JOURNAL OF DEGRADED AND MINING LANDS MANAGEMENT
Volume 9, Number 3 (April 2022):3561-3572, doi:10.15243/jdmlm.2022.093.3561
ISSN: 2339-076X (p); 2502-2458 (e), www.jdmlm.ub.ac.id

Research Article

Landslide frequency and its relationship with urban development in landform above groundwater basin area of Bogor, Indonesia

Yulia Amirul Fata[1], Hendrayanto[2*], Nur Febrianti[3]

[1] Forest Management Science, Graduate Study Program, IPB University, Bogor, 16680, Indonesia
[2] Forest Management Department, IPB University, Bogor, 16680, Indonesia
[3] Remote Sensing Application Center, Indonesian National Institute of Aeronautics and Space, Jakarta, 13710, Indonesia

[*]corresponding author: hendrayanto@apps.ipb.ac.id

Article history:
Received 3 February 2022
Accepted 7 March 2022
Published 1 April 2022

Keywords:
discharge
groundwater basin
landslide
non-groundwater basin
recharge
urban development

Abstract

The presence of groundwater in the groundwater basin increases the potential of rainwater seeping into the soil and reaching the groundwater system. As a result, the soil takes longer to get saturation and maintain its stability. The groundwater basin stability is also influenced by the layer's lithological, soil, and morphological properties above the groundwater system and human activities on the land. The purpose of this study was to characterize the groundwater basins, non-groundwater basins, and landslides that happened in those locations in the tropical region of Bogor, Indonesia. The characteristics of landslide events, including lithological, groundwater table, soil, slope, and land use in each groundwater basin zone, were evaluated using quantitative descriptive analysis. The result showed 686 landslides from 2015 to 2019 that mainly occurred in the discharge zone, characterized by slope classes of >45%, soil types of Technosol (Inceptisols), Quaternary lithology periods, and settlement land use. The landslide type in the groundwater basin is dominated by surface landslides, while the landslides in the non-groundwater basin are mostly shallow landslide types.

To cite this article: Fata, Y.A., Hendrayanto, and Febrianti, N. 2022. Landslide frequency and its relationship with urban development in landform above groundwater basin area of Bogor, Indonesia. Journal of Degraded and Mining Lands Management 9(3):3561-3572, doi:10.15243/jdmlm.2022.093.3561.

Introduction

Landslides are Indonesia's third-largest natural disaster after floods and tornadoes. Over the last ten years (2009-2019), over 4663 landslides occurred, accounting for 23.3 percent of all disasters, resulting in over 235 thousand fatalities, 35 thousand damaged dwellings, and 473 damaged public buildings, including health, religious, and education facilities (BNPB, 2019).

In Bogor, 686 landslides occurred in landforms over groundwater basins between 2015 and 2019. Landslide susceptibility assessment resulted from lithology, land cover (Hidayat et al., 2019), and soil (Silalahi et al., 2019) are the dominant factors that caused landslides in Bogor. The lithology and soil as the static factors characterized the groundwater basin, while the land use as the landform above the groundwater basin is the dynamic factor triggering a landslide. Landslides in the Bogor area from 2015 to 2019 mostly occurred in the discharge zone of the groundwater basin (the density of 0.00602 event/ha). Other landslides occur in the recharge zone of the groundwater basin (the density of 0.001126 event/ha) and the non-groundwater basin zone (the density of 0.00048 event/ha) (Fata et al., 2020). Theoretically, the groundwater basin is more stable than the non-groundwater basin. Since groundwater is available in the groundwater basin, rainfall can permeate the soil and reach the groundwater system. Therefore, the soil is longer to reach saturation, except in the shallow groundwater basin. The groundwater basin itself consists of the recharge and discharge zones (Kodoatie, 2012).

Groundwater and non-groundwater basins have different geological and morphological characteristics in recharge and discharge zones. The recharge zone has permeable lithology and high groundwater levels, allowing water infiltration to form a thick water column and high hydraulic pressure to fill the aquifer system. The discharge zone has impermeable lithology with shallow groundwater levels, preventing water column infiltration and providing hydraulic pressure to fill the aquifer system. The non-groundwater basin, on the other hand, has impermeable lithology, no aquifer system, and faults that induce morphological alterations. Groundwater basin aquifer systems allow water to infiltrate, and lithology without faults is more stable than non-groundwater basin lithology (Kodoatie, 2012). However, the groundwater basin stability is also influenced by the landform's lithological, soil, and morphological characteristics above the groundwater system and human activities on the land. The high rate of population growth and economic activity in Bogor has resulted in land-use change. Land-use change mostly has occurred in the groundwater basins of Bogor City and Regency. Land-use change affects the land subsidence in the landform above groundwater basins.

Land-use changes, such as converting natural land-covers to man-made land-covers such as developed areas of a building, settlement, industries, constructions, and agricultural lands with unappropriated, contributed to the fatal landslide (Froude and Petley, 2018). As an anthropogenic factor, human activity also causes changes in land cover and water use that reduce groundwater level by increasing pumping, decreasing recharge, or increasing groundwater abstraction by vegetation (Pourghasemi et al., 2017; Rahmati et al., 2019).

Other elements influencing an area's stability include topography, slope steepness, soil type, rainfall attributes, earthquake, land use/cover, and human intervention (Marui and Wanfg, 2015; Froude and Petley, 2018; Segoni et al., 2018). The interaction of those factors with groundwater can modify geology properties and result in geological hazards such as landslides (Wu, 2003).

Rainfall provides water that infiltrates the soil and excess water that flows as surface flows. The surface flow that creates canals causes shallow landslides (Hao et al., 2019; Marin and Velasquez, 2019), and rainwater infiltrates the soil, increasing water content, decreasing matric suction, increasing pore-water pressure, and decreasing shear strength (Alsubal et al., 2019). Heavy rainfall creates a perched water table, significantly raising the groundwater table. Heavy rainfall forms a perched water table and raises the groundwater table extensively. The groundwater table rising is critical when reaching the slip surface of the slope that causes a deep-seated landslide (Kim et al., 2014; Ling et al., 2016). The infiltrated water and groundwater flow, which seepage out of slopes or in the foot slopes, such as springs, also triggered landslides (Denchik et al., 2019).

