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Applicability Evaluation of Landslide Vulnerability Criteria for Decision on Landcreep-Vulnerable Areas in South Korea

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Abstract: Landcreep, which is a natural hazard, frequently occurs in South Korea. However, despite many differences between general landslides and landcreep, landcreep is still treated as a kind of landslide. A bigger problem in this reality is that no verification has been made on whether the national landslide vulnerability criteria can be applied to the decision on landcreep-vulnerable areas. Therefore, this study was conducted to examine the applicability of the landslide vulnerability criteria for the decision on landcreep-vulnerable areas. For verification, first, as a result of a correlation analysis that extracted seven types of geomorphological environment criteria that are used in deciding landslide-vulnerable areas from 57 landcreep areas, a positive correlation was shown only in the slope type and the parent rock. Second, as a result of the evaluation of the landcreep area by applying the landslide vulnerability criteria, it was analyzed that 61.4% were areas with low or no possibility of the occurrence of landslides. Third, on the basis of the overlapping analysis of the landslide hazard map and landcreep areas, 67.6% were in Level 3 or lower, except for Levels 1 and 2, which had high hazards, and 21.5% were landcreep areas that were not included in the hazard levels. Applying the landslide vulnerability criteria for deciding on landcreep-vulnerable areas is not appropriate, and it is urgent to prepare landcreep vulnerability criteria.

Keywords: landcreep; landslide; vulnerability criteria; slope type; parent rock

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1. Introduction

Natural hazards are a frequent phenomenon worldwide [1]. In particular, landslides are the most destructive natural hazards in many parts of the world. Moreover, these landslides can cost billions of dollars and can cause serious problems, such as deaths, injuries, and widespread damage to property and infrastructure, which can cause further landslides [2,3]. According to a World Bank report, around 300 million people worldwide live in landslide-vulnerable areas, and about 600 people die each year in landslides [4]. The economic loss from landslides is estimated at USD 20 billion worldwide. Countries such as the United States, Italy, India, China, and Germany experience significant losses each year [5]. Recently, landslide damage has increased in South Korea because of frequent heavy rains. In particular, the area that was damaged by localized heavy rain during Typhoons Maysak and Haishen in 2020 was 1343 ha, and the restoration cost was USD 305 million. There were also nine deaths [6].

On the other hand, the natural hazards in Hyuseok-dong and Choongcheongbuk-do of South Korea in 1995 turned out to be landcreep that was first reported in South Korea, and not general landslides [7]. Since then, interest in landcreep has gradually increased, especially in academia. However, the reality is that the South Korean administrative authorities have been treating landcreep as a kind of general landslide until now.

Landcreep is different from general landslides in its fundamental mechanism and in the attributes of the debris flow that is generated [8]. There are several differences between landcreep and landslides. First, landcreep is generated underground, while landslides occur on the ground surface. Second, the effect of landcreep extends up to approximately 100 m underground, while landslides are very shallow in depth. Third, landcreep progresses much slower than landslides: for landcreep, the form of the activity clod is like a circle, but that of a landslide is closer to tears or falls. Fourth, landcreep tends towards recurrence: landcreep moves slightly, owing to specific geological features or underground structures in gentle slope areas, while landslides frequently occur owing to precipitation. Fifth, underground water greatly affects landcreep, and the affected areas were primarily used as farmland in South Korea. Sixth, landcreep exhibits precursors, including the tilting of trees and cracks on the ground, while landslides normally do not present any precursors [9,10].

Landcreep may be caused by weathered clay particles that are contained in the soil [11,12]; discontinuity, and the fragmental zone of faults in the strata [8,13–15]; erosion due to freezing–thawing [16]; a reduced shearing force of the soil due to skyrocketing underground water levels and pore water pressure [17–19]; and various development activities [8,10]. Landcreep is known to occur in Japan continuously; however, South Korea has also been consistently witnessing it since 1995, with recurrences in the same areas [8] and discoveries of previously affected areas, which has added to the number of cases of landcreep. In Pohang and Gyeongsangbuk-do, the cases are being affected by soil vibrations that are due to earthquakes [20]. In addition, the mountain hazards that are caused by landcreep have led to much larger areas of damage, which do not measure up to those from regular landslides or from collapse and recurrence [8,10,21].

Therefore, constant vigilance is needed in order to mitigate these mountain hazards. Lee et al., in 2009, 2011, and 2015 [22–24], established a national landslide forecast system using the soil function index by assessing the areas of debris flow through the extraction of the optimal parameters of a random work model, and by calculating the criteria of the precipitation for generating evacuation alerts against mountain soil hazards by using a tank model. However, landcreep has a different fundamental mechanism, as well as different geological features and topographies, than other landslides, and it occurs more frequently in areas with low risks and in Level 1 areas [10], which require preventive measures against landcreep hazards through the creation of landcreep vulnerability criteria.

Previous studies have published results on the causes of landcreep [8–20]. However, in the reality that landcreep is being treated as a kind of landslide, research on whether the national landslide vulnerability criteria can be applied to the decision on the vulnerability of the land has not been studied.

Therefore, this study was carried out to inform the justification and urgency of preparing the landcreep vulnerability criteria, and to provide basic data to prepare the criteria. For this purpose, a correlation analysis between the geomorphological environment criteria of the landcreep areas that occurred in South Korea, an evaluation of the landcreep areas through the application of the landslide vulnerability criteria [25], and an overlapping analysis of a landslide hazard map [6] and the landcreep areas were conducted in this study. In addition, we attempted to prove the clear difference between the occurrences of landcreep and landslides, and to assert the necessity and urgency of an in-depth study to establish landcreep vulnerability criteria.

