PROBABILISTIC-BASED PREDICTION OF RAINFALL-INDUCED LANDSLIDES

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ABSTRACT

Prediction of rainfall-induced landslides has received considerable attention amongst the scientific community due to the geological hazard's catastrophic impacts. The prediction is commonly performed based on rainfall threshold. However, less attention has been given to physical-based thresholds. The thresholds are also mainly determined based on deterministic model. The inherent uncertainties in soil properties are neglected. Therefore, this study aims to improve the prediction of landslides in unsaturated slopes by incorporating the uncertainties in soil properties. The performance of the landslide predictive models can be enhanced towards a more reliable landslides warning system. One of the major slope failure events in Kota Kinabalu, Sabah, Malaysia, is selected as a case study. Statistical analyses have been conducted to characterize the uncertainties in hydro-mechanical soil variables by identifying best-fitted marginal distribution amongst normal, lognormal, Gumbel, and Weibull distribution. The dependencies of the multivariate are assessed using different types of vine copula models. Then, a reliability-based probabilistic analysis has been proposed to determine the performance level of the slope by integrating the Monte Carlo Simulation and Multilayer Perceptron regressor, using 120 samples of soil properties generated from the Latin Hypercube Sampling. Three types of rainfall thresholds, namely intensity-duration, cumulative rainfall-duration, and daily rainfall-antecedent rainfall for various antecedent days of 5, 10, 15, 20, 25, and 30 days are proposed. Comparison of rainfall threshold based on probabilistic and deterministic models shows that the former outperforms the latter in threat score. The antecedent rainfall of 10 and 15 days can well describe the landslides initiation compared to other antecedent rainfall durations for the daily rainfall-antecedent rainfall threshold. This study mainly contributes to the development of a new physical-based rainfall threshold for predicting landslides initiation using a reliability-based probabilistic approach by incorporating the uncertainties in dependent hydro-mechanical soil variables for the first time.

ABSTRAK

Ramalan kejadian tanah runtuh akibat hujan telah menerima banyak perhatian dalam kalangan komuniti saintifik kerana bencana alam tersebut boleh mendatangkan impak yang memudaratkan. Ramalan tersebut lazimnya dilaksanakan berdasarkan nilai ambang hujan. Walau bagaimanapun, perhatian yang diberikan kepada ambang hujan berdasarkan pendekatan fizikal adalah kurang. Nilai ambang tersebut juga biasanya dikenal pasti dengan menggunakan model berketentuan. Ketidakpastian terwujud dalam sifat-sifat tanah diabaikan. Oleh itu, kajian ini bertujuan untuk menambahbaik ramalan kejadian tanah runtuh dalam cerun tak tepu dengan mempertimbangkan ketidakpastian dalam sifat-sifat tanah. Prestasi model ramalan tanah runtuh dapat dipertingkatkan bagi mewujudkan sistem amaran tanah runtuh yang lebih dipercayai. Salah satu kejadian utama kegagalan cerun di Kota Kinabalu, Sabah, Malaysia telah dipilih sebagai kajian kes. Analisis geostatistik telah dilaksanakan untuk memperincikan ketidakpastian dalam pembolehubah hidro-mekanik tanah dengan mengenalpasti agihan jidar melibatkan agihan normal, lognormal, Gumbel, dan Weibull. Kebersandaran berbilang pembolehubah dinilai dengan menggunakan model kopula *vine* yang pelbagai. Kemudian, analisis kebarangkalian berdasarkan kebolehharapan telah dibuat bagi menentukan tahap perlakuan cerun dengan menggabungkan Simulasi Monte Carlo dan regresi *Perceptron* Berbilang Lapis, menggunakan 120 sampel sifat-sifat tanah yang dijana daripada persampelan *Latin Hypercube*. Tiga jenis ambang hujan iaitu keamatan-tempoh, hujan kumulatif-tempoh, dan hujan harian-hujan anteseden bagi pelbagai tempoh anteseden 5, 10, 15, 20, 25, dan 30 hari telah dikemukakan. Perbandingan ambang hujan antara model kebarangkalian dan berketentuan menunjukkan bahawa model kebarangkalian mempunyai skor prestasi yang lebih baik. Untuk ambang berdasarkan hujan harian-hujan anteseden, hujan anteseden bagi tempoh 10 dan 15 hari boleh menjelaskan permulaan tanah runtuh dengan lebih baik berbanding tempoh hujan anteseden yang lain. Secara utamanya, kajian ini menyumbang kepada pembangunan ambang hujan berdasarkan kaedah fizikal bagi meramalkan kejadian tanah runtuh dengan menggunakan pendekatan kebarangkalian berdasarkan keboleharapan yang mengambil kira ketidakpastian dalam pembolehubah hidro-mekanik tanah yang bersandaran buat pertama kalinya.

