

**MATHEMATICAL APPROACHES  
SIGNIFYING THE STREAMBED AND  
AQUIFER PROPERTIES IN A COMBINED  
GW-SW SYSTEM**

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**JANUARY 2023**

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STREAMBED AND AQUIFER PROPERTIES IN A  
COMBINED GW-SW SYSTEM**

by

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**Submitted**

In the fulfilment of the requirements of the degree of Doctor of Philosophy

**To the**



**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**JANUARY 2023**

Dedicated to  
My Mother  
Dr. Neeta Tripathi

## CERTIFICATE

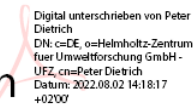
This is to certify that the thesis entitled “**Mathematical approaches signifying the streambed and aquifer properties in a combined GW-SW system**”, being submitted by **Ms. Moulshree Tripathi**, to the **Indian Institute of Technology Delhi** for the award of the degree of ‘**Doctor of Philosophy**’ in Department of Civil Engineering is a record of the bonafide research work carried out by her under our joint supervision and guidance. She has fulfilled the requirements for the submission of this thesis, which to the best of our knowledge has reached the requisite standard.

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



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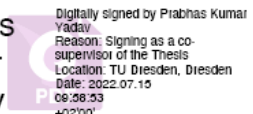
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## ACKNOWLEDGEMENTS

*We must find time to stop and thank the people who makes a difference in our lives.*

*-John F. Kennedy*

The developed thesis is the result of a valuable contribution by several individuals directly or indirectly who helped shape and achieve my goal. I feel privileged to express my sincere gratitude to all those who were with me during my working tenure in terms of their persuasion, motivation, guidance, encouragement, affection and blessings.

First and foremost, it is a pleasure to express sincere gratitude to my esteemed supervisor Prof. B. R. Chahar. His invaluable scholastic suggestions and constructive criticism culminated in the form of present work. He inculcated the work culture and research attitude in me. His advice on both research as well as on my career has been priceless. I am incredibly grateful for his valuable insights, fruitful discussions and innovative approach throughout my journey at IIT Delhi. I feel highly indebted to him.

I am deeply grateful to my incredible co-supervisor, Prof. P. Dietrich. His guidance and encouragement helped me to develop great enthusiasm and respect for research. His thorough comments and astute suggestion immensely enhanced the quality of my research work. I especially thank him for his continuous encouragement, which has driven me to this end.

I sincerely thank my co-supervisor, Dr P. K. Yadav, for his valuable suggestions, guidance and timely co-operation inspite of his hectic schedule. I am extremely grateful for his invaluable insights, fruitful discussions and innovative approach throughout PhD tenure.

I extend heartfelt thanks to my SRC members, Prof. R. Khosa, Prof. G. V. Ramana and Dr S. Z. Ahammad, for rendering me their valuable comments, encouragement and time towards my research.

My indebtedness to all faculty and staff members of the Civil Engineering Department, IIT Delhi, for their kind cooperation, help and support throughout my PhD tenure. I am also thankful to the Academic and Student section of IIT Delhi for providing me at the opportune moment with all the facilities required for my research work.

The project was carried out in collaboration with Helmholtz Centre for Environmental Research-UFZ Leipzig, Germany. I take this opportunity to acknowledge Dr M. Walther, Prof. R. Liedl and the faculty and staff of the Department of Monitoring and Exploration Technologies for their timely cooperation and kind support during my stay. I thank DAAD: German Academic Exchange Service for providing me Bi-Nationally Supervised Doctoral Degree Scholarship to fund my research and stay in Leipzig, Germany.

My sincere thanks to Nikhil Ghodichore for his continuous support, motivation and encouragement throughout my PhD journey. A special thanks to my friends Aparna Sharama, Sandhya Birla and Shikha Vats for being my support system at IIT Delhi. I extend my gratitude to Garima Gupta, Dr Gourab Ghatak, Himanshu P. Singh and Shaswat Panda for being my constant motivators. I thank Satya Pribadi Rishabh Gupta and Amanda Vinson for their efficient help and support.

