ASSESSMENT OF INFILTRATION PROCESS CONSIDERING SLOPE AND DIURNAL TEMPERATURE VARIATION IN HUMID SUBTROPICAL REGION

LOHIT JAIN

DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI

AUGUST 2022

ASSESSMENT OF INFILTRATION PROCESS CONSIDERING SLOPE AND DIURNAL TEMPERATURE VARIATION IN HUMID SUBTROPICAL REGION

by

LOHIT JAIN

Department of Civil Engineering

Submitted

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

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

AUGUST 2022

This thesis is dedicated to

My Parents

(Mrs. Alka Jain and Mr. Vijay Jain)

For their constant encouragement, endless love and support

CERTIFICATE

This is to certify that the thesis, entitled “***Assessment of infiltration process considering slope and diurnal temperature variation in humid subtropical region***”, being submitted by Mr. Lohit Jain to the Indian Institute of Technology, Delhi, for the award of Doctor of Philosophy, is a record of bonafide research work carried out by him under my supervision. The thesis work, in our opinion, has reached the standard, fulfilling the requirements for the said degree. Further, we certify that this submission is Mr. Lohit’s own work and that, to the best of our knowledge and belief, it contains no material previously published or written by another person which to a substantial extent has been accepted for the award of any other degree or diploma of any University or Institute, except where due acknowledgement has been made in the text.

(Sumedha Chakma)
Associate Professor
Department of Civil Engineering
Indian Institute of Technology Delhi

ACKNOWLEDGEMENTS

During my doctoral studies, I have been very fortunate to be a part of the prestigious institute IIT Delhi, an institute of eminence. I consider it a proud privilege to express my heartfelt gratitude to my supervisor, Prof. Sumedha Chakma, Department of Civil Engineering, for his excellent supervision during this research work. Prof. Sumedha Chakma has been a source of vital support, constant motivation, and valuable suggestions that have helped me shape this dissertation. In addition to their technical guidance, he has set forth examples of personal attributes which I hope to emulate as a good human being. I sincerely acknowledge my SRC members, Prof. Alok Madan, Prof. Sawan Suman, and Prof. C. T. Dhanya, for their valuable feedback. I am thankful to the Ministry of Education for funding me with the Junior and Senior Research Fellowship.

I am incredibly thankful to my sister Saloni Jain for motivating me from time to time and supporting me in this journey. She has been a constant source of inspiration to me, and without her help, this work would not be able to reach the finishing line

I am very thankful to my wife, Anubhuti Jain, to help me in this challenging journey and to tolerate me in the most critical period of my life. She is the reason I could focus on my work without any interruption. For the successful completion of this thesis, I am deeply indebted to several people, of which a few names cannot go without being mentioned here. I wish to extend my sincere thanks to Dr. Alemayehu Abate Shawul, Dr. Tamru Tesseme Argawa. Mr. Abhay Guleria, all my lab-mates and fellow researchers in the water resources department.

I am equally grateful to the staff members of the Simulation Laboratory, Department of Civil Engineering, who, with their immense cooperation and friendly attitude, made work as exciting initiative to look forward to in routine. I cannot thank enough Mr. Rajveer Agrawal, Mr. N. R.

Gehlot, Mr. Amit Bundela, Mr. Teeka Ram and Mr. Yadram who lent their prompt help in anything and everything.

Apart from these, my special acknowledgement is due for Dr. Neeta who shared endless moments of laughter and she has proven herself to be a dependable friend time and again. Heartfelt appreciation is reserved for all my friends, whom I may have missed out on mention, for their help.

I have no word to express my gratitude and regard toward my father and mother for their contribution whatever I have achieved till date is beyond comparison. Their unconditional love, affection, and encouragement have helped me move ahead in my difficult times and complete my work successfully. Last but not least, I would like to thank my mother-in-law and father-in-law for their constant encouragement and love, without which I would not have been able to succeed.