Earthquake tremor reduces shear strength in some types of soil. When an earthquake occurs, the soil pores of loose fine sand soil or silt laid below the groundwater table swell, increasing pore water pressure. Earthquake-induced landslides, 84.7% of which were influenced by roads and rivers that form steep slopes, reducing the strength of the foot slope (Ling and Chigira, 2020). The earthquake reduces slope stability, resulting in landslides and liquefaction (Doi et al., 2019). Liquefaction typically occurs in saturated soil where the pore cavity is filled with water; when an earthquake occurs, the pore water pressure rises, causing a loss of shear strength. The soil further liquefies (Hutagalung and Tarigan, 2019).

The multi-factors that cause landslides and the human intervention in the landform above groundwater basin and non-groundwater basin must be researched further better to understand the causes of landslides in the landform above groundwater basin and non-groundwater basin. This study aimed to characterize the landslide and its relationship with urban development in the landform above the groundwater basin and non-groundwater basin in the tropical region of Bogor-Indonesia.

Materials and Methods

Study site

This study was carried out in the Bogor Area, including the Bogor Regency and City, West Java Province, Indonesia. The Bogor Area is located upstream of Jakarta, Indonesia's capital. The Bogor Area consists of Groundwater Basins (GwB) of Bogor Groundwater Basin (BGwB), Serang-Tangerang Groundwater Basin (STGwB), Jakarta Groundwater Basin (JGwB), and Bekasi-Karawang Groundwater Basin (BKGwB), as well as Non-Groundwater Basin (Non-GwB) (Groundwater Basin map scale 1: 125000). The GwB occupies 152412.5 ha (54.8%) of the Bogor Area, while the Non-GWB occupies 125837.5 ha (44.2%). The discharge zone in Bogor Area is only in the BGwB, and the area is 51.8% of GwB or 28.4% of Bogor Area (Figure 1 and Table 2).

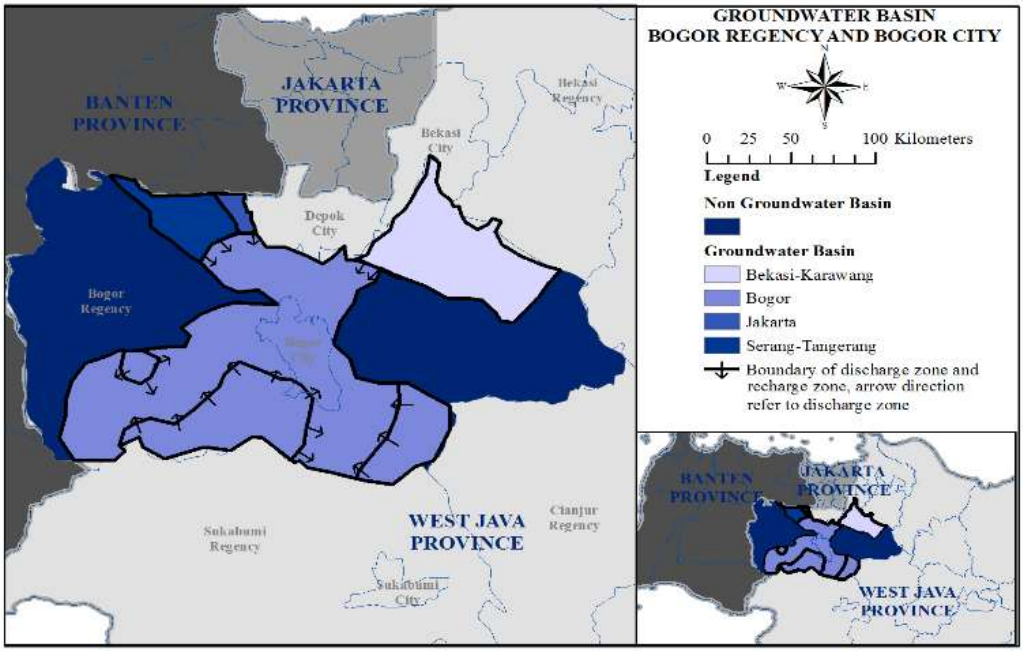

Figure 1. Groundwater basin in Bogor area.

Data collection

The data types and sources used in the study are presented in Table 1.

Table 1 The data types and sources.

Data Type	Time Series	Data Source	Note
Landslide	2015-2019	Regional Disaster Management Agency of West Java (*Badan Penanggulangan Bencana Daerah,* BPBD)	Location and area of impact
Governmental Administration Boundaries	2019*	Geospatial Information Agency (*Badan Informasi Geospatial,* BIG)	Bogor area
Lithology and structure	2019*	Ministry of Energy and Mineral Resources (*Kementerian Energi dan Sumber Daya Mineral,* ESDM)	Geological map, scale 1: 50000 and attributes
Slope steepness classes	2019*	Generated from the National Digital Elevation Model (DEMNAS) of BIG	The spatial resolution of 5 m x 11.25 m and mapped at Scale 1:25000
Soil types and properties	2019*	Center for Research and Development on Agricultural Land Resources (*Balai Besar Litbang Sumber Daya Lahan Pertanian*, BBSDLP)	Soil map, scale 1: 50000, and attributes according to World Reference Base (WRB) for a soil classification system
Land use	2015-2019	Generated from SPOT 6 and 7 imagery of Indonesian National Institute of Aeronautics and Space (*Lembaga Penerbangan dan Antariksa Nasional*, LAPAN)	Spatial resolution 1.5 m x 1.5 m, interpreted visually at scale 1:25000
Earthquake	2015-2019	USGS (United States Geological Survey) (2020) and Meteorology Climatology and Geophysics Agency (*Badan Meteorologi, Klimatologi, dan Geofisika*, BMKG)	Magnitude and earthquake depth
Faults	2017	Ministry for Public Works and Human Settlements (Kementerian Pekerjaan Umum dan Perumahan Rakyat, PUPR)	Fault map
Rainfall	2015-2019	BMKG of West Java Province and BMKG (2020)	Daily rainfall
Groundwater basin	2019*	Ministry of Energy and Mineral Resources (ESDM)	Groundwater basin map scale 1: 125000

Note: * downloaded.

Data analysis

Spatial analysis was carried out to analyze the spatial distribution of landslides. The landslides distribution map was overlaid with a groundwater basin, lithology, soil, slope steepness class, rainfall distribution, earthquake, and land-use maps. The results of this spatial analysis were used to determine the landslides to be ground-checked. The ground check was carried out to check the landslide locations, land covers/uses, slope steepness, solum depth, and the landslides dimension. The ground-checked landslides were chosen purposively to represent the heterogeneity of land covers/uses, slope steepness classes, lithology, and soil types according to WRB for the soil classification system, considering the accessibility of landslide locations.