2. Materials and Methods

2.1. Research Sites and Basic Data Acquisiton

This study was conducted in the landcreep areas in South Korea from 1995 to 2017. The target site of this study was 57 sites (n = 57), which included all areas where restoration was completed or where the landcreep occurred again (Figure 1). For each landcreep area, boundary data with non-occurring areas were acquired by using a portable GPS. Information on each geomorphological environment criterion was acquired for the entire landcreep area by using the data, and not by a sampling method. The geomorphological environment criteria described below were extracted by using boundary data from the topographic map (National Geographic Information Institute (Suwon, Korea), 1:5000), the forest type map (Korea Forest Service (Daejeon, Korea), 1:5000), the forest soil map (Korea Forest Service, 1:25,000), and the geological map (Korea Institute of Geoscience and Mineral Resources (Daejeon, Korea), 1:50,000), and then the average values were calculated. Moreover, the boundary data of the landcreep area were used to evaluate the actual landcreep area to which the landslide vulnerability criteria were applied, and for the overlap analysis of the landslide hazard map and the landcreep area.

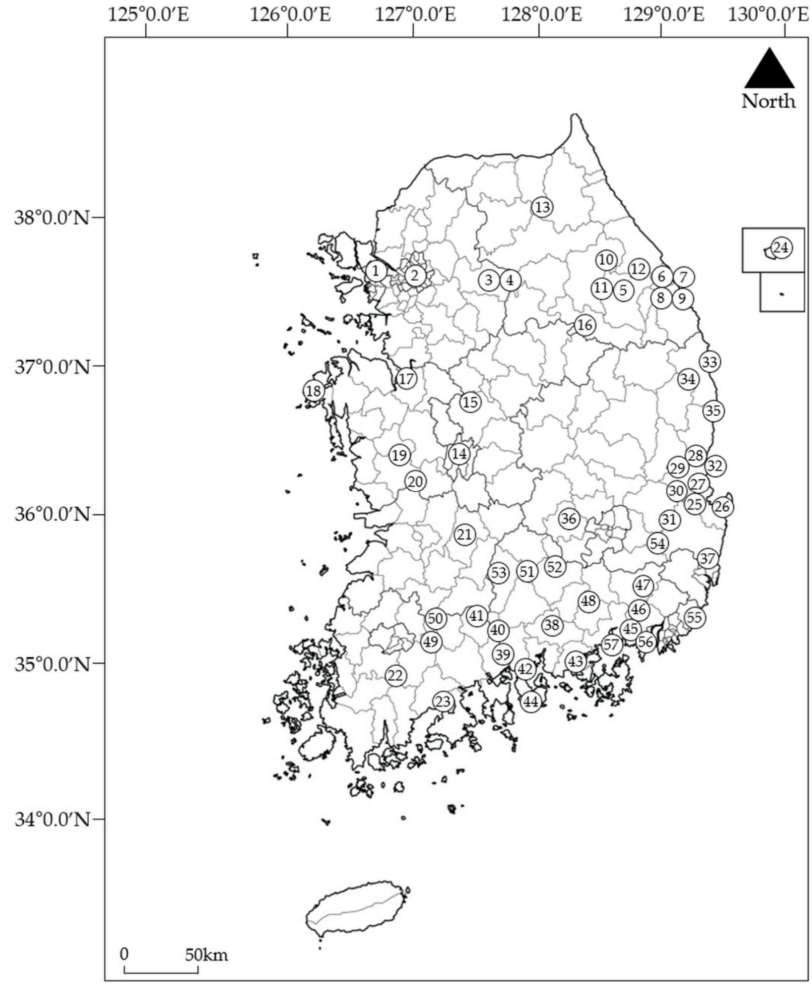

Figure 1. Location map of the research sites in South Korea. Note: The circled numbers indicate the numbers assigned to the study areas, which are the landcreep areas.

2.2. Research Methods

2.2.1. Correlation Analysis between Geomorphological Environment Criteria of the Landcreep Areas

To analyze the criteria that affect the occurrence of landcreep, 7 types of geomorphological environment criteria, which are the landslide vulnerability criteria [25] that are stipulated in the Enforcement Rule of the Mountainous Districts Management Act in South Korea, were extracted from 57 landcreep areas, and a correlation analysis was performed. The landslide vulnerability criteria in South Korea include the slope length (m), the parent rock, the slope position (10 divisions), the forest type, the slope type, the soil depth (cm), and the degree of slope (°), and it is composed of 7 geomorphological environment criteria and the investigator's correction score (personal judgment on the site). However, in this study, only 7 types of geomorphological environment criteria that can be objectively analyzed were used for analysis. The likelihood of landslides in South Korea increases as the slope length increases, the slope position increases, and the soil depth increases. The lower the degree of the slope below 40 degrees, the higher the likelihood of landslides. Moreover, the probability of landslides increases when the parent rock is metamorphic rock (gneiss type and schist type) and igneous rock (porphyry type and andesite type), when the forest type is coniferous forest, and when the slope type is an equilibrium slope and a convex slope. The analysis was performed using SPSS Ver. 21 by IBM (Armonk, NY, USA).

2.2.2. Evaluating Landcreep Areas by Applying the Landslide Vulnerability Criteria

We analyzed whether the landslide vulnerability criteria [25] can be applied to the decision on landcreep-vulnerable areas. To this end, the vulnerability grade was analyzed by applying 7 geomorphological environment criteria among the landslide vulnerability criteria to the landcreep areas (n = 57). According to the criteria in South Korea, the landslide vulnerability grade is divided into four categories, and the sums of the scores corresponding to the criteria are classified as follows: (1) Areas with a very high probability of the occurrence of landslides (180 points $\leq$ the score); (2) Areas with a high probability of the occurrence of landslides (120 points $\leq$ the score < 180 points); (3) Areas with a low probability of the occurrence of landslides (61 points $\leq$ the score < 120 points); and (4) Areas where landslides are not likely (the score $\leq$ 60 points).