Lohit Jain

ABSTRACT

The water infiltration into a soil system is a complex process dealing with oversimplified standard models by not considering important physical features like slope and temperature variation that govern the soil-water interaction and flow. Quantitative infiltration analysis of a soil surface becomes very complex when the collective impacts of slope and temperature are considered for micro-macro flow based on the land use and land type (LULC). This study focuses on the infiltration responses of the topsoil layer in the ponding condition for flat surface (0^o-4^o), gentle slope (5^o-15^o), and moderate slope (16^o-25^o) depending on the availability at the site incorporating the diurnal temperature variation by conducting Double-ring experiments in morning and afternoon session for each category of slope keeping all other factors similar. The influence of slope was investigated separately as well on the conceptually designed hillslope experimental set-up by analysing simulated rainfall and generated runoff on the soil samples extracted from the agriculture, landfill, and bare surfaces incorporating the effects of 10^o, 20^o, and 30^o slopes. The experimental study was emphasised four common LULC such as agricultural field, grassland, bare surfaces, and, from the environmental perspective, solid waste landfill for the impacts of slope and temperature variation on corresponding infiltrated volume. Three popular classical infiltration models, such as Kostiakov, Horton, and Philip models, were optimised to generate the parameters producing the closest outcomes to the observed cumulative infiltration in all slope and temperature variation conditions based on the field experimental data. Statistical tools- Coefficient of determination (R^2), Nash Sutcliffe Efficiency (NSE), Percentage Biased (PBIAS), and Root mean Square Error- observations standard deviation ratio (RSR) were engaged to evaluate the best performing model incorporating the slope and temperature impacts. Total 20 scenarios were studied to determine the quantitative impact of local topographical and local climatic conditions on cumulative infiltration. After the experimental studies, the physical-based analytical infiltration module was developed by combining the modified Green-Ampt model for micropores flow in the soil matrix and the Hagen Poiseuille-Manning equation for preferential flow from macropores incorporating the impacts of diurnal temperature variation on soil-water physical characteristics and inclination of surfaces. The model was calibrated by experimental data observed from flat and gentle slope surfaces for all focused LULC in morning and afternoon sessions and validated the estimated cumulative infiltration for moderate slope in a higher temperature range. The results show that initial and final infiltration rates were not significantly correlated with temperature and slope; however, initial infiltration rates were majorly affected by the LULC and were found 2.56 times higher for harvested agricultural areas than grass areas. Cumulative infiltration was generally lowest in solid waste landfill and highest in bare surfaces among all selected (LULC). Cumulative infiltration volume has positively correlated with slope and temperature variation for all LULC under ponded conditions. The observations of the hillslope experimental set-up show that agricultural soil has experienced higher abstractions for all slopes and got saturated earlier than other-focused land uses. The infiltered volume was significantly affected by the slope of the surface when runoff was allowed and showed the average reduction in cumulative infiltration was analysed as 7.62% and 27.8% when the surface slope increased from 10^{o} to 20^{o} and $30^{o,}$ respectively. The mean rise in runoff was observed as 18.34% and 45.5% for the same increment of the slope. Overall, the Philip model showed the most efficient performance after the developed infiltration model (GIM) as per the statistical analysis.

The study is expected to be valuable for decision making in land management of focused land covers, irrigation management in terms of estimating field-scale runoff and infiltration by providing experimental supported data. The developed General Infiltration Model (GIM) proved to be more efficient and useful for better estimating the infiltration characteristics incorporating the combined impacts of slope and temperature. The results are expected to be useful for landfill management regarding the environmental aspects situated in the humid subtropical region of India.

