Hydrodynamics of Interaction between Coastal Water Bodies and Open Seas - A Case Study of the Kochi-Vembanad Wetland System in Kerala, India

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Hydrodynamics of Interaction between Coastal Water Bodies and Open Seas - A Case Study of the Cochin-Vembanad Wetland System in Kerala, India

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THESIS CERTIFICATE

This is to certify that I/we have examined the thesis entitled "**Hydrodynamics of Interaction between Coastal Water Bodies and Open Seas - A Case Study of the Cochin-Vembanad Wetland System in Kerala, India**", submitted by **Manish Shukla** (Entry Number: **2016CEZ8428**) to Indian Institute of Technology Delhi, New Delhi (India), is worthy of consideration for the award of the degree, **Doctor of Philosophy**. Moreover, this thesis is a record of the original research work carried out by this student under my/our supervision. We hereby accord that the results contained in this thesis, which may have been previously communicated in the form of manuscripts, conference presentations or patent filings, have not been submitted in part or full to any other University or Institute for the award of any academic degree.

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ABSTRACT

Estuaries, the dynamic transition zones where freshwater from hinterland source areas and oceanic tidal currents interact, are among Earth's most complex and productive ecosystems. These coastal environments are characterised by intricate hydrodynamic processes arising from the interplay of sediment-laden riverine discharge, tidal forces, and oceanic currents. The resulting mixing of fresh and saltwater creates unique salinity gradients that vary spatially and temporally, significantly influencing the ecosystem's physical, chemical, and biological properties. Estuaries serve critical ecological functions and have historically been focal points for human activity.

The hydrodynamics of estuaries are particularly fascinating due to their multifaceted nature contributed in no small measure by cycles and epicycles of tidal influences from the ocean side and coupled with the influences of the annual/seasonal hydrological cycle on river and sediment inflows from contributing source catchments. Together with anthropogenic and other influences, these processes, in an integrated sense, encompass a wide range of overlapping spatial and temporal scales. From microscale turbulence to large-scale circulation patterns, these dynamics govern the transport and distribution of various constituents within the estuarine system. The complexity is further amplified by geomorphology, wind stress, and freshwater inflow variability. Understanding these intricate multi-scale dynamics is crucial for the effective management of estuarine resources, water quality prediction, morphological integrity maintenance, and ecological health assessment.

This study presents a comprehensive analysis of hydrodynamic transport phenomena in the Vembanad Estuary, utilising various modelling techniques to investigate salinity behaviour, sediment transport, and anthropogenic impacts. The research aims to provide insights into

these intricate processes occurring at different scales within the estuary by addressing four interconnected objectives: modelling salinity behaviour at different scales, quantifying the presence and influence of dynamic barriers, modelling sediment movement, and understanding the influence of structural interventions.

A multifaceted approach was employed, centred on a 3D salinity model developed using Tuflow FV. Once calibrated with data sources, this model simulated salinity movement over 12 years and was validated against observed values. Results revealed monsoonal variabilities in salinity, with hourly data demonstrating more significant fluctuations than daily data, highlighting tidal influence. Vertical salinity profiles illustrated stratification and mixing effects in various estuary regions. Tidal dynamics analysis further elucidated their impact on different estuary sections.

While seasonal changes exhibited consistent patterns in most areas, finer-scale analysis uncovered variations in salinity patterns, particularly during monsoon and dry seasons. Anomalous salinity structures in certain sections necessitated advanced diagnostic methods for a more nuanced understanding of these unique patterns.

Building upon this foundation, high-resolution simulations were performed on these smaller sections to identify coherent structures in the flow domain. Finite-time Lyapunov Exponent (FTLE), which characterises the rate of separation trajectories, were calculated to determine Lagrangian coherent structures (LCS), offering insights into the estuary's dynamic boundaries. Smoothed Particle Hydrodynamics (SPH), a fully lagrangian method, is employed to validate and further explore these structures, enabling the study of particle movement and comparison with LCS-predicted stretching and folding patterns. The congruence between LCS and SPH results confirmed the presence of time-evolving dynamic barriers, creating distinct zones with varying flow properties. Particle tracking

and resident analysis were conducted to determine residence times and particle trajectories. Results demonstrated considerable variability in particle trajectories and flushing times for particles released in close proximity.