2.2.3. Overlapping Analysis of Landslide Hazard Map and Landcreep Areas

The landslide hazard map, another piece of information, was provided, in addition to the landslide vulnerability criteria, through the Landslide Information System of the Korea Forest Service (KFS). An overlapping analysis was performed to determine whether the landslide hazard map can be applied to the decision on landcreep-vulnerable areas. The landslide hazard map of South Korea is produced using nine criteria: the degree of the slope, the slope bearing, the slope length, the slope curvature, the topographic wetness index (TWI), the forest type, the diameter of breast height (DBH), the soil depth, and the parent rock. Each criterion is extracted from the topographic map (National Geographic Information Institute, 1:5000), the forest type map (Korea Forest Service, 1:5000), the forest soil map (Korea Forest Service, 1:25,000), and the geological map (Korea Institute of Geoscience and Mineral Resources, 1:50,000). Among these nine criteria, the probability of landslides, which is calculated according to the influence of each criterion through logistic regression analysis, is divided into 5 hazard levels and produced as a map [6]. Meanwhile, ArcGIS 10.3.1 by ESRI (Redlands, CA, USA) was used for the overlapping analysis.

In addition, the overall flow of the study is as shown in the flow diagram (Figure 2). Here, in this study, the null hypothesis was established that the occurrence mechanisms of general landslides and landcreep are the same. On the other hand, the alternative hypothesis is that the occurrence mechanisms of general landslides and landcreep are different.

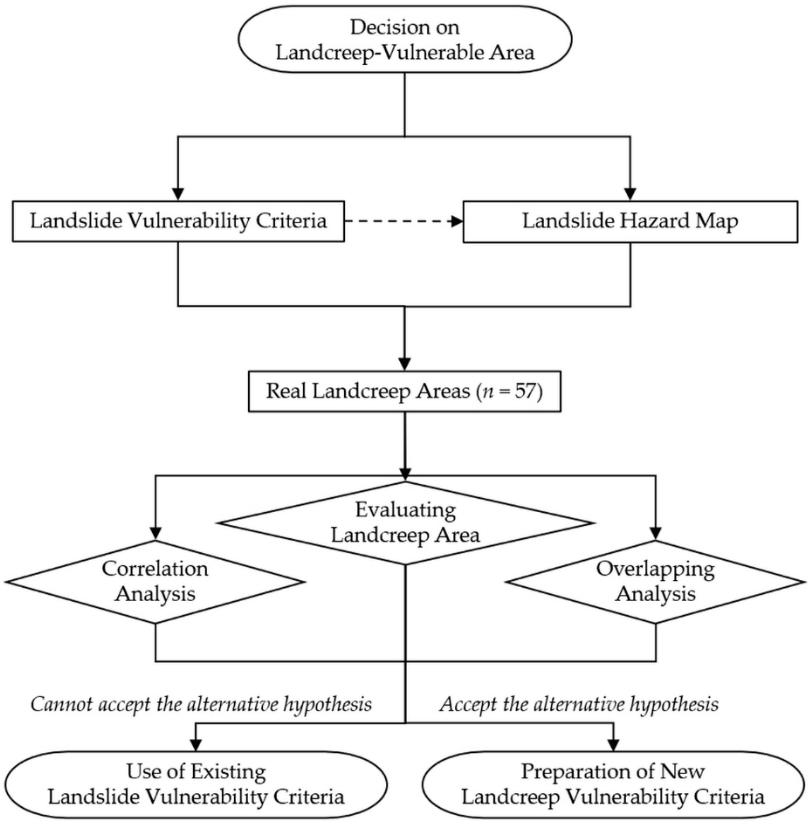

Figure 2. Flow diagram of the study.

3. Results and Discussion

3.1. Correlation Analysis Results between the Geomorphological Environment Criteria of the Landcreep Areas

The correlation analysis was conducted by extracting seven types of geomorphological environment criteria, which are the landslide vulnerability criteria, from 57 landcreep areas. As a result, the slope type and the parent rock showed a positive correlation at the 5% significance level (Pearson correlation = 0.494). There was no statistical significance among the criteria, excluding these criteria (Table 1). In correlation analysis, it is generally judged that there is a problem with multicollinearity if the correlation coefficient is more than ±0.9. However, if it is less than ±0.7, it is judged to be safe from the multicollinearity problem. On the basis of these results, the slope type and the parent rock were important factors that were used as landcreep vulnerability criteria. It is judged that the five types of geomorphological environment criteria (the slope length, slope position, forest type, soil depth, and degree of slope) of the landslide vulnerability criteria were not suitable for application to the decision on landcreep-vulnerable areas.

Meanwhile, in previous studies, precipitation [26], rainfall [27], the soil texture [28,29], the groundwater level [30,31], the soil temperature, and artificial forest development [31] were suggested as major factors for landcreep occurrence. However, the seven criteria (national landslide vulnerability criteria) used in the analysis are extremely geomorphological environment factors. Therefore, an analysis that includes the various external environmental factors reported in previous studies will be required.

In the slope types of 57 landcreep areas, the largest number were convex slopes in 31 areas (54.4%), followed by 14 complex slopes (24.6%), and 12 concave slopes (21.1%) (Table A1). Many landcreep areas occur on convex slopes, while many common landslides occur on composite slopes [23]. Different slope types are considered to bring about different consequences (i.e., the occurrence of landslides or landcreep).

Table 1. Correlation analysis results between geomorphological environment criteria of the landcreep areas.