I would like to thank and dedicate this work to my mother, Dr Neeta Tripathi. She is my inspiration to pursue a doctorate and not let go of things even during the worst times. Her constant encouragement kept me motivated during the ups and downs of my research work. I am highly indebted to my father, Dr Rajesh Kumar Tripathi. He is the foundation of my

academic career and my constant support. His never-failing trust, love and motivation made this journey possible.

My sincere gratitude to my life partner, Saurabh Sharma, for supporting me in every aspect of life and helping me to see the light at the end of the tunnel. For his motivation, care and affection, I am forever grateful. I am extremely thankful to my brother Rachit Tripathi for his support, which has always been and will always be crucial to my personal life as well as in my career endeavours.

I render my gratitude to my mother-in-law Smt. Lakshmi Sharma, father-in-law Shri Ashok Kumar Sharma and sister-in-law Divya Sharma for their love, encouragement and blessings.

I bow to the feet of the Almighty for making everything worthwhile and for always showering his pious blessing on me and giving me the opportunity to come so far in the journey of my life.

In appreciation,

Moulshree Tripathi

## ABSTRACT

Groundwater (GW) and surface water (SW) are the two interconnected components of the hydrological cycle. The GW-SW interaction plays a significant role in maintaining flow and transport in the riverine ecosystem. Therefore, it is crucial to understand the GW-SW interaction mechanism, governing processes, interaction scale, and quantification methods. The factors like hydrological and hydrogeological properties of the streambed and the aquifer, streambed topography, vegetation, and climatic changes govern the interactions. Considering all the governing factors in a single model for a holistic characterisation of GW-SW interaction is challenging.

The GW-SW exchanging flux is either measured directly in the field or quantified using numerical modelling techniques. Modelling techniques identify two governing components a) the streambed and b) the underlying aquifer. The thickness and width of the streambed, the hydraulic properties of the streambed and the underlying aquifer are the key parameters. However, there are limited studies which highlight the effect of individual parameters on the exchanging flux ( $Q_r$ ). The present study uses scenario-based numerical modelling to quantify their influence on the flux exchange using a 2D, steady-state and homogenous GW-SW combined model. The scenarios have been simulated using OpenGeoSys (v6.1) and adopting different hydraulic (hydraulic conductivity –  $K_r$ ,  $K_a$ ) and geometric (width –  $W_r$ ,  $W_a$  and thickness –  $t_r$ ,  $t_a$ ) properties of the streambed and the aquifer. The influence of these properties on exchanging flux has been analysed under high and low streambed conductance ( $K_r/t_r = C_r$ ). As can be seen, the aquifer properties dominate the exchanging flux at a higher  $C_r$  values, whereas for lower  $C_r$  values, streambed properties dominate the exchanging flux. The developed empirical expression provides a qualitative assessment of the influence of  $W_r$ ,  $K_a$ , and  $t_a$  with respect to  $C_r$  on  $Q_r$ .

A quantitative assessment has been performed using an analytical approach on the same GW-SW setup. The developed approach can define the criteria to identify when streambed or/and aquifer properties are governing  $Q_r$ . The approach also highlights the significance of head measurement location for flux quantification. In the case of a narrow stream with a low hydraulic conductivity streambed and an aquifer with a high transmissivity, the head should be measured near the stream edge. On the other hand, for wider streams, the head should be measured at larger distances from the stream edge. The analytical approach has matched well with a similar numerical model; hence, the solution can replace the numerical modelling for a similar setup.

The 2D model can capture the individual influence of parameters. However, it is limited to the application of different boundary conditions. These boundary conditions represent the GW flow occurring in the underlying aquifer. This 2D model has been extended to a 3D model to capture the effect of the different setup of boundary conditions (flow parallel and perpendicular to the streamflow). The infiltrating flux follows a logistic relation in both cases of GW flow. Field validation of the developed analytical approach and addressing complexities like streambed and aquifer heterogeneity, GW flow orientation, and external stresses like the recharge from the flood plains in a numerical model will further improve the performance.