To investigate the influence of these dynamic barriers on inertial particles, a multi year sediment deposition model was developed using Tuflow FV for the entire estuary. The results showed a maximum bed elevation change of approximately 1 cm per year in the various regions of the estuary. Suspended sediment concentration and deposition patterns also showed coherence with identified LCS in the section and also revealed significantly different patterns within zones formed by dynamic barriers.

This research further investigated the impact of anthropogenic influence by modelling two scenarios without the man-made Willingdon Island, reflecting the bathymetry from approximately a century ago. Comparison with the current salinity model revealed significantly lower salinity levels (15 to 30%) in upstream regions for both pre-Willingdon scenarios. Six additional scenarios with varying dredging depths and patterns were analysed to understand their effect on flow patterns and salinity structure.

Looking forward, this research lays the groundwork for further investigations in estuarine hydrodynamics, offering a robust methodological framework applicable to other systems. The integration of 3D modelling, LCS analysis, and particle simulations provides a comprehensive approach to understanding estuarine hydrodynamics. This has implications for contaminant fate, sediment management, and sustainable coastal development. The research not only advances our understanding of the Vembanad Estuary but also serves as a template for comprehensive studies of estuarine systems worldwide.

सार

मुहाना (Estuaries), जो एक गतिशील संक्रमण क्षेत्र है जहाँ अंतर्देशीय स्रोतों से आने वाला मीठा पानी और समुद्र की ज्वारीय धाराएँ आपस में मिलती हैं, पृथ्वी के सबसे जटिल और उत्पादक पारिस्थितिक तंत्रों में से एक है। इन तटीय वातावरणों में जटिल जलगतिकीय प्रक्रियाएँ होती हैं, जो गाद से लदी नदी के प्रवाह, ज्वारीय बलों और समुद्री धाराओं के परस्पर क्रिया से उत्पन्न होती हैं। ताज़े और खारे पानी के इस मिश्रण से अद्वितीय लवणता प्रवणता (salinity gradients) बनती है जो स्थानिक और अस्थायी रूप से बदलती रहती है, जो पारिस्थितिक तंत्र के भौतिक, रासायनिक और जैविक गुणों को महत्वपूर्ण रूप से प्रभावित करती है। मुहाना महत्वपूर्ण पारिस्थितिक कार्यों की पूर्ति करते हैं और ऐतिहासिक रूप से मानवीय गतिविधियों के केंद्र रहे हैं।

मुहानों की जलगतिकी विशेष रूप से आकर्षक है, क्योंकि इसमें कई पहलू शामिल हैं जो समुद्री ज्वारीय प्रभावों के चक्रों और उपचक्रों और साथ ही साथ नदी और तलछट के अंतर्वाह पर वार्षिक/मौसमी जल विज्ञान चक्र के प्रभावों से प्रभावित होते हैं। मानवीय और अन्य प्रभावों के साथ, ये प्रक्रियाएँ एक एकीकृत अर्थ में, स्थानिक और अस्थायी पैमानों की एक विस्तृत श्रृंखला को शामिल करती हैं। सूक्ष्म पैमाने के अशांति से लेकर बड़े पैमाने के परिसंचरण पैटर्न तक, ये गतिकियाँ मुहाना प्रणाली के भीतर विभिन्न घटकों के परिवहन और वितरण को नियंत्रित करती हैं। भू-आकृति विज्ञान, पवन का दबाव और मीठे पानी के प्रवाह की परिवर्तनशीलता से जटिलता और बढ़ जाती है। इन जटिल बहु-स्तरीय गतिकियों को समझना मुहाना संसाधनों के प्रभावी प्रबंधन, जल गुणवत्ता की भविष्यवाणी, रूपात्मक अखंडता बनाए रखने और पारिस्थितिक स्वास्थ्य मूल्यांकन के लिए महत्वपूर्ण है।