सार

मृदा प्रणाली में पानी की अंतःस्यंदन एक जटिल प्रक्रिया है जो मिट्टी-पानी के संयोजन और प्रवाह को नियंत्रित करने वाली ढलान और तापमान भिन्नता जैसी महत्वपूर्ण भौतिक विशेषताओं पर विचार न करके अतिसरलीकृत मानक मॉडल से निपटती है। मिट्टी की सतह का मात्रात्मक अंतःस्यंदन विश्लेषण बहुत जटिल हो जाता है जब भूमि उपयोग और भूमि प्रकार (एलयूएलसी) के आधार पर सूक्ष्म मैक्रो प्रवाह के लिए ढलान और तापमान के सामूहिक प्रभावों पर विचार किया जाता है। यह अध्ययन समतल सतह (0°-4°), जेंटल ढलान (5°-15°), और मध्यम ढलान (16°-25°) के लिए एकत्रित पानी की स्थिति में अन्य सभी कारकों को समान रखते हुए ढलान की प्रत्येक श्रेणी के लिए सुबह और दोपहर के सत्र में डबल-रिंग प्रयोग करके दैनिक तापमान भिन्नता को शामिल करते हुए ऊपरी मिट्टी की परत की अंतःस्यंदन प्रतिक्रियाओं पर ध्यान केंद्रित करता है, जो प्रयोगात्मक पर ढलान की उपलब्धता पर निर्भर करता है। ढलान के प्रभाव की अलग-अलग जांच की गई और साथ ही अवधारणात्मक रूप से डिजाइन किए गए पहाड़ी ढलान प्रयोगात्मक सेट-अप पर नकली वर्षा का विश्लेषण करके और कृषि, लैंडफिल, और खुली सतहों से 10o, 20o, और 30o ढलानों के प्रभावों को शामिल करते हुए मिट्टी के नमूनों पर उत्पन्न अपवाह का विश्लेषण किया गया। प्रायोगिक अध्ययन ने चार सामान्य एलयूएलसी जैसे कृषि क्षेत्र, घास के मैदान, खुली सतह, और, पर्यावरणीय दृष्टिकोण से, ढलान के लिए ठोस अपशिष्ट लैंडफिल और संबंधित अंतःस्यंदन की मात्रा पर तापमान भिन्नता प्रभावों पर जोर दिया। क्षेत्र प्रयोगात्मक डेटा के आधार पर सभी ढलान और तापमान भिन्नता स्थितियों में देखे गए संचयी अंतःस्यंदन के निकटतम परिणाम उत्पन्न करने के लिए तीन लोकप्रिय पारंपरिक अंतःस्यंदन मॉडल, जैसे कि कोस्टियाकोव, हॉर्टन और फिलिप मॉडल के पैरामीटर अनुकूलित किए गए थे। सांख्यिकीय उपकरण- निर्धारण का गुणांक (R2), नैश सटक्लिफ दक्षता (NSE), प्रतिशत बायस्ड (PBIAS), और रूट माध्य वर्ग त्रुटि- अवलोकन मानक विचलन अनुपात (RSR) का उपयोग ढलान और तापमान प्रभावों को शामिल करते हुए सर्वश्रेष्ठ प्रदर्शन करने वाले मॉडल का मूल्यांकन करने के लिए किया गया था। संचयी अंतःस्यंदन पर स्थानीय स्थलाकृतिक और स्थानीय जलवायु परिस्थितियों के मात्रात्मक प्रभाव को निर्धारित करने के लिए कुल 20 परिदृश्यों का अध्ययन किया गया था। प्रायोगिक अध्ययनों के बाद, भौतिक-आधारित विश्लेषणात्मक अंतःस्यंदन मॉड्यूल को मिट्टी के मैट्रिक्स में माइक्रोप्रोर्स प्रवाह के लिए संशोधित ग्रीन-