## सारांश

भू जल (GW) और सतही जल (SW) जलीय चक्र के दो परस्पर जुड़े घटक हैं। GW-SW इंटरैक्शन नदी के पारिस्थितिक तंत्र में प्रवाह और परिवहन को बनाए रखने में महत्वपूर्ण भूमिका निभाता है। इसलिए, GW-SW इंटरैक्शन क्रियाविधि, गवर्निंग प्रक्रिया, इंटरैक्शन पैमाने और परिमाणन तरीकों को समझना महत्वपूर्ण है। प्रवाहित और जलभृत के जलीय और हाइड्रोजियोलॉजिकल गुण, प्रवाहित स्थलाकृति, वनस्पति और जलवायु परिवर्तन जैसे कारक परस्पर क्रियाओं को नियंत्रित करते हैं। GW-SW इंटरैक्शन के समग्र लक्षण वर्णन के लिए एकल मॉडल में सभी शासकीय कारकों पर विचार करना चुनौती पूर्ण है।

GW-SW विनिमय प्रवाह या तो सीधे क्षेत्र में मापा जाता है या संख्यात्मक मॉडलिंग तकनीकों का उपयोग करके निर्धारित किया जाता है। मॉडलिंग तकनीक दो गवर्निंग घटकों की पहचान करती है a) प्रवाहित और b) अंतर्निहित जलभृता प्रवाहित की मोटाई और चौड़ाई, प्रवाहित के हाइड्रोलिक गुण और अंतर्निहित जलभृत प्रमुख पैरामीटर हैं। हालांकि, ऐसे सीमित अध्ययन हैं जो विनिमय प्रवाह ( $Q_r$ ) पर व्यक्तिगत मापदंडों के प्रभाव को उजागर करते हैं। वर्तमान अध्ययन एक 2D, स्थिर-अवस्था और समरूप GW-SW संयुक्त मॉडल का उपयोग करके विनिमय प्रवाह पर उनके प्रभाव को निर्धारित करने के लिए परिदृश्य-आधारित संख्यात्मक मॉडलिंग का उपयोग करता है। परिदृश्यों को OpenGeoSys (v6.1) का उपयोग करके सिमुलेटे किया गया है और विभिन्न हाइड्रोलिक (हाइड्रोलिक चालकता –  $K_r, K_a$ ) और ज्यामितीय (चौड़ाई –  $W_r, W_a$  और मोटाई –  $t_r, t_a$ ) गुणों को अपनाया गया है। प्रवाह के आदान-प्रदान पर इन गुणों के प्रभाव का विश्लेषण उच्च और निम्न प्रवाहित चालन ( $K_r/t_r = C_r$ ) के तहत किया गया है। जैसा कि देखा जा सकता है, जलभृत गुण उच्च  $C_r$  विनिमय प्रवाह पर हावी होते हैं, जबकि निम्न  $C_r$  के लिए प्रवाहित गुण विनिमय प्रवाह पर हावी होते हैं। विकसित प्रयोगसिद्ध समीकरण  $Q_r$  पर  $C_r$  के संबंध में  $W_r, K_a$ , और  $t_a$  के प्रभाव का गुणात्मक मूल्यांकन प्रदान करती है।

उसी GW-SW प्रतिमान पर एक विश्लेषणात्मक दृष्टिकोण का उपयोग करके एक मात्रात्मक मूल्यांकन किया गया है। विकसित दृष्टिकोण यह पहचानने के लिए मापदंड को परिभाषित कर सकता है कि कब प्रवाहित या/और जलभृत गुण  $Q_r$  को नियंत्रित कर रहे हैं। दृष्टिकोण प्रवाह परिमाणन के लिए हेड माप स्थान के महत्व पर भी प्रकाश डालता है। कम हाइड्रोलिक चालकता वाली एक संकीर्ण धारा के मामले में और उच्च संप्रेषण के साथ एक जलभृत के मामले में, हेड को नदी के किनारे के पास मापा जाना चाहिए। दूसरी ओर, व्यापक धाराओं के लिए, हेड को नदी के किनारे से