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LIST OF ABBREVIATIONS

$\overline{\text{FOS}}_{\text{actual}}$	-	Mean of Actual Factor of Safety
$\text{FOS}_{\text{actual}}$	-	Actual Factor of Safety
$\text{FOS}_{\text{predicted}}$	-	Predicted Factor of Safety
A	-	Angle
ADAM	-	Adaptive Moment Estimation
AIC	-	Akaike Information Criterion
BIC	-	Bayesian Information Criterion
Cl	-	Clayton Copula
COV	-	Coefficient of Variation
E	-	East
E-D	-	Cumulative rainfall-duration
FN	-	False Negative
FOS	-	Factor of Safety
Fr	-	Frank Copula
Gm	-	Gumbel Copula
Gs	-	Gaussian Copula
GWT	-	Groundwater Table
h	-	Hour
H	-	Height
HCF	-	Hydraulic Conductivity Function
I-D	-	Intensity-duration
KM, km	-	Kilometre
MAE	-	Mean Absolute Error
ML	-	Machine Learning
MSE	-	Mean Squared Error
N	-	North
NM	-	Numerical Modelling
P	-	Probability
PDF	-	Probability Density Function
POF	-	Probability of Failure

R_1-AR	-	Daily rainfall-antecedent rainfall
RI	-	Relative Importance
RMSE	-	Root Mean Squared Error
S	-	Sample
SA	-	Statistical Analysis
SPT	-	Standard Penetration Test
SRF	-	Shear Reduction Factor
St	-	Student's *t* Copula
SWCC	-	Soil Water Characteristic Curve
TP	-	True Positive
TRIGRS	-	Transient Rainfall Infiltration and Grid-based Regional Slope Stability
TS	-	Threat Score

LIST OF SYMBOLS

σ	-	total normal stress
χ	-	effective stress parameter
Λ	-	contact angle
γ	-	unit weight of soil
ν	-	Poisson's ratio
ϕ'	-	effective internal friction angle
ϕ^b	-	friction angle due matric suction increase
θ_r	-	residual volumetric water content
θ_s	-	saturated volumetric water content
θ_{vi}	-	water content of the *i*-th fraction
γ_w	-	surface tension of water
θ_ψ	-	volumetric water content at a matric suction
h, h_i	-	pressure head of water
A_{ev}	-	air-entry value
K_s	-	saturated hydraulic conductivity
K_ψ	-	hydraulic conductivity at a matric suction
N_h	-	number of hidden node
R_i	-	average of particle radius for the *i*-th fraction
S_e	-	effective water content
V_b	-	volume of soil sample
V_{vi}	-	pore volume
b_h	-	bias (also known as threshold) for the hidden node *h*
b_o	-	bias for the output node *o*
f_{hidden}	-	transfer function of the hidden layer
f_k	-	marginal densities in vine copula
f_{output}	-	transfer function for the output layer
l_i	-	length of pore
n_i	-	number of spherical particles for fractions of particle size
n_{inp}	-	number of input node

r_i	-	pore radius
u_a	-	pore air pressure
u_w	-	pore water pressure
var_{max}	-	minimum values of dataset
var_{min}	-	minimum values of dataset
$var_{normalised}$	-	normalised values of the variable
w_{ho}	-	weight between the hidden node h and output node o
w_i	-	solid mass of the i-th fraction
w_{ih}	-	weight between the input node i and hidden node h
x_i	-	i-th input unit
z_s	-	soil depth
λ_L	-	coefficients of lower tail dependence
λ_U	-	coefficients of upper tail dependence
ρ_b	-	bulk density
ρ_p	-	particle density
τ_f	-	shear strength
C	-	copula function or bivariate copula
c	-	copula density function
D	-	dimension of input variables
E	-	Young's modulus
F	-	joint probability density function
f	-	probability density function
I	-	rainfall intensity
k	-	number of distribution parameter
N	-	number of random samples
N_θ	-	cumulative distribution function of standard bivariate normal distribution with Pearson's correlation coefficient θ
P	-	probability
p, q	-	marginal distribution parameters
R^2	-	correlation coefficient
R^2	-	correlation coefficient
s	-	second
t	-	time