Characterization of the landslide and the landform above groundwater basin

The 72 of 686 landslides that occurred in the Bogor area from 2015 to 2019 (BNPB, 2019) were selected to ground check the parameters of slope steepness, landslide depth, land use types, and the presence of human activities. The landslide characteristics were analyzed using frequency analysis and quantitative descriptive analysis.

Results and Discussion

Groundwater basin characteristics

Table 2 shows the general characteristics of GwB and Non-GwB in the Bogor area. Figure 2 shows the land-use change in the landform above GwB and Non-GwB of Bogor Area. Figures 3, 4, and 5 show the spatial distributions of lithology, soil type, slope steepness, and groundwater basin.

Land-use change from 2015 to 2019 is shown in Figure 2. Land use in the study area is dominated by mixed plantations by 50% (2015) and reduced to 38% (2019) of the total area. Garden land use decreased from 5% to 4% (2015-2019). However, forest land use and settlement land use increased from 18% to 24% and from 15% to 18% (2015-2019). Meanwhile, waterbody, vacant land, mining land, paddy field, and shrubs and bushes remained constant during 2015-2019. The decreased area of the garden and mixed garden is dominantly changed into forest and settlements (Figure 2).

The geology of GwB and non-GwB in the Bogor Area is dominated (68%) by Quaternary Period lithology as young lithologies. Another lithology is formed in the Neogene Period as the older lithologies. The Quaternary Period lithology dominated the GwB discharge and recharge zones, whereas Neogene Period lithology dominated the non-GwB (Table 2). The young lithologies are less stable than the old lithologies. Alluvium Fans, Endut Volcanic, and Older Deposits are the dominant lithology of the Quaternary Period, and the Bojongmanik and Jatiluhur Formations are the lithologies of the non-GwB Neogene Period (Figure 3). Cambisols soil dominates the Bogor Area, accounting for 56% of the total area. Cambisols soil type dominated in the discharge zone of GwB and non-GwB, whereas Arenosols soil type dominated in the recharge zone of BGwB (Table 2 and Figure 4).

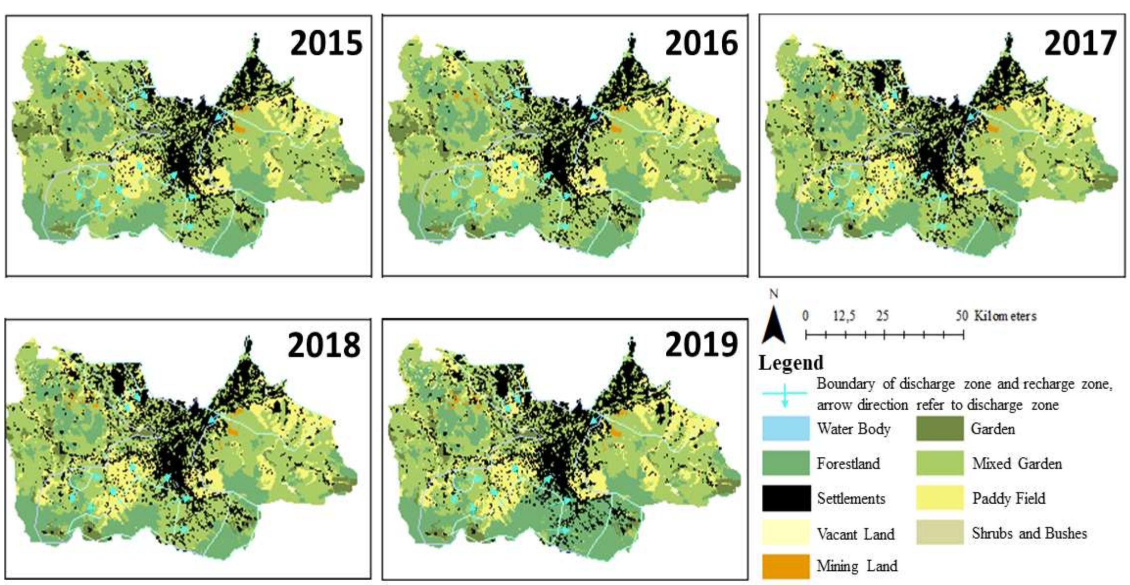

Figure 2. Land use change from 2015 to 2019 in landform above GwB and Non-GwB of Bogor area.

Table 2 The characteristics of GwB dan non-GwB parameter.

Parameter (unit)	Class/ Type/ Presence	GwB						Non-GwB
		Discharge Zone	Recharge Zone					
		BGwB	BGwB	STGwB	BKGwB	JGwB	Total	
Total Area (ha)	Area	**79019.0**	**34046.6**	9663.9	27943.4	1739.7	73393.5	**125837.5**
Geology (ha)	Quaternary	**76588.9**	**33825.3**	4613.5	21615.3	1721.1	**61776.0**	49763.0
	Neogene	2430.1	221.3	5050.4	**6328.1**	18.6	11617.5	**76074.5**
Soil (ha)	Andosols	9749.7	5280.0	28.5			5308.4	13488.2
	Anthrosols	1944.5	184.9				184.9	
	Arenosols	7200.2	**19320.1**				19320.1	8985.6
	Cambisols	**38495.9**	3725.9	8258.9	19159.4	1739.7	**32883.9**	**83404.7**
	Fluvisols	120.0						
	Gleysols	4132.6	3.1	1376.5	3214.5		4594.1	9025.2
	Luvisols	294.4			5569.5		5569.5	10866.8
	Regosols	9371.2	5379.3				5379.3	66.7
	Technosols	7710.5	153.3				153.3	0.3
Slope (ha)	<8%	**39622.2**	9973.2	6327.1	8865.8	1739.7	26905.8	39766.3
	8–15%	30832.9	9194.0	2905.9	**14843.4**		**26943.3**	**41897.1**
	15–25%	8028.3	9795.7	370.0	3545.0		13710.7	24748.5
	25–40%	5973.5	5034.7	24.3	684.7		5743.7	14806.6
	>40%	535.5	49.0	36.6	4.5		90.0	4619.0
Rainfall (mm/year)	High				3040			
Fault (-)	Present(P)/ Absent (A)	P	A	A	A	A		P
Earthquakes (SR)	Magnitude				2.22 – 6.09			
Groundwater (m)	below soil surface	2–40	2–22	0–150	8–160	0–250		1–27