एम्प्ट मॉडल और मिट्टी पर दैनिक तापमान भिन्नता के जल भौतिक विशेषताओं पर प्रभाव और सतहों का झुकाव को शामिल करते हुए मैक्रोपोर्स से अधिमानी प्रवाह के लिए हेगन पॉइज़ुइल-मैनिंग समीकरण को मिलाकर विकसित किया गया। मॉडल को सुबह और दोपहर के सत्रों में सभी केंद्रित LULC के लिए सपाट और जेंटल ढलान सतहों से देखे गए प्रयोगात्मक डेटा द्वारा कैलिब्रेट किया गया था और उच्च तापमान सीमा में मध्यम ढलान के लिए अनुमानित संचयी अंतःस्यंदन को मान्य किया गया। परिणाम बताते हैं कि प्रारंभिक और अंतिम अंतःस्यंदन दर तापमान और ढलान के साथ महत्वपूर्ण रूप से सहसंबद्ध नहीं थे; हालाँकि, प्रारंभिक अंतःस्यंदन की दर LULC द्वारा प्रमुख रूप से प्रभावित हुई थी और घास वाले क्षेत्रों की तुलना में कटाई वाले कृषि क्षेत्रों के लिए 2.56 गुना अधिक पाई गई। सभी चयनित (एलयूएलसी) के बीच संचयी अंतःस्यंदन आम तौर पर ठोस अपशिष्ट लैंडफिल में सबसे कम और खुली सतहों में सबसे अधिक थी। संचयी अंतःस्यंदन मात्रा तालाब की परिस्थितियों में सभी LULC के लिए ढलान और तापमान भिन्नता के साथ सकारात्मक रूप से सहसंबद्ध है। पहाड़ी ढलानों के प्रायोगिक सेट-अप के अवलोकन से पता चलता है कि कृषि मिट्टी ने सभी ढलानों के लिए उच्च अमूर्तता का अनुभव किया है और अन्य केंद्रित भूमि उपयोगों की तुलना में पहले संतृप्त हो गई है। जब अपवाह की अनुमति दी गई थी तब सतह के ढलान से अंतःस्यंदन की मात्रा काफी प्रभावित हुई थी और दिखाया गया था कि संचयी अंतःस्यंदन में औसत कमी का विश्लेषण 7.62% और 27.8% के रूप में किया गया था, जब सतह ढलान क्रमशः 10° से 20° और 30° तक बढ़ गया था। ढलान की समान वृद्धि के लिए अपवाह में औसत वृद्धि 18.34% और 45.5% के रूप में देखी गई थी। कुल मिलाकर, फिलिप मॉडल ने सांख्यिकीय विश्लेषण के अनुसार विकसित अंतःस्यंदन मॉडल (जीआईएम) के बाद सबसे कुशल प्रदर्शन दिखाया।

प्रायोगिक समर्थित डेटा प्रदान करके क्षेत्र-स्तरीय अपवाह और अंतःस्यंदन के आकलन के संदर्भ में केंद्रित भूमि कवर के भूमि प्रबंधन, सिंचाई प्रबंधन में निर्णय लेने के लिए प्रस्तुत अध्ययन के मूल्यवान होने की उम्मीद है। विकसित सामान्य अंतःस्यंदन मॉडल (जीआईएम) ढलान और तापमान के संयुक्त प्रभावों को शामिल करते हुए अंतःस्यंदन की विशेषताओं का बेहतर आकलन करने के लिए अधिक कुशल और उपयोगी साबित हुआ। भारत के आर्द्र उपोष्णकटिबंधीय क्षेत्र में स्थित पर्यावरणीय पहलुओं के संबंध में प्रस्तुत परिणामों के लैंडफिल प्रबंधन के लिए उपयोगी होने का अनुमान है।

