-aquifer boundary with a mixed barrier as a remediation technique. The T_L/H ratio in the base case perpendicular stratification without barrier installation ranged from 0.2 to 0.9 for all four layers,

while this ratio ranged from 0.67 to 1.164 in barrier installed condition for mixed barrier installed condition. Both the lower and upper limits of the range increase and approach unity, indicating a proportional intrusion in the vertical and horizontal directions. There was a 40-48% decrease in the extent of toe length after installation. With a mixed barrier installed, the height of the intrusion was reduced, resulting in an increase in the T_L/H and a decrease in the potential for toe length. The intrusion was delayed by 86.67% in parallel stratification and 28.22% in perpendicular stratification after comparing the time period for the base case and the mixed barrier installed condition. A parabolic profile of intrusion was observed in the low-permeability layer, while a convex-outward profile was observed in the higher-permeability layer. The results of this investigation shed light on the mixed barrier's suitability for use in realistically diverse coastal aquifers.

For the fifth phase, the focus of the research shifted to the understanding of studying the influence of sea level rise on the layered formation with inclined ocean-aquifer boundary. The toe length to height ratio corresponds to a value of 0.8 to 3.5 and 1.02 to 1.83, assuming a top horizontal surface, which changes to 0.42 to 4.7 and 0.84 to 1.62 after implementing inclined top ground for parallel and perpendicular stratification, respectively. The results imply that the migration of toe length in parallel stratification is much faster than that in perpendicular stratification. A comparison of increasing intrusion area ranged from 8.3% to 206% for all layering cases, with less time needed to reach the vertical boundary. It was concluded that for the smaller openings, the interaction opening governs the intrusion and not the available head of saltwater above the point. The induced intrusion from the top surface dominates the process for a larger interaction opening.

The results derived from the research may be applied to real-life scenarios for estimating the effectiveness of coastal protection structures such as cutoff walls, under-surface barriers, and subsurface barriers. Applicability of results is subjected to upscaling (Froude's similitude),

temporal dynamics, heterogeneity, and the understanding of boundary conditions under case-specific scenarios having heterogeneous formations, such as the eastern coastline and western coastline of India. Finally, the outcomes attained could be helpful for better understanding the behavior of seawater wedges and in providing remediation techniques to save coastal aquifers.

सार

समुद्री जल की घुसपैठ एक निरंतर मुद्दा है जो तटरेखाओं के साथ ताजे पानी की बढ़ती आवश्यकता के कारण अंतरराष्ट्रीय स्तर पर बढ़ रहा है, जो समुद्र के स्तर में बदलाव और जलवायु में बदलाव से प्रभावित है, जो स्थायी प्रबंधन को चुनौती दे रहा है। एक ओर, समुद्र के स्तर में प्रत्याशित वृद्धि, और दूसरी ओर, प्राकृतिक भूजल पुनर्भरण में कमी, पानी की मांग में वृद्धि, और जलवायु परिवर्तन, समुद्री जल की घुसपैठ को खराब कर सकते हैं। जलभृत एकरूपता पर अधिकांश अध्ययन जिनका उपयोग प्रबंधन दिशानिर्देश बनाने के लिए किया जाता है, लवणता संवेदनशीलता पर ध्यान केंद्रित करते हैं। हालांकि, कुछ निष्कर्षण स्थितियों के तहत, कम पारगम्यता बाधाओं और पसंदीदा प्रवाह मार्गों के साथ भौगोलिक संरचना काफी विविध हो सकती है जो परिसंचरण और खारे परिवहन तंत्र को प्रभावित करते हैं। यह शोध विभिन्न परतों और संरचना सामग्री की पैकिंग के परिदृश्यों के तहत घुसपैठ के व्यवहार को खोजने पर केंद्रित है। अधिक यथार्थवादी और पारंपरिक उपचार तकनीकों का झुकाव वाले महासागर-जलीय सीमा के प्रभाव में उनकी दक्षता के लिए परीक्षण किया जाता है। यहाँ, 70° झुके हुए इंटरफेस के साथ प्रयोग करने के लिए 100 × 50 × 10 सेमी³ आयाम के एक प्रयोगशाला-पैमाने के ग्लास बॉक्स उपकरण का उपयोग किया गया था। स्तरीकृत संरचनाओं को बनाने के लिए अलग-अलग पारगम्यता वाली व्यक्तिगत सामग्री का उपयोग किया गया था। उच्च-रिज़ॉल्यूशन वाली छवियों को परिभाषित अंतराल पर लिया गया था और स्पष्ट घुसपैठ दृश्यों के लिए बढ़ाया गया था।