T_θ	-	cumulative distribution function of Student's t copula with Pearson's correlation coefficient θ
T_λ	-	cumulative distribution function of Student's *t* copula with λ degree-of-freedom
$x_1, x_2, \ldots, x_n$	-	random vector
z	-	elevation head
α, n, m	-	fitting parameters of Soil Water Characteristic Curve
β	-	reliability index
μ	-	mean value
σ	-	standard deviation
Φ	-	standard normal distribution function
Φ	-	standard normal cumulative distribution function
$\phi_\theta(t)$	-	generator function in bivariate copula
$D(\theta)$	-	hydraulic diffusivity
$F(x\|v)$	-	functions of conditional distribution for variable *x* and *v*
$K(\theta)$	-	permeability
L	-	log-likelihood function
$c(\theta)$	-	specific moisture capacity
c'	-	effective cohesion
e	-	void ratio
$f(x_i)$	-	distribution of variable x_i
g	-	acceleration due to gravity
$g(x)$	-	limit state function for variable *x*
k	-	node number in the hidden layer
l	-	parameter describing the pore structure of soil
n_s	-	number of samples
var	-	value of input variable
θ	-	Pearson's correlation coefficient
λ	-	degree-of-freedom
τ	-	Kendall's correlation coefficient
ψ	-	matric suction
y_{MLP}	-	output of Multilayer Perceptron
$F_1, F_2, \ldots, F_n$	-	marginal distribution function

$u_1, u_2, \ldots, u_n$	-	standard uniform variables
F_i^{-1}	-	inverse of marginal cumulative distribution function
$c_{i,i+j\|1:(i-1)}$	-	bivariate copula densities with *j*-th tree and *i*-th root node

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CHAPTER 1

INTRODUCTION

1.1 Background

Landslide is one of the widespread geological hazards around the globe, which has caused damage to properties, economic loss, and numerous casualties. Based on natural hazards worldwide, landslides account for at least 17% of the fatalities (Chae *et al.*, 2017). Most landslide occurrences are associated with rainfall. The antecedent rainfall is one of the main predisposing factors in triggering landslides, as it may cause a surge in the soil's moisture content. The role of antecedent rainfall, which occurs for several days closely before the landslide event, has been widely accepted.

The growth of population, urbanisation on hilly terrain, and global climate change have sharpened the impact of rainfall-induced landslides. The associated damages and losses are increasing with intensification in landslide frequency. Awareness of the catastrophic impacts that landslides can bring to life and social well-being has led to study initiatives in mitigating the risk. One of the research areas which shows growing advances in recent times pertains to landslide prediction. The early detection of landslides can be performed based on in-situ ground movement monitoring, in response to changes in physical soil properties subjected to rainfall infiltration. This approach may provide a nearly real-time indicator of landslide initiation. However, establishing a proper setup of a landslide warning system may incur an expensive budget for both instrumentation and monitoring. Fortunately, the landslide prediction based on a rainfall threshold can provide a more cost-effective and practical yet reliable alternative for landslide forecasts (Segoni, Piciullo and Gariano, 2018). The rainfall threshold may serve as a basis for on-ground monitoring of landslide initiation.

The rainfall thresholds can be developed using an empirical- or physical-based approach (Guzzetti *et al.*, 2007). The former is commonly performed based on a statistical analysis of historical landslide events. The method is preferred by various researchers. It is relatively easy and can be carried out by relying on rainfall data and landslide incidents that are obtainable in most cases. The empirical-based approach for identifying rainfall thresholds has been observed as early as the 1970s (Onodera, Yoshinaka and Kazama, 1974). The latter mainly involves numerical modelling to simulate physical processes involving seepage and slope stability. Early application of the physical-based approach to identify the relationship between rainfall and slope failure can be observed since the 1980s (Crozier and Eyles, 1980). However, limited studies have been carried out based on the physical-based method compared to the empirical-based approach. The limited studies are mainly due to the complexity involved in the physical-based approach. Comprehensive spatial information such as hydrology, lithology, and morphology are required. The information is unavailable in most cases. Sufficient technical skills and knowledge are also essential for numerical simulation. Nonetheless, more attention should be given to the physical-based approach as it can provide a more in-depth understanding of the actual underlying landslide process.

