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ORIGINAL ARTICLE

Analysis of the Changes of the Vegetated Area in an Unregulated River and Their Underlying Causes: A Case Study on the Naeseong Stream

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ABSTRACT: This study aims to investigate the changes in the riparian vegetated area in the Naeseong stream, an unregulated river, in order to analyze the main factors leading to these changes. For this purpose, the land surface cover in the channel area of the Naeseong stream was classified into 9 categories using past aerial photographs collected between 1970 and 2016, which recorded the long-term changes of the Naeseong stream. The increase or decrease in the vegetated area was calculated for each category using a pair of before and after images. The changes in the vegetated area were divided into 6 periods: the unvegetated channel period (1970 - 1980), the first rapid increase (1980 - 1986), the period of decrease due to flood (1986 - 1988), the period of repetitive man-induced disturbance and vegetation increase (1988 - 2008), the period of gradual vegetation increase (2008 - 2013), and the period of second rapid increase (2013 - 2016). Multiple regression analysis was performed using independent variables representing hydrology, climate, and geomorphology. The major variables found to be involved in the changes in the vegetated area of the Naeseong stream were the discharge during June - July, channel width, and temperature during April - June. Among the three variables, discharge and temperature were respectively the main independent variables in the downstream and the upstream reaches as per a single variable model. Channel width was the variable that distinguished the upstream and downstream reaches of the stream. The implication of the long-term increase in the vegetated area in the Naeseong stream was discussed based on the result of this study.

KEYWORDS: land surface cover, multiple regression analysis, Naeseong stream, vegetated area

1. Introduction

Many modern rivers are now being managed in engineered ways that aim at securing flow conveyance capacity and maintaining a stable channel form for safe land use of the surrounding floodplains. However, in terms of fluvial geomorphology, rivers are a part of nature and the physical basis of aquatic ecosystems, which are characterized by the dynamics of the interaction between the composing elements of water, vegetation and geomorphology. As one of them, riparian vegetation and its influence on a stream channel have been investigated in various studies since William reported vegetation establishment and the effects of it in the stream channels in the United States in the 1970s (Williams 1978).

Vegetation establishment as a part of the stream channel change has been prominent in regulated rivers that are mainly affected by dams (Johnson 1994, Azami et al. 2004, Choi et al. 2005, Park et al. 2008,

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Woo et al. 2010). Thereby, a decrease in flood discharge due to a dam and the resulting decrease in tractive forces were naturally considered as the main causes of vegetation establishment. Most studies have determined the relationship between a hydrological factor, such as peak discharge reduction, and the increase in vegetated area only on the basis of reasoning; however, they have not presented a quantitative relationship. In addition, they neglect the change of vegetation in a stream channel may be affected by other environmental factors than the hydrological ones. Above all, such analysis does not comprehensively consider the interactions between flowing water, vegetation, and geomorphology. These limitations present fundamental difficulties in providing guidelines for vegetation management in rivers. Therefore, it is necessary to quantitatively analyze the increase and decrease in vegetated area and the potential factors affecting these changes to address these limitations.

Vegetation establishment frequently occurs along regulated reaches of rivers downstream of dams, but a decrease in flood discharge and tractive force may occur in an unregulated river during a drought period. As compared to regulated rivers, unregulated rivers show more natural changes, including increased and decreased discharge; corresponding changes in vegetation are also expected to occur naturally. Before 2016 when impoundment of Youngju dam began, the Naeseong stream had been an unregulated sand river with great hydrological variability, where the interaction between flowing water-vegetation-geomorphology is dynamic (Gurnell and Petts 2002). Furthermore, the vegetated area has been steadily increasing over the past 40 years (Fig. 1). This implies that the Naeseong stream is suitable for carrying out a study on changes in the vegetated area and their underlying causes.

In the background, this study aimed to investigate the changes of the vegetated area in the Naeseong stream from 1970 to 2016, before the start of dam operation, and to quantitatively analyze their main causes. The results of this study will increase our understanding of rivers as a physical space and basis of the aquatic ecosystem, where geomorphic changes continuously occur with flowing water-vegetation-geomorphology interaction, and contribute to the knowledge necessary to prepare guidelines for sustainable river management.