Notes:

Andosols	:	Soil distinguished by Fe/Al chemistry (Allophanes or Al-humus complexes)
Anthrosols	:	Soil with strong human influence (Long and intensive agriculture use)
Arenosols	:	Soil with little or no profile differentiation (Sandy)
Cambisols	:	Soil with little or no profile differentiation (Moderately developed)
Fluvisols	:	Soil with little or no profile differentiation (Stratified fluviatile, marine, and lacustrine sediment)
Gleysols	:	Soil distinguished by Fe/Al chemistry (Groundwater-affected, underwater, and in tidal areas)
Luvisols	:	Soil with clay-enriched subsoil (high-activity clays, high base status)
Regosols	:	Soil with little or no profile differentiation (No significant profile development)
Technosols	:	Soil with strong human influence (Containing significant amounts of artefacts)

Cambisol soil types have deep solum, fine to moderate texture, and good drainage, whereas Arenosol soil types have moderate–deep solum, slightly coarse texture, and fast drainage. Andosols, Anthrosols, Fluvisols, Gleysols, Luvisols, Regosols, and Technosols are also found in the area. Based on the United States Department of Agriculture (USDA) soil classification system, those soil also classified as Alfisols, Andisols, Entisols, and Inceptisols soil type. Inceptisols soil dominates 89% of the total area, resulting in the soil type classified by WRB soil classification system dominated by Inceptisols. The total area of Alfisols, Andisols, and Entisols are 2%, 0.5%, and 8%, respectively. Those soil types are distinguished by deep solum. Soil types with a deep solum, coarse texture, well drainage, and groundwater table have a greater capacity to store water and infiltrate water deeper than soil types with a medium solum depth. When soil water is laid on the aquifer (recharge zone), it can penetrate or percolate to reach the aquifer system.

The discharge zone of the groundwater basin is dominated by slope classes of 8%, whereas slope classes of >8% dominate the recharge zone and non-groundwater basin (Figure 5). Slope failure is more likely on steeper slopes than on gentler slopes. The earthquake frequently occurs in the Bogor area. According to Meteorology Climatology and Geophysics Agency (BMKG) and the United States Geological Survey (USGS), from 2015 to 2019, 1584 earthquake events with magnitudes of 2.22–6.09 occurred at depths greater than 10 km (Table 2). The largest earthquake, with a magnitude of 6.09, was recorded on January 23, 2018. Earthquake-induced earthquake-triggered landslides during and after the earthquake (Doi et al., 2019).

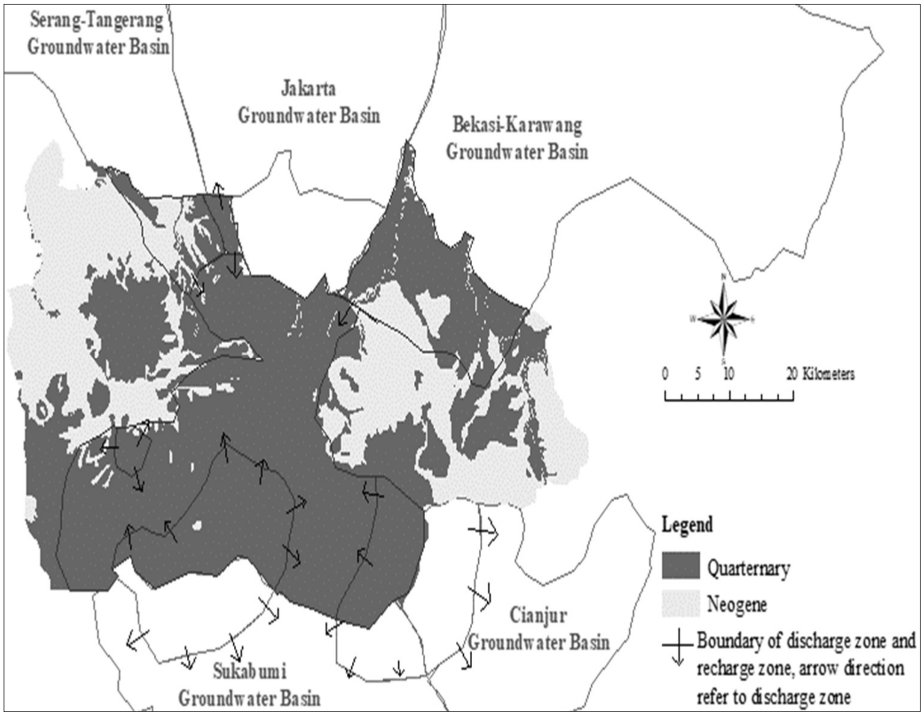

Figure 3. Lithology distribution in GwB and Non-GwB of Bogor area.

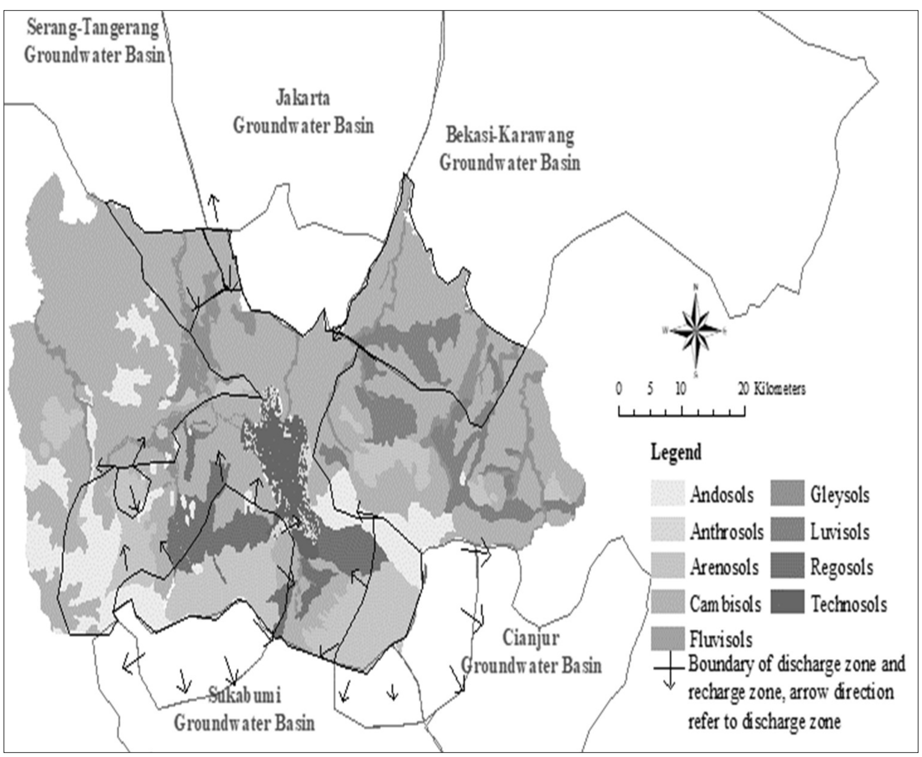

Figure 4. Soil types distribution in GwB and Non-GwB of Bogor area.