यह अध्ययन वेम्बनाड मुहाना (Vembanad Estuary) में जलगतिकीय परिवहन घटनाओं का एक व्यापक विश्लेषण प्रस्तुत करता है, जिसमें लवणता व्यवहार, तलछट परिवहन और मानवजनित प्रभावों की जांच के लिए विभिन्न मॉडलिंग तकनीकों का उपयोग किया गया है। इस शोध का उद्देश्य चार आपस में

जुड़े उद्देश्यों को संबोधित करके मुहाना के भीतर विभिन्न पैमानों पर होने वाली इन जटिल प्रक्रियाओं में अंतर्दृष्टि प्रदान करना है: विभिन्न पैमानों पर लवणता व्यवहार का मॉडल बनाना, गतिशील बाधाओं की उपस्थिति और प्रभाव को मात्रा निर्धारित करना, तलछट की गति का मॉडल बनाना, और संरचनात्मक हस्तक्षेप के प्रभाव को समझना।

एक बहुआयामी दृष्टिकोण अपनाया गया था, जो Tuflow FV का उपयोग करके विकसित किए गए 3D लवणता मॉडल पर केंद्रित था। एक बार डेटा स्रोतों के साथ कैलिब्रेट होने के बाद, इस मॉडल ने 12 वर्षों में लवणता की गति का अनुकरण किया और देखे गए मूल्यों के विरुद्ध मान्य किया गया। परिणामों में लवणता में मानसूनी परिवर्तनशीलता का पता चला, जिसमें दैनिक डेटा की तुलना में प्रति घंटे के आंकड़ों में अधिक महत्वपूर्ण उतार-चढ़ाव दिखा, जो ज्वारीय प्रभाव को उजागर करता है। ऊर्ध्वाधर लवणता प्रोफाइल ने विभिन्न मुहाना क्षेत्रों में स्तरीकरण और मिश्रण प्रभावों को दर्शाया। ज्वारीय गतिशीलता विश्लेषण ने विभिन्न मुहाना खंडों पर उनके प्रभाव को और स्पष्ट किया।

जबकि मौसमी परिवर्तनों ने अधिकांश क्षेत्रों में सुसंगत पैटर्न प्रदर्शित किए, सूक्ष्म-स्तरीय विश्लेषण ने लवणता पैटर्न में भिन्नता का पता लगाया, विशेष रूप से मानसून और शुष्क मौसम के दौरान। कुछ खंडों में असामान्य लवणता संरचनाओं ने इन अद्वितीय पैटर्न की अधिक सूक्ष्म समझ के लिए उन्नत नैदानिक विधियों की आवश्यकता बताई।

इस नींव पर आगे बढ़ते हुए, प्रवाह डोमेन में सुसंगत संरचनाओं की पहचान करने के लिए इन छोटे खंडों पर उच्च-रिज़ॉल्यूशन सिमुलेशन किए गए। परिमित-समय लिपुनोव एक्सपोनेंट (FTLE), जो अलगाव प्रक्षेपवक्र की दर को दर्शाता है, की गणना लैग्रेंजियन सुसंगत संरचनाओं (LCS) को निर्धारित करने के लिए की गई थी, जो मुहाना की गतिशील सीमाओं में अंतर्दृष्टि प्रदान करती है। स्मूथेड पार्टिकल हाइड्रोडायनामिक्स (SPH), एक पूरी तरह से लैग्रेंजियन विधि, का उपयोग इन संरचनाओं को मान्य करने और आगे पता लगाने के लिए किया जाता है, जिससे कण गति का अध्ययन और LCS-अनुमानित स्ट्रेचिंग