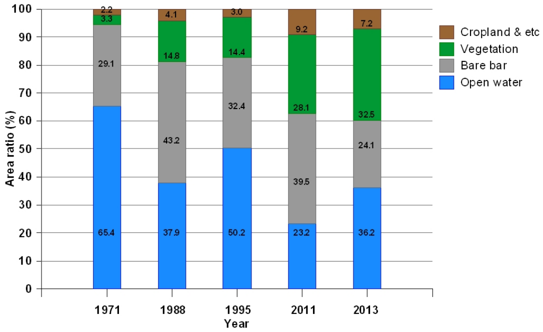

Fig. 1. Change in land surface cover in the Naeseong stream during 1971 - 2013 (modified from Kim and Lee 2014).

2. Target river

2.1 Overview of the Naeseong stream

The subject of this study is the Naeseong stream, the first tributary stream of the Nakdong River. Its watershed is located in the southern part of the Sobaeksanmaek and northern inland region of Gyeongsangbuk-do (Fig. 2). The mainstream of the Naeseong stream originates from Ojeon-ri, Muryamyeon, Bonghwa-gun in Gyeongsangbuk-do, after which it joins the Nakhwaamcheon, the Toilcheon, the Yeongjooseocheon, the Okgyecheon, the Seokgwancheon, the Hancheon, and the Geumcheon, in the same order. Finally, it flows into the Nakdong River at Hyangseok-ri, Yonggung-myeon, Yecheon-gun in Gyungsangbuk-do. In the upper reach, the Naeseong stream joins the main tributaries; in the midstream and downstream, which is the study reach, it flows through mountains, and a broad valley is developed partially. In the study area, the width of the river valley is 1.5 to 3 times the channel width; therefore, the Naeseong

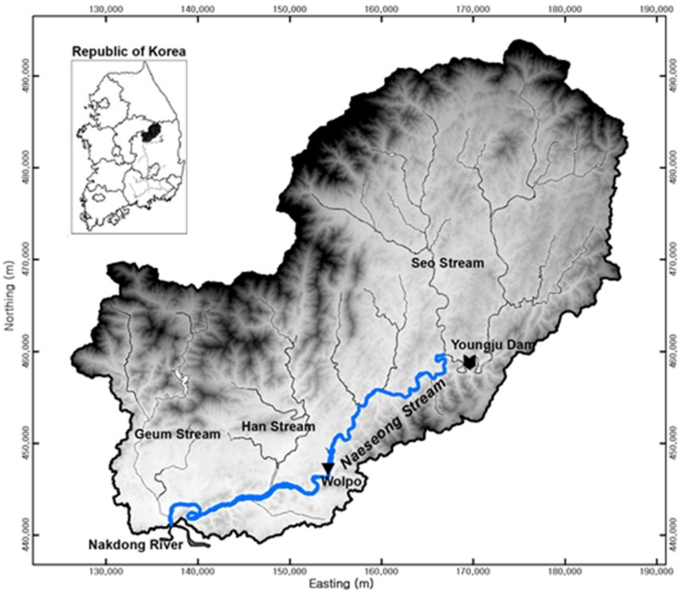

Fig. 2. Watershed and study reach of the Naeseong stream.

stream is close to being a confined river, which is far from lateral migration (Alabyan and Chalov 1998). The Naeseong stream is famous for its unique geomorphic landscape of a sandy river, which is represented by sandbars with shallow and fast-flowing water, such as Hoeryongpo, Museom Village, and Seonmongdae Pavilion. This is because the Naeseong stream has retained the substantial characteristics as a sand-bed river for more than 100 years. This is because Daebo granite (53.3%) and Sobaegsan gneiss (27.0%) occupy lithology more than 80% of the watershed of the Naeseong stream, thereby continuously supplying granite-based coarse sand. The typical particle size (D_{50}) of the bed material in the study area is 0.92 - 1.63 mm; thus, coarse sand is dominant. The watershed area is 1,814.7 km^2, and the statutory river length is 108 km. The Yeongju dam, which was constructed by blocking the mainstream of the Naeseong stream, is located at the bend of Yonghyeol-ri, Pyeongeun-myeon, Yeongju-si; the overall watershed area of the dam is 496.6 km^2 (MLTM 2013). The target reach for this study was about 52 km long and from the Seocheon confluence to the Nakdong river confluence (Fig. 2).

2.2 Climate and hydrology

The average annual air temperature of the Naeseong stream watershed, based on Yeongju meteorological observation station, is 11.4°C, and the average annual precipitation is 1,230.8 mm in Yeongju, 1,238.1 mm in Moonkyung, and 1,190.3 mm in Bonghwa. Rainfall at every meteorological observation station varies, but annual variations are consistent overall. In this study, the temperature and precipitation at the Yeongju meteorological observation station, which has data for the longest time period and is located at the center of the watershed upstream, were considered representative values. The rainfall at Yeongju increased until the early 2000s, but it has been decreasing recently (Fig. 3).