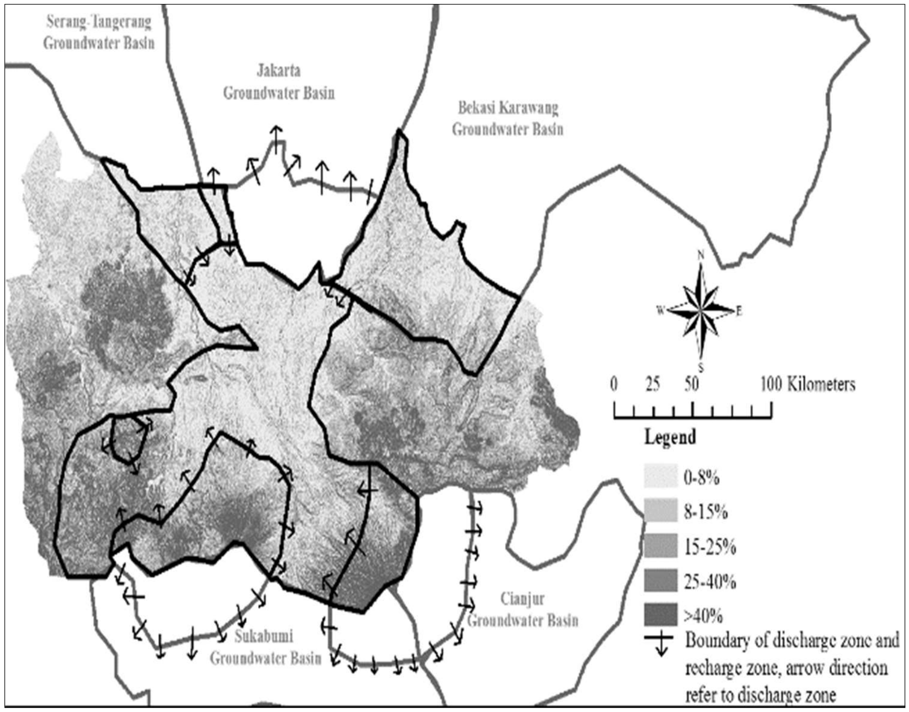

Figure 5. Slope steepness classes distribution in GwB and Non-GwB of Bogor area.

Bogor Area is a moist tropical region with frequent and heavy rainfall. Over the last five years, the average annual rainfall was 3040 mm/yr. The maximum daily and monthly rainfall totaled 164 mm/day and 907 mm/month, respectively. The average number of rainfall days per month was 20 days, and the maximum number of rainfall days per month was 29 days. Heavy and frequent rainfall accelerates soil saturation and the rise of the water table, both of which cause landslides and slope failure. The dominant man-made slope can efficiently reduce land sliding through controlled surface water flow using a rainwater drainage system in a developed area.

Landslide characteristics

The number of landslides that occurred in the Bogor area from 2015 to 2019 was 686, and based on mapping landslide location on Ground Water Basin Map scale 1:125000, the landslides mainly occurred (77%) in the GwB discharge zone. Landslides occurred in the recharge zone at a rate of 13% (92 landslides) and 10% (67 landslides), respectively (Figure 6). Figure 7 represents the spatial distribution of the 686 landslides in the Bogor area. Considering the area of each zone of the GwB and non-GwB, the density of landslide occurrence in discharge, recharge zones, and non-GwB were 0.67, 0.13, and 0.05 landslides/km^2, respectively.

The 686 landslides have 172 different characteristics of geology (A), slopes steepness (B), soil type (C), the presence of earthquakes (D), land use type (E), and rainfall intensity (F). The landslide characteristics that occurred ≥5 times during 2015-2019 are presented in Figure 8. The data in Figure 7 shows the landslides in Discharge and Recharge Zones of GwB as well as in Non-GwB occurred in quarternary period geological period (A1), the soil types of Technosols (C9), Cambisols (C4), and Regosols (C8), absence earthquake (D2), land use of settlements, agriculture lands, any range of rainfall intensities, and slope steepness <8%.

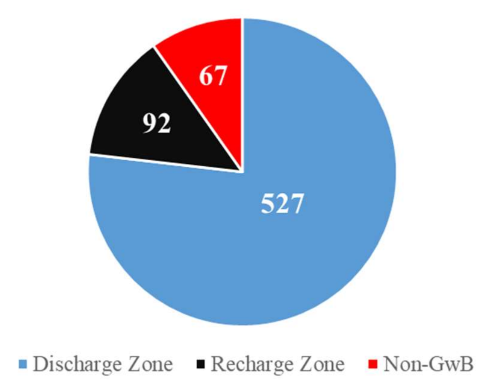

Figure 6. The number of landslides occurred in discharge and recharge zones of GwB and Non-GWB.

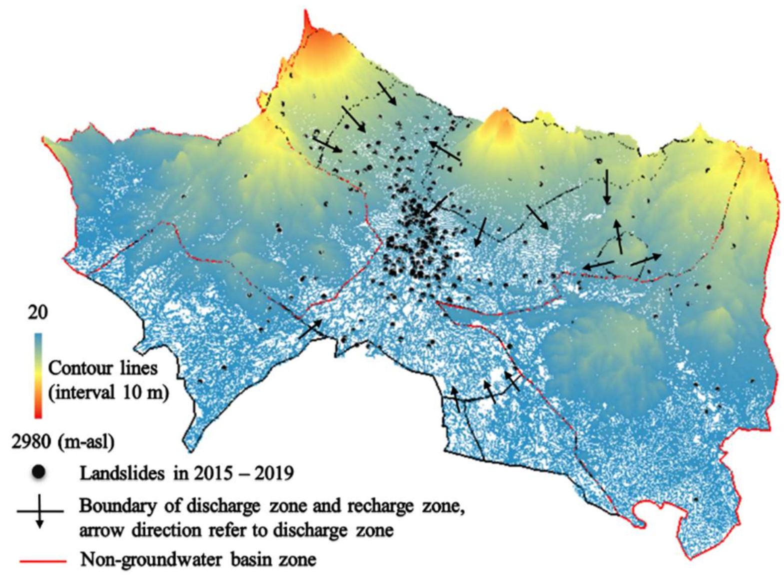

Figure 7. Spatial distribution of landslides in GwB and Non-GwB in Bogor area.