पहला चरण एक विषम जलभृत में एक ढलान सीमा के भीतर घुसपैठ व्यवहार को निर्धारित करने और उपसतह बाधाओं की दक्षता का आकलन करने के साथ शुरू हुआ। विषम आधार मामले और बाधा स्थापित स्थिति के परिणामों की तुलना करते हुए, लगभग 38.93% भूजल की एक बड़ी मात्रा को दूषित होने से बचाया गया था। सजातीय मीडिया संदूषण की प्रगतिशील दर के साथ घुसपैठ की तेज दर दिखाता है, जबकि विषम मीडिया, बिना किसी बाधा के, कम पारगम्यता के कारण घुसपैठ की धीमी दर दिखाता है।

विषम मामले में संवेदनशीलता विश्लेषण का उपयोग करके T_L की लंबाई का विश्लेषण बाधा स्थापना से पहले 24.82 सेमी से 75 सेमी की सीमा और बाधा की स्थापना के बाद 13.05 सेमी से 65.24 सेमी की सीमा दिखाता है।

दूसरे चरण के लिए स्तरीकृत मीडिया तैयार किया गया था और सतह के नीचे नए अवरोध की दक्षता का परीक्षण किया गया था। परिणाम बताते हैं कि सतह के नीचे की बाधा घुसपैठ को रोकने में बहुत अधिक सफल होती है जब मोनोटोनिक रूप से बढ़ती पारगम्यता वाली सामग्री पर विचार किया जाता है, क्योंकि बढ़ती पारगम्यता के साथ T_L की लंबाई बढ़ जाती है। लंबवत स्तरीकरण के लिए, पारंपरिक अवरोध का उपयोग सतह के नीचे के अवरोध की तुलना में बहुत कम कुशल है क्योंकि पैर की T_L और ऊंचाई का अनुपात कम हो जाता है। विभिन्न परतों में सतह के नीचे की बाधा का उपयोग करने के बाद घुसपैठ की ऊंचाई बाधा के बिना की तुलना में बाद में कम हो जाती है। परिणाम यह भी दर्शाते हैं कि सतह के नीचे की बाधा का उपयोग उस बिंदु से शुरू होता है जहां पानी का संतुलन पहुंच गया है और अभेद्य स्तर की ओर बढ़ना अनुसरण करने के लिए सबसे कुशल दृष्टिकोण है।

तीसरे चरण के लिए मोनोटोनिक में सामग्री की परत के तहत घुसपैठ का व्यवहार समानांतर स्तरीकरण में नीचे से ऊपर तक और ताजा भूजल की ओर से समुद्र की ओर सामग्री की पारगम्यता बढ़ रही है। घुसपैठ को 2-परत, 3-परत और 4-परत के गठन के साथ दर्ज किया गया था। घुसपैठ की ऊंचाई 28.3 से 32.2 सेमी तक थी। सामग्री की उच्च पारगम्यता के कारण घुसपैठ तेज और सटीक थी। यह निष्कर्ष निकाला गया कि T_L की लंबाई और ऊंचाई का अनुपात 0.43 से 7.0 तक भिन्न होता है। कम पारगम्यता वाली सामग्री के लिए, यह अनुपात छोटा है क्योंकि घुसपैठ धीमी है लेकिन दोनों दिशाओं में स्थिर है; हालाँकि, उच्च पारगम्यता वाली सामग्री के लिए, यह अनुपात उच्च मूल्य से मेल खाता है। घुसपैठ को अलग-अलग परत तक सीमित किया जाता है जब तक कि यह एक अभेद्य परत का सामना नहीं करता है और जैसे-जैसे उद्घाटन क्षेत्र बढ़ता है घुसपैठ के बढ़ते क्षेत्र के साथ आनुपातिक पैटर्न का पालन करता है।