In the physical-based rainfall threshold, slope stability assessment is carried out to determine the rainfall condition which may trigger a landslide. The stability of the slope subjected to rainfall infiltration is commonly analysed using a deterministic approach (Tang, Li and Cao, 2016; Senthilkumar, Chandrasekaran and Maji, 2018; Z. Li *et al.*, 2019). A factor of safety is quantitively used to indicate the slope stability condition, where the value of 1.0 theoretically marks the boundary between stable and unstable states. Nonetheless, the factor of safety is subjected to uncertainties since the slope's resistance and disturbing factors involve various uncertainties mainly due to inherent variabilities in soil properties. Thus, it may not be reasonable to apply a similar minimal value of factor of safety for different conditions with various ranges of uncertainties degree. This shortcoming in deterministic analysis has led to the introduction of probabilistic analysis in slope engineering since the 1970s (Alonso, 1976; Tang, Yucemen and Ang, 1976). The probabilistic approach systematically estimates the performance of the slope in terms of reliability index and probability of failure (POF) by incorporating various sources of uncertainties.

1.2 Problem Statement

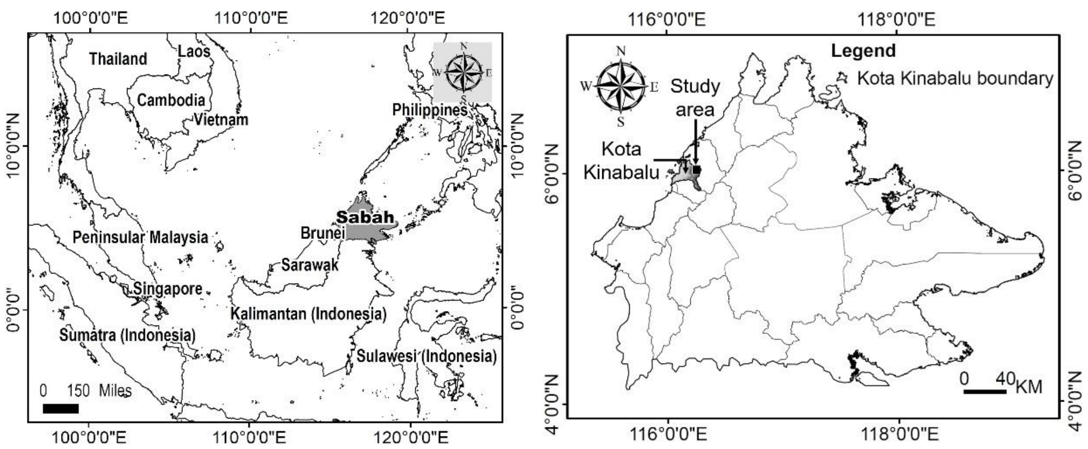
The stability of unsaturated slopes subjected to rainfall infiltration is governed by the coupled effect of mechanical and hydraulic soil properties. Current research shows that determinate values of hydro-mechanical soil properties have been considered in the slope stability analysis to predict landslide initiation. In contrast, variabilities in soil properties exist.

In predicting rainfall-induced landslides, the physical-based thresholds in the literature have been identified based on deterministic analysis where the soil uncertainties have been neglected. The deterministic approach is adopted to identify the condition at which slope failure may occur, *i.e.*, when the factor of safety is lesser than unity. The deterministic method relies on a single and unique value of factor of safety. The factor of safety is computed based on the determinate value of the selected soil properties. However, using specific values of soil properties may not represent the uncertainties in the soil properties. Thus, the proposed threshold may not reflect a reliable slope stability condition. The shape and location of critical slip planes in the deterministic analysis may not necessarily be equal to that in the probabilistic analysis. The distributions in soil properties variabilities are not considered in the former analysis. Some applications of probabilistic analyses have been demonstrated in geotechnical engineering over the past few decades. However, not much recent progress has been observed in the method application, especially in assessing rainfall-induced landslides in unsaturated slopes. The limited progress is likely due to the perception that the probabilistic analysis is more rigorous and time-consuming. Researchers and practising engineers may also receive inadequate exposure to the application of probabilistic methods in slope engineering.