Classification	Parent Rock	Slope Position	Forest Type	Slope Type	Soil Depth	Degree of Slope
Slope length	0.184 (0.413)	0.214 (0.112)	0.000 (1.000)	−0.085 (0.679)	0.023 (0.888)	−0.081 (0.551)
Parent rock		0.104 (0.645)	0.117 (0.666)	0.494 * (0.019)	−0.304 (0.169)	−0.062 (0.784)
Slope position			0.126 (0.642)	−0.134 (0.515)	−0.186 (0.250)	−0.188 (0.165)
Forest type				−0.126 (0.642)	−0.258 (0.334)	−0.250 (0.350)
Slope type					0.267 (0.187)	0.299 (0.137)
Soil depth						0.175 (0.279)

* $p < 0.05$. Values indicate Pearson correlation (Sig. (2-tailed)).

As for the parent rocks of the 57 landcreep areas, the igneous rocks were 7 (12.3%), the metamorphic rocks were 14 (24.6%), and the sedimentary rocks were 36 (63.2%) (Table A1). The landcreep in South Korea was the most common in sedimentary rock areas because sedimentary rocks of the Mesozoic and Cenozoic periods usually appear as a mixture of sandstone, clay rock, shale, and limestone, or as an alternation of these. Among these rocks, clay rock or shale becomes clay soil when weathered, which makes the occurrence of landcreep easier [21]. Therefore, this is different from the report that states that general landslides occur mainly in weathered igneous rock [21], whereas landcreep mainly occurs in sedimentary rock areas, including clay rock [12]. Park, in 2016 [10], stated that the criteria that affect landcreep are the geological features, the supergroup, the parent rocks, the number of days of precedent rainfall, and the amount of precedent rainfall. Woo, in 1992 [9], stated that landcreep is included in the broad category of landslides; however, it creeps very slowly, in the range of 0.01–10 mm/day, with a different mechanism from that of a general landslide, which is a phenomenon where the earth becomes saturated by external criteria, such as rainfall, and collapses abruptly. Choi et al., in 2011 [32], stated that slanted trees and trees that are bent by creep are strong evidence that support fluidal landslides, such as past or presently progressing landcreep, and that the damage to trees that is due to a landslide that collapses at once differs from that due to landcreep, where we can identify its progress.

On the other hand, Lee et al., in 2009, 2011, and 2015 [22–24], noted that the longer the slope is, the more landslides are likely to happen in weathered igneous rock areas. As for the slope position, landslides tend to be more severe when more rain falls on a valley that is already filled with water from precipitation [9]. In the forest type, artificial coniferous forests with shallow roots were vulnerable to landslides. It is said that the slope type is dangerous near the inflection point, where the slope changes suddenly, or near a straight line, and that landslides occur on steep slopes [22–24]. However, among the 57 landcreep areas, the average length was 200.3 m (22.1–920.6 m), which is inconsistent with the slope length that was calculated by using the landslide vulnerability criteria. The longest one was 920.6 m, where the effect reached the top owing to the impact of the soil-and-stone-gathering activities, and it tremendously lengthened the slope length of the damaged area. Except for this case, the lengths were below 110 m in 18 landcreep areas, which accounted for approximately 31.6% of all the affected areas (Table A1). The mountainous areas are divided into 10 in South Korea. General landslides are mainly focused on the top of a mountain ((7–10)/10) or at mountain bellies ((4–6)/10), while landcreep frequently occurs at the bottom of a mountain ((1–3)/10) or at a lower location. To support this, the upper parts of 36 areas (63.2%) of the 57 landcreep areas were below the bottom of a mountain (Table A1).

Kim, in 2006 [33] (2006), reported that the soil layer in landslide areas shows a bad distribution of particles and a loose ground state, compared to non-landslide areas, that the soil layer with a large void ratio and low density is more prone to landslides, and that the soil layer with good permeability is vulnerable to landslides when the geological conditions are the same. It is greatly affected by the environment for weathering or sedimentation. In addition, Jeon and Lee, in 2019 [34], when investigating landcreep areas, stated that a fault and fold that developed simultaneously with the valley area were highly likely to trigger the landcreep, considering the locational aspect of the landcreep—whether its source is a mountain belly, ridge, or valley—and they differentiated and investigated the location.

According to an analysis of the forest type in the 57 landcreep areas, the maximum was mixed forests in 30 areas (52.6%), the second was coniferous forests in 15 areas (26.3%), the third was deciduous forests in 10 areas (17.5%), and the fourth was non-stocked forest lands in 2 areas (3.5%) (Table A1), which is different from the study that states that landslides occurred in areas with coniferous forest and in areas with many shallow-rooted tree species [22]. Among 57 landcreep areas in South Korea, there were 8 bamboo planting areas (14.0%). This bamboo plantation was classified as a mixed forest because it grew along with other trees within the landcreep area. Therefore, more in-depth studies on the relationship between bamboo forests and the occurrence of landcreep are needed.

In terms of the soil depth in 57 landcreep areas, the maximum was 30–60 cm in 31 areas (54.4%), followed by 0–30 cm in 17 areas (29.8%), 60–90 cm in 7 areas (12.3%), and 90 cm or deeper in 2 areas (3.5%) (Table A1). However, Lee et al., in 2009 [22], stated that landslides often occur in barren and shallow areas (e.g., 0–30 cm-soil-depth areas, which causes many landslides in the devastated areas or bare mountains [9]). However, landcreep occurs a lot in colluvial soil with deep soil [10,35], and the landcreep shows different characteristics from the landslide.

The average degree of the slope of the landcreep areas (n = 57) was 23.3° (6.6–40.7°), which was close to the average degree of the slope of the mountains in South Korea [36]. Among the landcreep areas, there were 19 (33.3%) gentle slopes, with degrees of slope of less than 20°. On the other hand, it was analyzed that there were 9 landcreep areas (15.8%) of steep slopes with degrees of slope of 30° or higher, which shows the different characteristics among the landslides that occur at steep slopes [9] (Table A1). Kim and Kim, in 2015 [37], stated that, if the degree of slope exceeds 25° in the case of an infinite slope, and 30° in the case of a finite slope, there is the possibility of a landslide because of a potential decrease in the safety factor. In other words, when judged by the slope, landslides and landcreep show different characteristics in their mechanisms of occurrence [9].