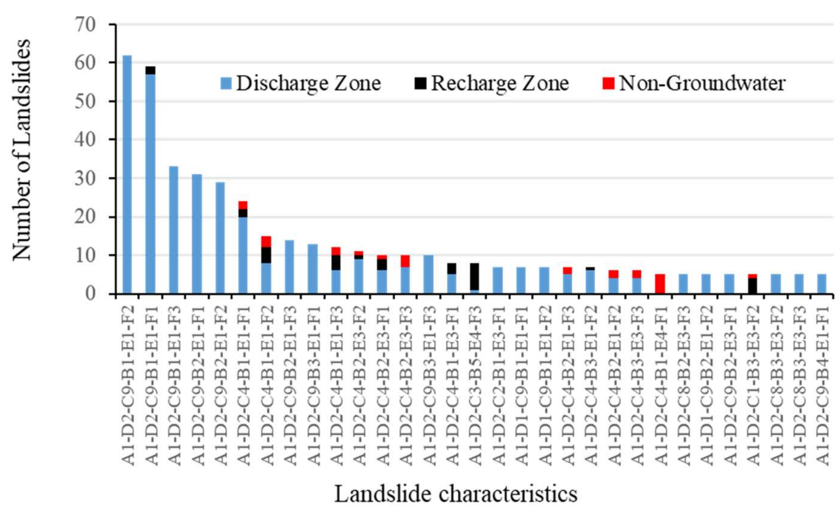

Figure 8. The landslide characteristics which their occurrence ≥ 5 times.

A	:	Geological Period; (A1) Quaternary and (A2) Neogene
B	:	Slope steepness class; (B1) <8%; (B2) 8-15%; (B3) 15-25%; (B4) 25-40%; (B5) >40%
C	:	Soil Type; (C1) Andosols; (C2) Anthrosols; (C3) Arenosols; (C4) Cambisols; (C5) Fluvisols; (C6) Gleysols; (C7) Luvisols; (C8) Regosols; (C9) Technosols
D	:	Earthquake; (D1) Presence; (D2) Absent
E	:	Land Use/Cover; (E1) Settlement and Industry; (E2) Shrubs and Bushes; (E3) Agriculture; (E4) Forest
F	:	Cumulative rainfall; (F1) >50 mm/5 days; (F2) 50-100 mm/5 days); (F3) >100 mm/5 days

The Quaternary period lithologies cover 97 percent of the Bogor area (Table 2), and this lithology is more prone to landslides than the older Neogene period lithology. The soil type of Technosols is a strongly human-influenced soil with a high concentration of artefacts (FAO, 2015). The strong human influence on soil results in changes in soil properties, which affect soil stability. The other Cambisol soil type has good slope stability properties. However, the presence of settlement on that soil may cause a change in the bulk density of the soil, which, when combined with improper land preparation during settlement development, results in land stability. The earthquake event did not affect the landslides in the Discharge Zone and the Recharge Zone of GwB and Non-GwB from 2015 to 2019 (D2). The tremor of earthquakes is a driving factor of landslide occurrence, which tends to reduce land stability; however, for physically unstable land, the absence of earthquake will cause landslide when other driving factors, such as rainfall and human activities, appear. Some studies showed that landslide mainly occurs in the construction areas (Jacobs et al., 2016; Hemasinghe et al., 2018; Pourghasemi et al., 2019a; Pourghasemi et al., 2019b).

Based on Figure 8, the landslides mainly occurred in the flat to gentle slopes (slope steepness < 25% (B1-B3). However, the ground check results showed that landslides occurred on slopes steeper than 45 percent (Table 4). This difference demonstrates that the slope steepness map generated from DEMNAS data with a spatial resolution of 5 m x 11.25 m and mapped at a scale of 1: 25000 is insufficient to describe the slope of generally small landslides with steep slopes in short horizontal distances.

The relationship of landslide and urban development in landform above GwB

Land-use change on landforms above GwB and non-GwB (Figure 2) indicates land-use change tendency, especially as a residential area. The relationship between land-use change in settlement and the population increase is presented in Table 3. The settlement increase for 5 years was accompanied by an increase in population (Table 3). Land use above the discharge zone increased every year, with the highest increase was in 2017. Meanwhile, land use above the recharge zone has increased almost 2 times in the same year and has increased almost 3 times in 2018 and decreased in 2019. In non-GwB, settlement decreased in 2016 and increased to almost double in 2018. Overall, the increase in settlements on land above discharge and recharge zones was 5% and 19%, respectively, while settlements on landform above non-GwB GwB experienced an average decrease of 1%. The total increase in settlements on landforms above GwB and Non-GwB is 5%, accompanied by a population increase of 2% per year.

The discharge zone of the GwB is dominated by settlement. In contrast, the recharge zones of the groundwater basin and non-groundwater basin are dominated by paddy fields and mixed gardens, respectively (Table 2). The rapid development occurs in the discharge zone of GwB, which discovered many activities that modify the natural slope and soil properties and affect landslide vulnerability.

Table 2 also shows that the landslides were mainly surface landslides (45 of 72), with 24 surface landslides occurring on slopes greater than 70%. Only six shallow landslides occurred on slopes of more than 70%. While the number of landslides occurrences of surface and shallow landslides on slopes of 45-70 percent was the same, 21 landslides respectively. Surface landslides with slopes of more than 70% mainly occurred (22 of 24 landslides) in the GwB Discharge Zone, with land-use types of settlements and agricultural lands. Surface landslides with 45-70 percent slopes mainly occurred (15 of 21 landslides) in the GwB discharge zone with land-use types of settlements and agricultural lands. Figure 8 represents field photos of surface and shallow landslides on steep to very steep slopes. The occurrence of groundwater outflow on the foot slope of the GwB discharge zone was uncommon, with only three landslide cases occurring in the foot slope or the location of the landslide exhibiting groundwater outflow. Based on ground checked landslide characteristics, the landslides in the discharge zone were caused by intensive human activities that disrupted slope stability and less appropriate construction to stabilize created slopes, as well as the naturally steep to very steep slopes. The rapid development caused human intervention in the natural slope, characterized by a surface landslide, topless landslide type, and small landslide area, which changed the slope stability (Zhang and Liu, 2009). In developing countries, unsustainable environmental management and protection were responsible for 95% of landslides (Temesgen et al., 2001; Pourghasemi et al., 2017).