1.3 Study Area

The capital city of Sabah in Malaysia, *i.e*., Kota Kinabalu, is one of the densely populated areas in the territory. Many rainfall-induced landslides have been reported in Kota Kinabalu. The density of the landslide is increasing with the pace of urban development in the city. The landslides that mostly happen in inhabited areas have attracted the local community's attention due to the direct adverse impact of the incident, especially in terms of socio-economic and safety. Therefore, a reliable landslide warning system should be established so that the authority can take proper action. A local rainfall threshold for landslide initiation in Kota Kinabalu is yet to be developed. Thus, this study is timely and will pioneer the development of rainfall threshold for Kota Kinabalu area.

One of the landslide-prone areas within the vicinity of Kota Kinabalu is situated at a natural hilly terrain around a local access road, known as Jalan Penempatan. Thus, the location is selected as a case study. The study area is situated to the east of Kota Kinabalu city (Figure 1.1), which can be found at latitude and longitude of 5°59'7.41" N and 116°4'41.63" E, respectively. The road stretches about 3 km long (from 5°57'16.14" N, 116°5'40.19" E to 5°56'5.36" N, 116°5'32.13" E). It serves as an important route that connects several housing areas to the city centre. The study location covers an area of about 320 hectares.



(a) (b)

Figure 1.1 Location of study area in (a) Sabah at east of Malaysia and (b) Kota Kinabalu in Sabah

1.4 Goal and Objectives

The goal of this study is to improve the prediction of rainfall-induced landslides within a probabilistic framework. To meet the goal, three (3) objectives have been identified as follows:

1. To characterise the variabilities, uncertainties, and dependencies of soil properties.

2. To propose an efficient reliability-based probabilistic model for back analysis of unsaturated slope.

3. To develop probabilistic-based predictive models of rainfall-induced landslides.

1.5 Research Questions

Several research questions related to the study objectives have been identified, as explained in Table 1.1.

Table 1.1 Research questions in this study

No.	Objective	Research Questions
1	To characterise the variabilities, uncertainties, and dependencies of soil properties.	i. What are the soil properties that should be considered as random variables? ii. Which probability density functions can best describe the variabilities and uncertainties for each soil property? iii. How can the dependencies of the multivariate be modelled and assessed?

No.	Objective	Research Questions
2	To propose an efficient reliability-based probabilistic model for back analysis of unsaturated slope.	i. How does the soil uncertainties affect the unsaturated slope behaviour under rainfall infiltration? ii. How can the probabilistic approach be integrated with machine learning for the optimization of computational cost? iii. What is the performance level which can initiate a landslide in the study area? iv. What is the effect of different dependencies models in slope reliability assessment? v. What is the contribution of each selected random variable on the slope performance?
3	To develop a probabilistic-based predictive model of rainfall-induced landslides.	i. What is the effect of different combinations of slope geometry and groundwater table on slope stability? ii. What is the dominant factor that should be considered for the development of the rainfall threshold? iii. What is the rainfall threshold which can initiate landslides in the study area? iv. How can the proposed rainfall threshold be validated? v. How does the probabilistic-based rainfall thresholds differ than those based on deterministic model?

1.6 Scope of Study

This study presents the temporal prediction of landslide initiation in unsaturated soil slope subjected to antecedent rainfall within a probabilistic approach. The development of the predictive model mainly includes statistical analysis, machine learning, and two-dimensional numerical modelling. This research involves computer programming and finite element-based simulation.