3.2. Landcreep Area Evaluation Result Applying the Landslide Vulnerability Criteria

The landslide vulnerability criteria [25] decides the landslide vulnerability grade by assigning a score to each criterion, such as the slope length (m), the parent rock, the slope position (10 divisions), the forest type, the slope type, the soil depth (cm), and the degree of slope (°), and these are summed up with the investigator's correction score under Article 5 and Article 28–3 of the Enforcement Rule of the Mountainous Districts Management Act (Table 2).

As a result of applying the landslide vulnerability criteria to 57 landcreep areas, 1 area (1.8%) had a very high probability of landslides (Grade 1: 180 points $\leq$ the score), 21 areas (36.8%) had high probabilities of landslides (Grade 2: 120 points $\leq$ the score < 180 points), and 29 areas (50.9%) had low probabilities of landslides (Grade 3: 61 points $\leq$ the score < 120 points). In addition, 6 areas (10.5%) were found to have no chance of landslides (Grade 4: the score $\leq$ 60 points) (Tables 3 and A1). A total of 61.4% (35 areas), out of 57 landcreep areas in South Korea, had low probabilities or no chance of landslides, which makes it difficult to accurately decide landcreep-vulnerable areas on the basis of the landslide vulnerability criteria. Thus, when designating and managing landslide-prone areas, local governments decide and designate landslide-vulnerable areas on the basis of the criteria that are presented by the KFS. From the fact that they also designate landcreep-vulnerable areas on the basis of the criteria, we presume that there could be errors. Therefore, we believe it is necessary to enact new landcreep vulnerability criteria to suit reality and to study the impact criteria in order to decide.

Table 2. Landslide vulnerability criteria in South Korea.

Classification	Score by Criterion [1]				
Slope length (m)	<50 (0)	51–100 (19)	101–200 (36)	201≤ (74)	
Parent rock	SR (0)	IR–I (5)	MR–I (12)	MR–II (19)	IR–II (56)
Slope position (10 divisions)	0, 1/10 (0)	(2–6)/10 (9)	(7–10)/10 (26)		
Forest type	CF–I, UF (18)	CF–II, BF, MF–I (26)	BF, MF–II (0)		
Slope type	Convex slope (0)	Equilibrium slope (5)	Concave slope (12)	Complex slope (23)	
Soil depth (cm)	<20 (0)	21–100 (7)	101≤ (21)		
Degree of slope (°)	<25 (16)	26–40 (9)	41≤ (0)		
Correction criterion	1. Investigators or villagers believe it is a risky area for a landslide. (+10) 2. Investigators or villagers believe there is no risk of a landslide. (−10) 3. A site with incomplete hazard prevention facilities or one that is neglected as an artificial deforestation site. (+20) 4. Mountain areas with incomplete groundcover vegetation, such as orchards, grasslands, and plantations of fruit trees. (+20) 5. Areas where there is a risk of damage spread in the event of a landslide because the mountain is in the city. (+10)				

[1] SR = sedimentary rock (mudstone, shale, limestone, and sandstone); IR–I = igneous rock (granite type); MR–I = metamorphic rock (phyllite and slate); MR–II = metamorphic rock (gneiss type and schist type); IR–II = igneous rock (porphyry type and andesite type); CF–I = coniferous forest (newly grown seedlings and small-diameter trees); UF = unstocked forest land; CF–II = coniferous forest (medium- and large-diameter trees); DF = deciduous forest; MF–I = mixed forest (newly grown seedlings); and MF–II = mixed forest (small-, medium-, and large-diameter trees). Values in parentheses indicate scores.

Table 3. Evaluation results of the landcreep areas applying landslide vulnerability criteria.

Grade	Score	Probability [1]	Site No.	Percentage (%)
1	180≤	VH	3 (1)	1.8
2	120–179	H	1, 2, 4, 6, 7, 9, 11, 12, 13, 14, 20, 24, 25, 33, 34, 40, 45, 46, 47, 49, 50 (21)	36.8
3	60–119	L	5, 8, 10, 15, 16, 17, 18, 19, 23, 26, 28, 29, 31, 32, 35, 36, 37, 38, 39, 41, 42, 43, 44, 48, 51, 52, 54, 55, 57 (29)	50.9
4	<60	N	21, 22, 27, 30, 53, 56 (6)	10.5
Total			57 areas	100.0

[1] VH = very high probability of landslide; H = high probability of landslide; L = low probability of landslide; and N = no chance of landslide. Values in parenthesis indicate the number of landcreep areas.

3.3. Overlapping Analysis Result of Landslide Hazard Map and Landcreep Areas

The analysis was carried out by overlapping the landcreep areas (n = 57) on the landslide hazard map that was provided by the KFS. As a result, the landcreep areas corresponding to the landslide hazard, Level 1, was 11.7%, Level 2 was 20.7%, Level 3 was 22.0%, Level 4 was 14.0%, and Level 5 was 10.1%. Moreover, it was analyzed that 21.5% of the landcreep area was not at the hazard level. Areas classified below Level 3 in the landslide hazard rating accounted for 67.6% of the total landcreep areas. Thus, most of the landcreep occurred in areas except for Levels 1 and 2. In particular, it was found that the landcreep areas that are not included in the landslide hazard rating ranked second (Table 4).

Table 4. Overlapping analysis result of the landslide hazard map and the landcreep areas.