Table 3 The relationship between settlement land use and human population.

Years	GwB Zone		Non-GwB	Total	Population*
	Discharge (ha)	Recharge (ha)	(ha)	(ha)	(people)
2015	41472.3	15.5	40.5	41528.4	6507590
2016	42188.2	13.4	29.2	42230.8	6652077
2017	49223.4	23.4	33.3	49280.0	6796018
2018	49443.3	64.3	58.0	49565.6	6937735
2019	50267.4	56.2	48.6	50372.2	7077491

*Source: Indonesian Central Statistics Agency (*Badan Pusat Statistik* (BPS)) (2016-2020).

Figure 9. Surface and shallow landslides on steep to very steep slopes, (A) Surface landslide on settlement, very steep slope (>70%); (B) Surface landslide on agriculture, very steep slope (>70%); (C) Shallow landslide on settlement, steep slope (>45–70%); (D) Shallow landslide on the forest, steep slope (>45-70%).

Table 4 Ground-checked landslide characteristics.

No	Ground checked Landslides Characteristics	GwB Zone		Non-GwB	Σ
		Discharge	Recharge		
1	[>70%]-[Settlement]-[Disturbed]-[Surface]	12	0	0	12
2	[>70%]-[Agriculture]-[Disturbed]-[Surface]	10	0	0	10
3	[>70%]-[Road]-[Disturbed]-[Surface]	1	0	0	1
4	[>70%]-[Forest]-[Disturbed]-[Surface]	0	1	0	1
5	[>70%]-[Settlement]-[Disturbed]-[Shallow]	2	0	1	3
6	[>70%]-[Road]-[Disturbed]-[Shallow]	0	0	1	1
7	[>70%]-[Forest]-[Disturbed]-[Shallow]	0	1	1	2
8	[>45-70%]-[Settlement]-[Disturbed]-[Surface]	8	0	0	8
9	[>45-70%]-[Agriculture]-[Disturbed]-[Surface]	5	0	2	7
10	[>45-70%]-[Forest]-[Disturbed]-[Surface]	1	3	1	5
11	[>45-70%]-[Road]-[Disturbed]-[Surface]	1	0	0	1
12	[>45-70%]-[Agriculture]-[Disturbed]-[Shallow]	5	4	5	14
13	[>45-70%]-[Settlement]-[Disturbed]-[Shallow]	3	0	1	4
14	[>45-70%]-[Road]-[Disturbed]-[Shallow]	0	0	3	3
	Total	48	9	15	72

Note: [slope steepness]-[Land Use Types]-[disturbed=Presence human activities]-[type of landslide; surface < 1.5 m; shallow >1.5 – 10 m].

The geological and geomorphological structure can be vulnerable to landslides because of the landform above the groundwater basin. The number of buildings has expanded dramatically in the landform with high population density making the slope instability. Proper urban development management is required to restrict development in vulnerable landslide urban areas, conserve existing development and population, implement mitigation and monitoring systems.

Conclusion

The 686 landslides that occurred from 2015 to 2019 were mainly surface landslides in the discharge zone of the groundwater basin. Quaternary period lithology structures the geology of the discharge zone. This Quaternary period lithology also formed the groundwater basin's recharge zone, whereas the older Neogene period lithology formed the majority of the non-groundwater basin.

Landslides occurred in the discharge and recharge zones of groundwater basins, as well as in non-groundwater basins when the slope steepness was greater than 45%, and the soil types were Technosols, Cambisols, and Regosols, there was no earthquake, no settlements, no agriculture, and any range of rainfall intensities.

The frequent landslides in the discharge zone of the groundwater basin were caused by intensive human activities that disrupted slope stability and less appropriate construction to stabilize created slopes, naturally steep to very steep slopes and vulnerable soil properties.

Acknowledgements

This research was funded by the PMDSU (Program of Master leading to PhD scholarship of the Ministry of Education, Culture, Research, and Technology of Indonesia. We are grateful to the National Institute of Aeronautics and Space (LAPAN) for giving access to remote sensing laboratory and staff assistance. We thank the late Prof. Dr. Kukuh Murtilaksono, Indah Irayani, Dimas Wahyu Diono, Thomas A.H.P., and other Landslide Research Group members who helped collect data and fieldwork.

References

Alsubal, S., Sapari, N.B., Harahap, I.S.H. and Al-Bared, M.A.M. 2019. A review on mechanism of rainwater in triggering landslide. *IOP Conference Series: Materials Science and Engineering* 513:1-10, doi:10.1088/1757-899X/513/1/012009.

BMKG (Meteorology Climatology and Geophysics Agency (*Badan Meteorologi, Klimatologi, dan Geofisika*)). 2020. Daily rain data [Internet]. [downloaded on January 20, 2020]. http://dataonline.bmkg.go.id/.

BNPB, National Disaster Management Agency (*Badan Nasional Penanggulangan Bencana*). 2019. National disaster data [Internet]. [downloaded on 14 February 2019]. http://dibi.bnpb.go.id/ (*in Indonesian*).

Denchik, N., Gautier, S., Dupuy, M., Batiot-Guilhe, C., Lopez, M., Leonardi, V., Geeraert, M., Henry, G., Neyens, D., Coudray, P. and Pezard, P.A. 2019. In-situ geophysical and hydro-geochemical monitoring to infer landslide dynamics (Pégairolles-de-l'Escalette landslide, France). *Engineering Geology* 254:102-11, doi:10.1016/j.enggeo.2019.04.009.

Doi, I., Kamai, T., Azuma, R. and Wang, G. 2019. A landslide induced by the 2016 Kumamoto Earthquake adjacent to tectonic displacement-generation mechanism and long-term monitoring. *Engineering Geology* 248:80-88, doi:10.1016/j.enggeo.2018.11.012.

FAO (Food and Agriculture Organization of the United Nations). 2015. *World Reference Base for Soil Resource 2014*. FAO publications. Rome, IT.