A major incident of a rainfall-induced landslide at Jalan Penempatan Kilometre (KM) 2.00 in Kota Kinabalu, Sabah, is selected as a case study. This site-scale study aims to demonstrate the application of the proposed reliability-based method based on the actual scenario. Data such as soil investigation and laboratory testing reports, and rainfall records were obtained from government departments. Various hydraulic and mechanical soil properties are considered random variables. The uncertainties of the variables are quantified, and the dependencies of the multivariate are modelled systematically. A sampling-based probabilistic approach is adopted to estimate the slope's performance level in terms of probability of failure. The reliability analysis is coupled with supervised machine learning to determine the regression function, where training and testing of the dataset are performed.

The method in the case study will be extended to develop the predictive model of landslide initiation in the Kota Kinabalu area at a distributed scale. The soil properties in the case study are also considered representative for the Kota Kinabalu area as the locations are underlain by similar geological formations, namely Crocker Formation. The formation typically consisted of a thick sequence of grey to bluish-grey of fine to medium-grained sandstone and combinations of red and grey shale beds. Series of parametric analyses are performed to investigate the contribution of different combinations of slope geometry and groundwater table on the stability condition of the slope. The dominant factor will be adopted to construct the predictive model. Besides the probabilistic-based predictive model, the deterministic-based model is constructed to assess the performance of the former model.

1.7 Significance of Study

This study mainly improves the existing technique to predict rainfall-induced landslides in unsaturated slopes with a more reliable approach. Several benefits can be gained from this study as follows:

1. The proposed method for slope probabilistic analysis that systematically considers the quantification of uncertainties and dependencies of soil variables can be used as a practical guide for estimating the performance level of slope.
2. This study also forms the foundation of a more reliable landslide warning system in the future. Thus, the local authority can execute a proactive measure to reduce the risk of landslides, especially in populated areas near the hillsides.

1.8 Structure of Thesis

This thesis consists of eight chapters: Introduction (Chapter 1), Literature Review (Chapter 2), Methodology (Chapter 3), Verification Study of Numerical Modelling (Chapter 4), Characterisation of Variabilities, Uncertainties, and Dependencies of Soil Properties (Chapter 5), Probabilistic Model for Back Analysis of Unsaturated Slope (Chapter 6), Predictive Models of Rainfall-induced Landslides (Chapter 7), and lastly Conclusions and Recommendations (Chapter 8).

Chapter 1 explains the background, problem statement, study area, goal and objectives, research questions, scope of study, significance of study, and structure of thesis.

Chapter 2 presents a review on a coupled hydro-mechanical constitutive model, variability and uncertainty in geotechnical engineering, dependency of variables, probabilistic analysis in slope engineering, and prediction of rainfall-induced landslides.

Chapter 3 describes the case study, data, application of software, development of Soil Water Characteristic Curve (SWCC), best-fitting of marginal distribution, construction of vine copula, numerical modelling, Multilayer Perceptron regression, Monte Carlo simulation, sensitivity analysis, parametric analysis, and rainfall threshold for landslide initiation.

Chapter 4 explains the selected case study at Zaoyang, Hubei, China, soil properties, slope geometry model, meshing, and boundary conditions, initial condition, and the analysis and result.

Chapter 5 describes the characterisation of variabilities of soil properties, characterisation of uncertainties of soil properties, characterisation of dependencies of soil properties, and performance of vine copula models.

Chapter 6 discusses the soil properties, slope model, coupled seepage-deformation modelling, slope stability analysis, regression based on Multilayer Perceptron Network, Monte Carlo simulation, performance level threshold, impact of vine copula on slope performance, and sensitivity of hydro-mechanical soil properties.

Chapter 7 presents the parametric study, development of new rainfall thresholds, and the validation of rainfall thresholds.

Chapter 8 provides the conclusions of this study. Recommendations for future study are also presented.

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1. **Joe, E. J.**, Ali, N. and Jusoh, S. N. (2020) 'Numerical modelling of coupled seepage-deformation subjected to rainfall infiltration in unsaturated slope', World Journal of Engineering, 17(6), pp. 867–875. doi: 10.1108/WJE-01-2020-0039. **(Indexed by SCOPUS)**

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1. **Joe, E. J.**, Ali, N. and Jusoh, S. N. (2021) 'Reliability-based prediction of landslide using efficient Monte Carlo Simulation', IOP Conference Series: Materials Science and Engineering, 1153(1), pp. 1–10. doi: 10.1088/1757-899x/1153/1/012002. **(Indexed by Web of Science)**