और फोल्डिंग पैटर्न के साथ तुलना करना संभव होता है। LCS और SPH परिणामों के बीच समानता ने समय-विकासशील गतिशील बाधाओं की उपस्थिति की पुष्टि की, जिससे विभिन्न प्रवाह गुणों वाले विशिष्ट क्षेत्र बने। कण ट्रैकिंग और निवासी विश्लेषण निवास समय और कण प्रक्षेपवक्र निर्धारित करने के लिए किए गए थे। परिणामों ने आस-पास जारी किए गए कणों के लिए कण प्रक्षेपवक्र और फ्लशिंग समय में काफी परिवर्तनशीलता दिखाई।

इन गतिशील बाधाओं के जड़त्वीय कणों पर प्रभाव की जांच करने के लिए, पूरे मुहाने के लिए Tuflow FV का उपयोग करके एक बहु-वर्षीय तलछट जमाव मॉडल विकसित किया गया था। परिणामों में मुहाना के विभिन्न क्षेत्रों में लगभग 1 सेमी प्रति वर्ष की अधिकतम तल ऊंचाई परिवर्तन दिखाई दिया। निलंबित तलछट सांद्रता और जमाव पैटर्न ने खंड में पहचाने गए LCS के साथ सुसंगति भी दिखाई और गतिशील बाधाओं द्वारा गठित क्षेत्रों के भीतर महत्वपूर्ण रूप से भिन्न पैटर्न भी प्रकट किए।

इस शोध ने मानवजनित प्रभाव की जांच विलिंगडन द्वीप के बिना दो परिदृश्यों का मॉडल बनाकर की, जो लगभग एक सदी पहले के बाथिमेट्री को दर्शाता है। वर्तमान लवणता मॉडल के साथ तुलना करने पर दोनों पूर्व-विलिंगडन परिदृश्यों के लिए ऊपरी क्षेत्रों में काफी कम लवणता स्तर (15 से 30%) का पता चला। प्रवाह पैटर्न और लवणता संरचना पर उनके प्रभाव को समझने के लिए अलग-अलग ड्रेजिंग गहराई और पैटर्न के साथ छह अतिरिक्त परिदृश्यों का विश्लेषण किया गया।

आगे देखते हुए, यह शोध मुहाना जलगतिकी में आगे की जांच के लिए आधार तैयार करता है, जो अन्य प्रणालियों के लिए लागू एक मजबूत कार्यप्रणाली ढांचा प्रदान करता है। 3D मॉडलिंग, LCS विश्लेषण और कण सिमुलेशन का एकीकरण मुहाना जलगतिकी को समझने के लिए एक व्यापक दृष्टिकोण प्रदान करता है। इसके प्रदूषक भाग्य, तलछट प्रबंधन और टिकाऊ तटीय विकास पर प्रभाव पड़ता है। यह शोध न केवल वेम्बनाड मुहाना की हमारी समझ को आगे बढ़ाता है, बल्कि दुनिया भर में मुहाना प्रणालियों के व्यापक अध्ययन के लिए एक टेम्पलेट के रूप में भी काम करता है।

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LIST OF ABBREVIATIONS

ALP	:	Alappuzha
ALOS PALSAR	:	Advanced Land Observing Satellite Phased Array type L-band Synthetic Aperture Radar
BF	:	Both channels dredged at 18 m (full length)
BH	:	Both channels dredged at 18 m (half length)
CFD	:	Computational Fluid Dynamics
CFL	:	Courant–Friedrichs–Lewy (number)
CLS	:	Collecte Localisation Satellites
CMFRI	:	Central Marine Fisheries Research Institute
CNES	:	Centre National d'Études Spatiales (French National Centre for Space Studies)
CWRDM	:	Centre for Water Resources Development and Management
DEM	:	Digital Elevation Model
DNS	:	Direct Numerical Simulation
DSWM	:	Depth-integrated Shallow Water Model
EASM	:	Eddy viscosity Algebraic Second-Moment closure model
EFDC	:	Environmental Fluid Dynamics Code
ETM	:	Estuarine Turbidity Maxima
ETSMORF	:	Estuary and Coast Morphology Model
FEM	:	Finite Element Method
FDM	:	Finite Difference Method
FES	:	Finite Element Solution
FTLE	:	Finite-Time Lyapunov Exponent
FVM	:	Finite Volume Method
GLS	:	Generic Length Scale
GOTM	:	General Ocean Turbulence Model
INC	:	Indian Naval Command
IWAI	:	Inland Waterways Authority of India
KRM	:	Kumarakom