Fata, Y.A., Hendrayanto, and Murtilaksono, K. 2020. Investigation of Landslides in Groundwater Basin of Bogor, West Java Province, Indonesia. *Proceeding of 1st International Conference on Geography, Environment and Sustainability 2020,* 6.

Froude, M.J. and Petley, D.N. 2018. Global fatal landslide occurrence from 2004 to 2016. *Natural. Hazards and Earth System Sciences* 18:2161-2181, doi:10.5194/nhess-18-2161-2018.

Hao, S., Li F., Li Y., Gu C., Zhang Q., Qiao Y., Jiao L. and Zhu, N. 2019. Stable isotope evidence for identifying the recharge mechanisms of precipitation, surface water, and groundwater in the Ebinur Lake basin. *Science of the Total Environment* 657:1041-1050, doi:10.1016/j.scitotenv.2018.12.102.

Hemasinghe, H., Rangali R.S.S., Deshapriya N.L. and Samarakoon, L. 2018. Landslide susceptibility mapping using logistic regression model (a case study in Badulla District, Sri Lanka). *Procedia Engineering* 212:1046-1053, doi:10.1016/j.proeng.2018.01.135.

Hidayat, S., Pachri, H. and Alimuddin, I. 2019. Analysis of Landslide Susceptibility Zone using Frequency Ratio and Logistic Regression Method in Hambalang, Citeureup District, Bogor Regency, West Java Province. *IOP Conf. Series: Earth and Environmental Science* 280:012005, doi:10.1088/1755-1315/280/1/012005.

Hutagalung, M. and Tarigan, S.D. 2019. Analysis of the potential for liquefaction due to the earthquake (case study: reclamation of the container port of Belawan phase-2]. *Jurnal Rekayasa Konstruksi Mekanika Sipil* 2(1):15-33, doi:10.54367/jrkms.v2i1.433 (*in Indonesian*).

Jacobs, L., Dewitte, O., Poesen, J., Maes, J., Mertens, K., Sekajugo, J. and Kervyn, M. 2016. Landslide characteristics and spatial distribution in the Rwenzori Mountains, Uganda. *Journal of African Earth Sciences* 134:917-930, doi:10.1007/978-3-319-53498-5_10.

Kim, J., Lee, K., Jeong, S. and Kim, G. 2014. GIS-based prediction method of landslide susceptibility using a rainfall infiltration-groundwater flow model.

Engineering Geology 182(2014):63-78, doi:10.1016/j.enggeo.2014.09.001.

Kodoatie, R.J. 2012. *Groundwater Spatial Planning*. Andi Yogyakarta. Yogyakarta, ID. 225-274p (*in Indonesian*).

Ling, C., Xu, Q., Zhang, Q., Ran, J. and Lv, H. 2016. Application of electrical resistivity tomography for investigating the internal structure of a translational landslide and characterizing its groundwater circulation (Kualiangzi landslide, Southwest China). *Journal of Applied Geophysics* 131:154-162, doi:10.1016/j.jappgeo.2016.06.003.

Ling, S. and Chigira, M. 2020. Characteristics and triggers of earthquake-induced landslides of pyroclastic fall deposits: An example from Hachinohe during the 1968 M7.9 Tokachi-Oki earthquake, Japan. *Engineering Geology* 264:1-23, doi:10.1016/j.enggeo.2019.105301.

Marin, R.J. and Velasquez, M.F. 2019. Influence of hydraulic properties on physically modelling slope stability and the definition of rainfall thresholds for shallow landslides. *Geomorphology* 351:106976, doi:10.1016/j.geomorph.2019.106976.

Marui, H. and Wanfg, C. 2015. Earthquake-induced landslides: An overview. *Engineering geology for society and territory* 2:713-715, doi:10.1007/978-3-319-09057-3_119.

Pourghasemi, H.R. and Rossi M. 2017. Landslide susceptibility modeling in a landslide-prone area in Mazandarn Province, north of Iran: a comparison between GLM, GAM, MARS, and M-AHP methods. *Theoretical and Applied Climatology* 130(1-2):609-633, doi:10.1007/s00704-016-1919-2.

Pourghasemi, H.R., Kariminejad, N., Gayen, A. and Komac, M. 2019a. Statistical functions used for spatial modeling due to assessment of landslide distribution and landscape-interaction factors in Iran. *Geoscience Frontiers* 11(4):1257-1269, doi:10.1016/j.gsf.2019.11.005.

Pourghasemi, H.R., Kornejady, A., Kerle, N. and Shabani, F. 2019b. Investigating the effects of different landslide positioning techniques, landslide partitioning approaches, and presence-absence balances on landslide susceptibility mapping. *Catena* 187:1-15, doi:10.1016/j.catena.2019.104364.

Rahmati, O., Golkarin, A., Biggs, T., Keesstra, S., Mohammadi, F. and Daliakopoulos, I.N. 2019. Land subsidence hazard modeling: Machine learning to identify predictors and the role of human activities. *Journal of Environmental Management* 236:466-480, doi:10.1016/j.jenvman.2019.02.020.

Segoni, A., Piciullo, L. and Gariano, S.L. 2018. A review of the recent literature on rainfall thresholds for landslide occurrence. *Landslides* 15(8):1483-1501, doi:10.1007/s10346-018-0966-4.

Silalahi, F.E.S., Pamela, Arifianti, Y. and Hidayat F. 2019. Landslide susceptibility assessment using frequency ratio model in Bogor, West Java, Indonesia. *Geoscience Letters* 6(10):1-17, doi:10.1186/s40562-019-0140-4.

Temesgen, B., Mohammed, M.U. and Korme, T. 2001. Natural hazard assessment using GIS and remote sensing methods, with particular reference to the landslides in the Wondogenet Area, Ethiopia. *Physics and Chemistry of the Earth (C).* 26(9):665-615, doi:10.1016/S1464-1917(01)00065-4.

USGS (United States Geological Survey). 2020. Earthquake data [Internet]. [downloaded on January 20, 2020]. http://earthquake.usgs.gov/.

Wu, Y. 2003. Mechanism analysis of hazards caused by the interaction between groundwater and geo-environment. *Environmental Geology* 44:811-819, doi:10.1007/s00254-003-0819-9.

Zhang, M. and Liu, J. 2009. Controlling factors of loess landslides in western China. *Environmental Earth Sciences* 59:1671-1680, doi:10.1007/s12665-009-0149-7.