चौथे चरण के लिए मिश्रित बाधा की दक्षता का परीक्षण किया गया और एक उपचार तकनीक के रूप में एक मिश्रित बाधा के साथ एक झुकी हुई महासागर-जलीय सीमा के प्रभाव में स्तरीकृत परतों में घुसपैठ की सीमा का विश्लेषण किया गया। T_L/H अनुपात सभी स्तरीकरण स्थितियों और स्थापित उपचार के लिए 0.2 से 12.84 तक था। स्थापना के बाद T_L की लंबाई में 40-48% की कमी आई। एक मिश्रित अवरोध स्थापित होने के साथ, घुसपैठ की ऊंचाई कम हो गई थी, जिसके परिणामस्वरूप T_L/H में वृद्धि हुई और T_L की लंबाई की क्षमता में कमी आई। बेस केस और मिश्रित बाधा स्थापित स्थिति के लिए समय सीमा की तुलना करने के बाद समानांतर स्तरीकरण में घुसपैठ में 86.67% और लंबवत स्तरीकरण में 28.22% की देरी हुई थी। कम पारगम्यता परत में घुसपैठ की एक परवलयिक रूपरेखा देखी गई, जबकि उच्च पारगम्यता परतों में एक उत्तल-बाहरी रूपरेखा देखी गई। इस जांच के परिणाम वास्तविक रूप से विविध तटीय जलभृतों में उपयोग के लिए मिश्रित बाधा की उपयुक्तता पर प्रकाश डालते हैं।

पांचवें चरण के लिए अनुसंधान का ध्यान झुका हुआ महासागर-एक्विफर सीमा के साथ स्तरित गठन पर समुद्र के स्तर में वृद्धि के प्रभाव का अध्ययन करने की समझ पर स्थानांतरित हो गया। ऊंचाई के लिए T_L की लंबाई का अनुपात 0.8 से 3.5 और 1.02 से 1.83 के मान से मेल खाता है, एक शीर्ष क्षैतिज सतह को मानते हुए, जो क्रमशः समानांतर और लंबवत स्तरीकरण के लिए झुका हुआ शीर्ष जमीन को लागू करने के बाद 0.42 से 4.7 और 0.8 4 से 1.62 में बदल जाता है। परिणाम इंगित करते हैं कि समानांतर स्तरीकरण में पैर की उंगलियों की लंबाई का प्रवास लंबवत स्तरीकरण की तुलना में बहुत तेज है। ऊर्ध्वाधर सीमा तक पहुंचने के लिए कम समय की आवश्यकता वाले सभी लेयरिंग मामलों के लिए बढ़ते घुसपैठ क्षेत्र की तुलना 8.3% से 206% तक थी। यह निष्कर्ष निकाला गया कि छोटे उद्घाटन के लिए, अंतःक्रिया उद्घाटन घुसपैठ को नियंत्रित करता है न कि बिंदु के ऊपर खारे पानी के उपलब्ध शीर्ष को। एक बड़े अंतःक्रिया उद्घाटन के लिए, शीर्ष सतह से प्रेरित घुसपैठ प्रक्रिया पर हावी होती है।

शोध से प्राप्त परिणामों को तटीय सुरक्षा संरचनाओं की प्रभावशीलता का अनुमान लगाने के लिए वास्तविक जीवन के परिदृश्यों पर लागू किया जा सकता है जैसे कि कटऑफ दीवारें, सतह के नीचे की बाधाएं, और उपसतही बाधाएं जैसे कि अपस्केलिंग (फ़ाउंड की समानता) लौकिक गतिशीलता, विषमता, और विषमता पर विचार करने के बाद भारत की पूर्वी तटरेखा और पश्चिमी तटरेखा जैसे विषम संरचनाओं वाले मामले-विशिष्ट परिदृश्यों के तहत सीमा स्थितियों की प्रयोज्यता। अंत में, प्राप्त परिणाम समुद्री जल पट्टियों के व्यवहार को बेहतर ढंग से समझने और तटीय जलभृतों को बचाने के लिए उपचार तकनीक प्रदान करने में सहायक हैं।