LCS	:	Lagrangian Coherent Structure
LEGOS	:	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales
LES	:	Large Eddy Simulation
LF	:	Mattancherry Channel dredged at 18 m (full length)
LH	:	Mattancherry Channel dredged at 18 m half length)
MAE	:	Mean Absolute Error
MFSV	:	Manning Floc Settling Velocity
MOHID	:	Modelo Hidrodinâmico (Hydrodynamic Model - in Portuguese)
NLSWE	:	Non-Linear Shallow Water Equation
NTB	:	North Tanker Berth
POM	:	Princeton Ocean Model
RF	:	Ernakulam Channel dredged at 18 m (full length)
RH	:	Ernakulam Channel dredged at 18 m (half-length)
RMSE	:	Root Mean Square Error
ROMS	:	Regional Ocean Modeling System
RSIS	:	Ramsar Sites Information Service
RWM	:	Random Wave Model
SRTM	:	Shuttle Radar Topography Mission
SPH	:	Smoothed Particle Hydrodynamics
SSC	:	Suspended Sediment Concentration
STB	:	South Tanker Berth
TMB	:	Thaneermukkom Barrage
VKM	:	Vaikom
WBM	:	Winders, Barlow & Morrison Pty Ltd
WRIS	:	Water Resources Information System of India
WW1	:	Pre-Willingdon Scenario 1
WW2	:	Pre-Willingdon Scenario 2

LIST OF NOTATIONS AND SYMBOLS

δZ_0	:	Initial separation between two infinitesimally close trajectories.
$\delta Z(t)$	:	Final separation between two trajectories after time t.
LE	:	Lyapunov exponent (also FTLE for finite-time Lyapunov exponent).
$\nabla F_{t_0}^{t_1}(x_0)$	:	Flow map, deformation gradient of the flow map (Jacobian matrix).
x_0	:	Initial position of a particle or trajectory.
t_0, t_1	:	Initial and final times for FTLE calculation.
κ	:	Von Kármán constant (0.41)
h	:	Water depth (in shallow water equations).
u	:	x-velocity component.
v	:	y-velocity component.
w	:	z-velocity component (vertical velocity).
U	:	Vector of conserved variables in shallow water equations (h, hu, hv).
t	:	Time.
F(U)	:	Flux vector in shallow water equations.
S(U)	:	Source term vector in shallow water equations.
Ω	:	Control volume.
$\partial\Omega$	:	Boundary of the control volume.
n	:	Boundary unit normal vector.
F^I	:	Inviscid flux term.
F^V	:	Viscous flux term.
g	:	Acceleration due to gravity.
z_b	:	Bed elevation.
f	:	Coriolis coefficient.
ρ	:	Local fluid density.
ρ_0	:	Reference density.
p_a	:	Mean sea level pressure.