बड़ी दूरी पर मापा जाना चाहिए। विश्लेषणात्मक दृष्टिकोण एक समान संख्यात्मक मॉडल के साथ अच्छी तरह से मेल खाता है; इसलिए, समाधान समान प्रतिमान के लिए संख्यात्मक मॉडलिंग को प्रतिस्थापित कर सकता है।

2D मॉडल मापदंडों के व्यक्तिगत प्रभाव को पकड़ सकता है। हालांकि, यह विभिन्न सीमा शर्तों के आवेदन तक ही सीमित है। ये सीमा स्थितियाँ अंतर्निहित जलभृत में होने वाले GW प्रवाह का प्रतिनिधित्व करती हैं। इस 2D मॉडल को 3D मॉडल तक विस्तारित किया गया है ताकि सीमा स्थितियों के विभिन्न प्रतिमान के प्रभाव को प्रदर्शित किया जा सके (स्ट्रीमफ्लो के समानांतर और लंबवत प्रवाह)। विनिमय प्रवाह, GW प्रवाह के दोनों मामलों में एक रसद संबंध का अनुसरण करता है। विकसित विश्लेषणात्मक दृष्टिकोण का क्षेत्र सत्यापन और संख्यात्मक मॉडल में प्रवाहित और जलभृत विषमता, GW प्रवाह अभिविन्यास, और बाहरी तनाव जैसे बाढ़ के मैदानों से पुनर्भरण, जैसी जटिलताओं को संबोधित करने से प्रदर्शन में और सुधार होगा।

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## LIST OF SYMBOLS

<b>Symbol</b>	<b>Meaning</b>
$A_r$	Amplitude ratio
$A_2$	Final value (Flux_max)
$A_1$	Initial value (Flux_min)
$C_r$	Streambed conductance - $K_r/t_r$
$C$	Streambed conductance - $(K_r W_r L_r)/t_r$
$C_s$ and $C_w$	Heat capacity of the sediment water matrix and the water
$CV$	Critical value
$C_{r_{min}}$ and $C_{r_{max}}$	Maximums of curvature corresponding to lower boundary of flux, and minimums of curvature corresponding to upper boundary of flux
$D$	Distance of head measurement
$\Delta\theta$	Temperature phase change
$\Delta h$	Hydraulic difference driving the flux from stream to aquifer
$\gamma$	Ratio of heat capacity of the streambed material ( $\rho c$ ) to that of the saturated sediment-fluid system ( $\rho_f c_f$ )
$h_{r_{bot}}$	Head at the bottom of the streambed
$h_{int}$	Head at the streambed aquifer interface
$h_r$ and $h_a$	Head of the stream and in the aquifer at any point $D$ between the stream edge and the domain edge
$h_{al}, h_{ar}, h_{af}$ and $h_{ab}$	Head at the aquifer left, right, front and back boundary.
$i$	Vertical hydraulic gradient
$i_{rl}$ and $i_{rr}$	Gradients induced by the flux from the stream into the aquifer
$i_a$	Gradient induced by a head difference along the basic flow direction in the aquifer

$K$	Curvature of the flux curve
$K_a$ and $K_r$	Hydraulic conductivity of aquifer and streambed
$K_e$	Effective thermal diffusivity
$K_t$	Thermal conductivity
$L_a$ and $L_r$	Length of the aquifer and stream
$n, \eta$	Porosity
$P$	Period of the temperature signal
$p$	Power
$t_a$	Thickness
$t_r$	Thickness
$T$	Aquifer transmissivity
$W_a$ and $W_r$	Width of the aquifer and stream
$Q_r$	Exchanging flux
$Q_{rl}$ and $Q_{rr}$	Fluxes exiting the left side and the right side of the domain
$Q_a$	GW flow
$Q_{al}$ on $Q_{ar}$	Total flux at the left and at the right observed at a distance $D$
$q_{Ar}$	Vertical water flux calculated using amplitude ratio
$q_{\Delta\theta}$	Vertical water flux calculated using temperature phase change
$v_d$	Darcian flux
$v_f$	Vertical fluid velocity
$v$	Thermal front velocity
$x_0$	Centre value
$X$	Targeted accuracy