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LIST OF ABBREVIATIONS

ALERT	Automated Time-Lapse Electrical Resistivity Tomography
ANN	Artificial Neural Network
API	Application Programming Interface
ASR	Aquifer Storage and Recovery
CGWB	Central Ground Water Board
COCI	Open Citations Index of Crossref
CSV	Comma Separated Values
DCOM	Detrital Colored Organic Matter
EC	Electrical Conductivity
EPMC	Europe PubMed Central
FEFLOW	Finite Element subsurface Flow system
FWCI	Field Weighted Citation Impact
FWL	Fresh Water Lens
GIS	Geographic Information System
GPS	Global Positioning System
HBC	Homogeneous Base Case
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated Water Resource Management
MAR	Managed Aquifer Recharge
MODFLOW	Modular Finite-Difference Groundwater Flow Model
OCC	Open Citations Corpus
PCA	Principal Components Analysis
PHREEQC	PH (pH), RE (redox), EQ (equilibrium), C (program written in Q)

RCM	Regional Climate Models
RIS	Research Information Systems
SCIE	Science Citation Index Expanded
SEAWAT	Simulation of Three-Dimensional Variable-Density Ground-Water Flow and Transport
SIDS	Small Island Developing States
SMD	Subsurface Monitoring Device
SUTRA	Saturated-Unsaturated Transport
SWI	Seawater Intrusion
TDS	Total Dissolved Solids
TEM	Transient Electromagnetic
VES	Vertical electrical sounding
WoS	Web of Science

LIST OF SYMBOLS

A_T	Saltwater intrusion area at time T , cm ²
P_{e_m}	<i>Péclet</i> number
f_x	Function representing the saltwater intrusion
α_L	Longitudinal dispersivity, cm
α_T	Transverse dispersivity, cm
ρ_S	Saltwater density, kg/m ³
ρ_f	Freshwater density, kg/m ³
Δx and Δy	Quadratic element sizes in the horizontal and vertical directions
a	Initial value of toe length in x -direction, m
b	Final value of toe length in x -direction, m
c	Solute concentration (mass of solute per unit volume of fluid, kg/m ³)
C_F, C_S	Freshwater and saltwater concentration gm/l
C_T	Tracer dye concentration, gm/l
D	Dispersion tensor, m ² /s
H	Height of intrusion
H_1	Height of intrusion in layer 1
H_2	Height of intrusion in layer 2
H_3	Height of intrusion in layer 3
H_4	Height of intrusion in layer 4
K_1	Permeability of material retained on a 4.75 mm sieve
K_2	Permeability of glass beads of size 3 mm
K_3	Permeability of aggregate passing through a 4.75 mm sieve and retained on a 1.18 mm sieve

K_4	Permeability of material passing 1.18 mm and retained on a 600-micron sieve
L_1	Layer 1 with permeability K_1
L_2	Layer 2 with permeability K_2
L_3	Layer 3 with permeability K_3
L_4	Layer 4 with permeability K_4
ppt	Parts per thousand
Q	Sources or sinks, $\text{kg}/\text{m}^3 \cdot \text{s}$
Q_f	Sources or sinks of fluid mass
Q_s	Sources or sinks of solute transport
t	Time
T_L	Intrusion toe length
T_{L1}	Toe length in layer 1
T_{L2}	Toe length in layer 2
T_{L3}	Toe length in layer 3
T_{L4}	Toe length in layer 4
v	Darcy velocity or volumetric flux vector, m/s
x -, y -	Direction horizontal and vertical to ground
z	Drop of saltwater and freshwater interface below MSL [m]
α	Density ratio
ρ	Fluid density, kg/m^3
ρ_s	Saltwater density
dH	Head variation in sea level rise
ρ_f	Freshwater density
ϕ	Porosity of the porous medium (dimensionless)