s_{ij}	:	Short-wave radiation stress tensor.
τ_s	:	Surface shear stress.
τ_b	:	Bottom shear stress.
S	:	Salinity concentration.
K_x, K_y	:	Horizontal dispersion coefficients.
K_v	:	Vertical eddy viscosity.
ν_t	:	Eddy viscosity (Turbulent Viscosity).
S_s	:	Salinity source/sink term.
ρ_I	:	Density of particle I (SPH).
v_I, v_J	:	Velocity of particle I and J, respectively (SPH).
$W(\lvert x_I\text{-}x_J\rvert, h)$	:	Kernel function (smoothing function in SPH).
ΔV_J	:	Volume of particle J (SPH).
x_I, x_J	:	Position of particle I and J, respectively (SPH).
r_{JI}, r_{IJ}	:	Position vector from particle J to I, or I to J (SPH).
g_I	:	Gravitational acceleration at particle I (SPH).
μ	:	Dynamic viscosity (SPH).
P_I, P_J	:	Pressure of particle I and J, respectively (SPH).
h	:	Smoothing length (in SPH context).
α_D	:	Normalization constant for the kernel function (SPH).
q	:	Relative non-dimensional distance between particles (SPH).
h_t	:	Kernel support size (SPH).
ν_h	:	Horizontal eddy viscosity.
C_s	:	Smagorinsky coefficient.
Δ	:	Filter width (Smagorinsky).
S_{ij}	:	Strain rate tensor.
$\overline{u_i^{'}u_j^{'}}$	:	Reynolds stresses.
U_k	:	Mean velocity component.
P_{ij}	:	Production term (Reynolds stress equation).
Φ_{ij}	:	Pressure-strain correlation.

ϵ_{ij}	:	Dissipation term (Reynolds stress equation).
D_{ij}	:	Turbulent diffusion term.
k	:	Turbulent kinetic energy.
ϵ	:	Dissipation rate of turbulent kinetic energy.
P_k	:	Production of turbulent kinetic energy.
$\sigma_k, \sigma_\epsilon$	:	Model constants (k-ε model).
$C_{\epsilon 1}, C_{\epsilon 2}$	:	Model constants (k-ε model).
ψ	:	Generic length scale parameter.
l	:	Turbulent length scale.
c_μ^0	:	Model constant (GLS model).
p, m, n	:	Exponents in GLS model definition.
$c_\mu, c_\mu^{'}$	:	Constants in stability functions.
$\overline{b'w'}$	:	Fluctuating buoyancy flux.
B	:	Mean buoyancy.
ν_v	:	Vertical eddy viscosity.
ν_{ij}	:	Full 3D turbulent viscosity tensor.
k_s	:	Roughness height.
d_{50}	:	Median grain size.
k_{sc}	:	Bed roughness for currents.
k_{sw}	:	Bed roughness for waves.
$\tau_{b,cw}$	:	Combined bed shear stress due to currents and waves.
$\tau_{b,cw,m}$	:	Modified combined bed shear stress.
$\tau_{b,c}$	:	Current-induced shear stress.
$\tau_{b,w}$	:	Wave-induced shear stress.
f_c	:	Friction coefficient due to current.
f_w	:	Friction coefficient due to waves.
f_{wr}	:	Wave friction coefficient for rough beds.
f_{ws}	:	Wave friction coefficient for smooth beds.
U_w	:	Orbital velocity amplitude (waves).
A_w	:	Semi-orbital excursion (waves).

Re_w	:	Wave Reynolds number.
r	:	Relative roughness (waves).
T_w	:	Wave period.
τ_{*c}	:	Critical Shields parameter.
τ_c	:	Critical shear stress for incipient motion.
ρ_s	:	Sediment density.
d	:	Grain diameter.
D_*	:	Dimensionless grain size.
F_e	:	Erosion flux.
Er	:	Erosion rate constant.
α	:	Power coefficient (erosion).
τ_{ce}	:	Critical shear stress for erosion.
$F_{e,i}$	:	Erosion flux for fraction \$i\$.
p_i	:	Fraction of sediment class \$i\$.
w_s	:	Settling velocity.
q_t	:	Total load transport rate.
A_s	:	Total load transport coefficient.
A_{sb}	:	Bed load transport coefficient.
A_{ss}	:	Suspended load transport coefficient.
$\overline{U}$	:	Depth-averaged current velocity.
$U_{w,rms}$	:	Root-mean-square wave orbital velocity.
C_D	:	Drag coefficient due to current.
β	:	Slope of the stream.
$\overline{U}_{cr}$	:	Threshold current velocity.
z_0	:	Bed roughness length.
z'	:	Water depth (2D) or bottom cell thickness (3D)