Site No.	Landslide Hazard Level (ha)					Non-Hazard (ha)	Total (ha)
	Level 1	Level 2	Level 3	Level 4	Level 5		
1	0.0094	0.0056	0.5822	0.5435	0.0328	0.0000	1.1735
2	0.2376	0.0922	0.1528	0.2137	0.0000	0.1822	0.8785
3	0.3717	1.4519	0.7107	0.4233	0.1182	0.0369	3.1126
4	0.3646	0.1356	1.1851	0.0200	0.0000	0.5287	2.2340
5	2.8375	4.8002	2.8219	1.2810	0.1088	0.0000	11.8494
6	0.2897	0.3011	0.2196	0.0000	0.0000	0.2227	1.0331
7	0.0800	0.0803	0.0593	0.0049	0.0000	0.4500	0.6745
8	0.1206	1.0508	0.0000	0.0830	0.0000	0.0148	1.2693
9	0.3825	0.6655	0.1520	0.6165	0.0007	0.5928	2.4100
10	0.0217	0.1017	0.3579	0.7710	9.5019	0.0000	10.7543
11	0.2130	0.5984	0.8555	0.9707	0.2900	2.2319	5.1595
12	9.3073	7.1474	5.3716	3.3297	2.5919	0.0000	27.7480
13	0.0000	0.0000	0.0000	0.0000	0.0000	4.0266	4.0266
14	0.4986	3.4755	2.6061	2.1889	1.3174	0.0000	10.0866
15	0.5410	0.7110	0.1591	0.0047	0.0088	0.0000	1.4246
16	0.0260	0.1420	0.0385	0.0421	0.0000	3.6532	3.9017
17	0.0000	0.0000	0.0000	0.2704	0.5075	0.6472	1.4251
18	0.0510	0.5460	1.8566	0.7780	0.2426	0.0487	3.5229
19	0.0000	0.0000	0.1415	0.6520	0.2540	0.0769	1.1244
20	0.1680	3.7766	4.2702	3.9859	2.5469	0.5000	15.2476
21	0.2041	0.2098	0.1165	0.0282	0.0000	0.0000	0.5587
22	0.0000	0.0002	0.0322	0.0619	0.0000	0.0018	0.0961
23	0.0000	0.0800	0.6358	0.5788	0.4512	0.1020	1.8478
24	0.0000	0.0000	0.0000	0.2504	0.4512	5.4118	6.8053
25	0.4801	1.1193	1.6049	0.1628	0.0000	0.4455	3.8126
26	0.0200	0.2259	0.4055	0.4479	0.0000	0.7210	1.8203
27	0.0000	0.0200	0.1572	0.3425	0.0000	1.0971	1.6168
28	0.6307	0.8965	0.5569	0.3292	0.0000	0.5731	2.9863
29	0.0945	0.0532	0.0700	1.1273	0.0000	0.4999	1.8449
30	0.1348	0.1745	0.0400	0.0000	0.0000	0.0075	0.3568
31	0.0000	0.0811	0.6935	0.4505	0.0053	0.0000	1.2305
32	0.3263	0.5103	0.5126	0.2037	0.0000	0.0575	1.6104
33	0.4846	1.2569	0.6642	0.3557	0.2833	0.0000	3.0446
34	12.4697	15.5853	16.6991	7.8102	2.2699	26.7000	81.5342
35	0.0000	0.0045	0.1000	0.0000	0.0000	0.3555	0.4599
36	0.0000	0.0000	0.7243	0.7339	0.0300	0.0000	1.4882
37	0.0044	0.6506	1.8694	0.4456	0.6058	1.5214	5.0972
38	0.0000	0.0500	1.0180	0.5371	0.0000	0.0823	1.6875
39	0.0000	0.0000	0.0000	0.0000	0.0000	1.0478	1.0478
40	0.0000	0.8678	0.3071	0.0099	0.0000	1.7367	2.9216
41	0.0429	0.2010	1.8668	0.7947	0.0674	0.0099	2.9827
42	0.0000	0.0000	0.0000	0.0000	0.0000	0.6276	0.6276
43	0.0200	0.5805	0.7241	0.5921	0.1047	0.4281	2.4495
44	0.0000	0.0000	0.0000	0.0000	0.0000	0.3500	0.3500
45	0.0000	1.4862	2.5382	1.4842	0.1150	3.6310	9.2547
46	0.3962	1.7488	2.0888	1.8665	0.9910	0.3252	7.4165
47	0.3895	0.2711	0.1600	0.0406	0.0000	0.3220	1.1831
48	0.0000	0.2094	0.8244	0.4965	1.0580	0.0088	2.5971
49	0.3753	0.6308	0.6433	0.7902	0.7140	0.0000	3.1535
50	1.5318	5.0193	3.6581	2.7382	3.2663	0.0000	16.2137
51	0.1873	0.7381	0.2912	0.0000	0.0000	0.1905	1.4071
52	0.0000	0.3966	0.4509	0.1158	0.0499	0.2843	1.2976
53	0.0206	0.1854	0.3982	0.2121	0.0835	0.0000	0.8998
54	0.0000	0.3548	0.4191	0.0145	0.0000	0.0000	0.7883
55	0.0100	0.1710	0.4761	0.5884	0.0000	1.1346	2.3801
56	0.0172	0.1055	0.0699	0.0074	0.0000	0.3003	0.5004
57	0.0000	0.0279	0.3234	0.1566	0.0000	0.1308	0.6387
Total	33.3602 (11.7)	58.9943 (20.7)	62.6806 (22.0)	39.9531 (14.0)	28.7597 (10.1)	61.3163 (21.5)	285.0642 (100.0)

Values in parenthesis indicate the percentages (%) of the total areas.