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF NOMENCLATURE

Nomenclature	Description
f_t	Infiltration rate at time t
a, a_1	Multiplying constant parameter
b, b_1	Exponent parameter
f_c	Steady-state infiltration rate
t	Time/ duration
f_o	Initial infiltration rate
k	Decay coefficient
p	Rainfall intensity
t_p	Time when rainfall intensity equals to infiltration rate
Δt	Time interval
S_o	Storage potential of the soil
F_t	Cumulative infiltration at time t
GI	Growth index of crop maturity
y	Surface connected porosity index
S_a	Available storage in the surface layer
t_c	Time scale parameter
n	Total porosity
m	Exponent depending on LULC and cropping conditions
S	Sorptivity
t_o	Time to ponding
SR	Potential maximum retention parameter
k_{sat}	Saturated hydraulic conductivity
ψ	The suction head due to capillary attraction
θ_d	Moisture difference between saturated state and initial state
S_p	Total pressure heads
n_e	Effective porosity $(\theta_{\mathrm{Sat}} - \theta_i)$
Υ	Slope angle of the surface
z	Vertical depth of permeable soil layer
D	Diffusivity
k	Hydraulic conductivity
θ	Moisture content
S	Sorptivity
A	Constant addition parameter
q_i	Volumetric inflow into macropore
i_{mat}	Infiltration rate into the soil matrix
n_{mac}	Macropore density per unit area
h	Pressure head
Γ_{RWU}	Sink/source denoting root water uptake
Γ_{BF}	Water exchange between soil matrix and biopores

Γ_{DF}	Drainage flow
E	Objective function for minimum error
O(i)	Observed values at time step ‘i’
S(i)	Simulated values at time step ‘i’
$\overline{O}$	Mean value of observed data
$\overline{S}$	Mean value of simulated data
h_t & h_{t-1}	The water level at time t and t-1
T	Temperature
J	Number of observations
La	Land use coefficient
SL	Slope
FD	Field density
x	Slope coefficient
y	Field density coefficient
w	Temperature coefficient
P	Precipitation
R	runoff
$\overline{T}$	Weightage average temperature
V	Normalized variable
v_i	Variable value on i^{th} position
v_{min}	Minimum value of variable v
v_{max}	Maximum value of variable v
N	Number of neurons in hidden layer
A	Model constant
B	Model constant
δ	Lag in time
T_a	Air temperature
T_w	Water temperature
μ	Dynamic viscosity
A	1.98404 x 10^{-6} Pa-sec
B	1825.85 ^{o}C
ν_T	Kinematic viscosity at temperature T
ρ_T	Density of water at temperature T
k_T	Hydraulic conductivity at temperature T
Sa	% of sand
H_1 & H_2	Water level elevation inside the ring on the inclined surface
L	Length of macropore
ΔP	Pressure head gradient
Δx	Variable length of macropore
q_t	Water flow rate
g	Gravitational acceleration
r_{min}	Equivalent radius of minimum sized macropore

q_{m1}	Water flow rate from a minimum sized macropore in a single time step
ν	Kinematic viscosity
τ	Tortuosity
q_{m2}	Flow rate entering in soil due to the largest size of macropores
r_{max}	Largest size of macropores
S_f	Frictional slope
η	Manning coefficient representing the soil material surface
F_{mic}	Cumulative infiltration through micropores
θ_{sat}	Saturated water content $(n-\theta_r)$
θ_r	Residual water content
H	Depth normal to inclined the soil surface
Ψ	Wetting front matric potential
z	Depth normal to the surface
L_h	Length of hillslope
k_{sat}	Saturated hydraulic conductivity presented as a function of temperature
W_1	Weight assigned to water flow rate from a minimum sized macropore
W_2	Weight assigned to water flow rate from a maximum sized macropore
W_3	Weight assigned to cumulative infiltration through micropores
q_T	Total lateral flow volume
q_{mic}	Lateral flow volumes from micropores
q_{mac}	Lateral flow volumes from macropores
V(t)	The total volume received by the micropore domain (including seepage from macropore walls)
q_{m1}	Inflow in minimum sized macropores
q_{m2}	Inflow in maximised sized macropores
R_t	Moisture retention
$k_h(T)$	Lateral hydraulic conductivity function of water temperature T oc
L_f	Amount of water transacted to the micropore domain
P	Precipitation
r	Runoff
P & Q	Parameters of power equation