4. Conclusions

Landcreep is still treated as a type of landslide. However, since landcreep has a different mechanism of occurrence from landslides, it is necessary to treat them differently. Among the geomorphological environment criteria in South Korea (Enforcement Rule of the Mountainous Districts Management Act) for deciding landslide-vulnerable areas, the only criteria that showed a correlation in the landcreep areas were the slope type and the parent rock. When the landslide vulnerability criteria were applied to the actual landcreep areas, 61.4% of the total sites were areas with low or no possibility of landslides. Moreover, most of the landcreep area was classified as Level 3 or lower on the landslide hazard map. The landcreep area not included in the landslide hazard levels occupied a significant area. Applying the landslide vulnerability criteria for the landcreep-vulnerable area is inappropriate, and landcreep should be treated differently from landslides.

To prevent disasters due to landcreep, it is necessary to prepare criteria for deciding landcreep-vulnerable areas that are different from those for deciding landslides. To this end, this scientifically verifies the various factors (e.g., soil temperature, rainfall, precipitation, torrential rain, typhoon, earthquake, groundwater level, anthropogenic forest development) that are likely to cause landcreep. Thus, it will be necessary to prepare landcreep vulnerability criteria at the national level and to produce a precise landcreep hazard map. In countries with similar types of mountain areas to South Korea, such as China and Japan, it is necessary to recognize the distinction between landcreep and landslide, and to make efforts to prevent potential disasters.

This study mainly analyzed the relationship between the geomorphological environment factors that are related to landslides and landcreep vulnerability. However, natural disasters are caused by the complex action of numerous factors. Therefore, additional research is needed to find the vulnerability criteria by combining various factors that have the potential to influence the occurrence of landcreep with geomorphological environment factors.

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Appendix A

Table A1. Detailed data and evaluation results for each criterion of landcreep areas applying the landslide vulnerability criteria.

Classification [1] (SN)	ST	PR	SL	SP	FT	SD	DS	Score by Landslide Vulnerability Criteria							
								SL	PR	SP	FT	ST	SD	DS	Total
1	Complex slope	Metamorphic rock	165.20	2–3	Deciduous forest	30–60	14.08	36	74	9	0	23	7	16	165 (2)
2	Convex slope	Metamorphic rock	104.37	8–9	Mixed forest	0–30	26.67	36	74	26	0	0	0	9	145 (2)
3	Complex slope	Metamorphic rock	211.06	1–8	Coniferous forest	30–60	16.39	74	74	26	26	23	7	16	246 (1)
4	Complex slope	Metamorphic rock	201.46	1–3	Mixed forest	30–60	19.15	74	36	9	0	23	7	16	165 (2)
5	Convex slope	Sedimentary rock	475.90	8–9	Deciduous forest	30–60	32.95	74	0	26	0	0	7	9	116 (3)
6	Complex slope	Metamorphic rock	131.52	1–6	Mixed forest	0–30	32.66	36	74	9	0	23	0	9	151 (2)
7	Convex slope	Metamorphic rock	109.28	1–6	Mixed forest	0–30	29.49	36	74	9	0	0	0	9	128 (2)
8	Convex slope	Metamorphic rock	133.56	3–6	Mixed forest	30–60	18.32	36	36	9	0	0	7	16	104 (3)
9	Convex slope	Igneous rock	203.11	2–8	Coniferous forest	30–60	23.39	74	19	26	26	0	7	16	168 (2)
10	Complex slope	Sedimentary rock	467.24	3–4	Mixed forest	0–30	35.01	74	0	9	0	23	0	9	115 (3)
11	Complex slope	Sedimentary rock	330.60	4–8	Coniferous forest	30–60	30.37	74	0	26	18	23	7	9	157 (2)
12	Concave slope	Sedimentary rock	532.75	7–10	Coniferous forest	0–30	21.36	74	0	26	18	12	0	16	146 (2)
13	Complex slope	Igneous rock	243.11	5–7	Mixed forest	60–90	25.18	74	19	26	0	23	7	9	158 (2)
14	Convex slope	Metamorphic rock	297.93	1–2	Mixed forest	60–90	21.16	74	36	9	0	0	7	16	142 (2)
15	Convex slope	Metamorphic rock	160.59	3–4	Mixed forest	60–90	29.05	36	36	9	0	0	7	9	97 (3)
16	Convex slope	Sedimentary rock	252.09	2–3	Mixed forest	30–60	23.90	74	0	9	0	0	7	16	106 (3)

Table A1. *Cont.*

Classification [1] (SN)	ST	PR	SL	SP	FT	SD	DS	Score by Landslide Vulnerability Criteria							
								SL	PR	SP	FT	ST	SD	DS	Total
17	Convex slope	Metamorphic rock	108.87	2–3	Coniferous forest	30–60	16.71	19	36	9	26	0	7	16	113 (3)
18	Convex slope	Sedimentary rock	254.50	1–2	Mixed forest	60–90	22.26	74	0	9	0	0	7	16	106 (3)
19	Convex slope	Metamorphic rock	125.70	2–3	Mixed forest	30–60	17.58	19	36	9	0	0	7	16	87 (3)
20	Convex slope	Metamorphic rock	378.40	1–7	Mixed forest	30–60	23.36	74	36	9	0	0	7	16	142 (2)
21	Concave slope	Sedimentary rock	61.98	1–3	Mixed forest	30–60	40.73	19	0	9	0	12	7	0	47 (4)
22	Concave slope	Sedimentary rock	22.14	3–5	Deciduous forest	30–60	6.56	0	0	9	0	12	7	16	44 (4)
23	Concave slope	Sedimentary rock	98.17	3–5	Mixed forest	30–60	18.44	19	0	9	0	12	7	16	63 (3)
24	Concave slope	Sedimentary rock	319.48	1–3	Mixed forest	60–90	23.13	74	19	9	0	12	7	16	137 (2)
25	Concave slope	Sedimentary rock	285.75	1–6	Non-stocked forest land	0–30	22.78	74	0	9	18	12	0	16	129 (2)
26	Concave slope	Sedimentary rock	101.57	1–3	Non-stocked forest land	0–30	22.41	36	0	9	18	12	0	16	91 (3)
27	Concave slope	Sedimentary rock	62.03	1–3	Deciduous forest	0–30	27.66	19	0	9	0	12	0	9	49 (4)
28	Concave slope	Sedimentary rock	157.74	1–9	Coniferous forest	0–30	16.84	36	0	9	18	12	0	16	91 (3)
29	Complex slope	Sedimentary rock	97.10	1–6	Coniferous forest	0–30	11.09	19	0	9	26	23	0	16	93 (3)
30	Complex slope	Sedimentary rock	68.42	1–3	Deciduous forest	0–30	20.19	19	0	9	0	23	0	16	47 (4)
31	Convex slope	Sedimentary rock	108.16	2–3	Coniferous forest	30–60	22.94	36	0	9	26	0	7	16	94 (3)
32	Convex slope	Sedimentary rock	114.58	1–7	Coniferous forest	0–30	20.29	36	0	26	26	0	0	16	104 (3)
33	Complex slope	Sedimentary rock	287.12	8–9	Mixed forest	30–60	32.28	74	0	26	0	23	7	9	139 (2)

Table A1. *Cont.*

Classification [1] (SN)	ST	PR	SL	SP	FT	SD	DS	Score by Landslide Vulnerability Criteria							
								SL	PR	SP	FT	ST	SD	DS	Total
34	Complex slope	Sedimentary rock	920.55	4–7	Coniferous forest	30–60	32.64	74	0	26	18	23	7	9	157 (2)
35	Convex slope	Sedimentary rock	106.65	2–3	Mixed forest	0–30	20.79	36	0	9	0	0	0	16	61 (3)
36	Convex slope	Sedimentary rock	156.11	4–7	Coniferous forest	0–30	17.25	36	0	26	18	0	0	16	96 (3)
37	Complex slope	Sedimentary rock	169.42	1–6	Mixed Forest	≤ 90	15.56	36	0	9	0	23	21	16	105 (3)
38	Convex slope	Sedimentary rock	174.57	1–5	Mixed forest	30–60	22.60	36	0	9	0	0	7	16	68 (3)
39	Convex slope	Sedimentary rock	119.24	2–5	Mixed forest	30–60	19.25	36	0	9	0	0	7	16	68 (3)
40	Convex slope	Metamorphic rock	113.27	1–7	Mixed forest	30–60	13.58	36	74	26	0	0	7	16	159 (2)
41	Convex slope	Sedimentary rock	149.21	7–8	Mixed forest	30–60	23.87	36	0	26	0	0	7	16	85 (3)
42	Convex slope	Sedimentary rock	97.80	2–8	Coniferous forest	30–60	13.70	19	0	26	18	0	7	16	86 (3)
43	Convex slope	Sedimentary rock	155.15	1–3	Coniferous forest	60–90	25.74	36	0	9	0	0	7	16	68 (3)
44	Concave slope	Sedimentary rock	56.70	1–3	Deciduous forest	30–60	21.55	19	0	9	0	12	7	16	63 (3)
45	Complex slope	Igneous rock	365.61	2–3	Mixed forest	0–30	25.13	74	56	9	0	23	0	16	178 (2)
46	Complex slope	Igneous rock	271.62	2–3	Deciduous forest	30–60	29.95	74	56	9	0	23	7	9	178 (2)
47	Convex slope	Igneous rock	104.33	1–2	Coniferous forest	30–60	29.18	36	56	9	26	0	7	9	143 (2)
48	Convex slope	Sedimentary rock	160.84	3–4	Mixed forest	30–60	24.45	36	0	9	0	0	7	16	68 (3)
49	Convex slope	Metamorphic rock	270.71	4–5	Mixed forest	60–90	29.64	74	74	9	0	0	7	9	173 (2)
50	Convex slope	Igneous rock	529.17	1–4	Mixed forest	30–60	24.62	74	19	9	0	0	7	16	125 (2)

Table A1. *Cont.*

Classification [1] (SN)	ST	PR	SL	SP	FT	SD	DS	Score by Landslide Vulnerability Criteria							
								SL	PR	SP	FT	ST	SD	DS	Total
51	Concave slope	Sedimentary rock	130.45	3–5	Deciduous forest	30–60	26.32	36	0	9	0	12	7	9	73 (3)
52	Convex slope	Sedimentary rock	153.84	2–3	Coniferous forest	30–60	11.80	36	0	9	26	0	7	16	94 (3)
53	Convex slope	Sedimentary rock	98.05	2–3	Deciduous forest	30–60	31.33	19	0	9	0	0	7	9	44 (4)
54	Concave slope	Sedimentary rock	120.76	1–3	Mixed forest	≤ 90	18.50	36	0	9	0	12	21	16	94 (3)
55	Convex slope	Sedimentary rock	143.03	1–9	Deciduous forest	0–30	23.76	36	0	26	0	0	0	16	78 (3)
56	Convex slope	Sedimentary rock	83.34	1–3	Mixed forest	0–30	37.03	19	0	9	0	0	0	9	37 (4)
57	Convex slope	Igneous rock	97.79	4–6	Mixed forest	30–60	26.50	19	19	9	0	0	7	9	63 (3)

[1] SN = site number; SL = slope length (m); PR = parent rock; SP = slope position (10 divisions); FT = forest type; ST = slope type; SD = soil depth (cm); and DS = degree of slope (°). Values in parenthesis indicate the landslide vulnerability grade (Grade 1 = very high probability of landslide; Grade 2 = high probability of landslide; Grade 3 = low probability of landslide; and Grade 4 = no chance of landslide).

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