The streamflow gauging stations consulted in this study include Bonghwa, Songliwon, Joje, Miho, Wolpo, Jukjeon, Hyangseok, and Wolho in the Seocheon (the largest tributary). Among the stations, the Wolpo Station, that has the water level data from 1969 has the record of water level over the longest period and its data include the least missing and abnormal values. Thereby, Wolpo station was considered best suitable and was utilized to this study. In this study, using the

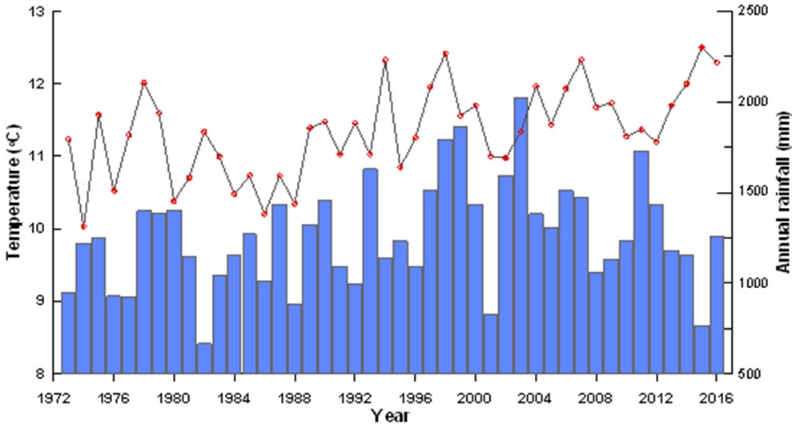

Fig. 3. Annual mean temperature and precipitation at Yeongju during 1973 - 2016 (Source: http://www.weather.go.kr).

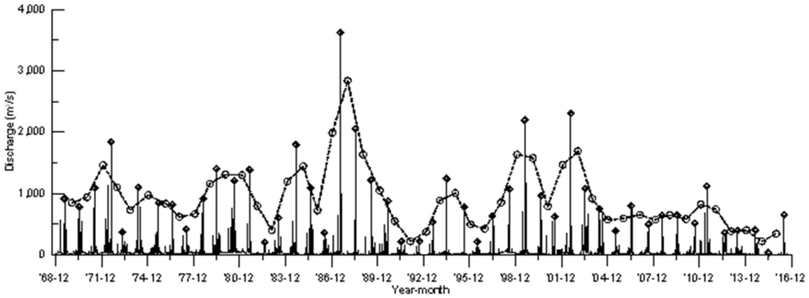

Fig. 4. Daily discharge as computed using water level data at Wolpo station. Dashed line means a 2-year moving average.

existing water level-discharge relationship and the measured water level data, we constructed daily discharge time series data as shown in Fig. 4. The discharge from the Naeseong stream is highly variable from year to year. In the past 44 years, the largest flood happened in 1987, while the year of the lowest peak flow was 2015. The two-year frequency flood discharge, recorded at Wolpo Station, which is considered channel forming discharge in terms of hydro-geomorphology is 780 m^3/s.

2.3 Segmentation of sub-reaches

The spatial range of this study was 52 km, which includes the mid- and downstream part of the Naeseong stream. It starts at Sudo-ri, where the Naeseong stream joins the Seocheon, and ends at Samganri, the confluence with the Nakdong River (Fig. 2). For statistical analysis, the whole study reach was equally divided into 13 sub-reaches that are 4-km long. The names of the sub-reaches were defined as R01~R13, downstream to upstream. Table 1 shows the drainage area, channel slope, sinuosity, and channel width in 1965 for every sub-reach. In terms of the stream channel characteristics, the downstream and upstream were topographically distinguished near the Gopyeong-ri close to R08. The downstream segment coincides with the national river and the upstream reach does the local one.

In the downstream segment, the valleys are broad; the upstream reach shows the aspect of the rivers flowing through the narrow valleys. Accordingly, the differences in channel width are relatively clear. Though channel gradient and grain size tend to gradually increase with the upstream, difference of the downstream and the upstream segments is not so clear. Thereby, it was thought to be more reasonable to

Table 1. Drainage area and channel characteristics of the 13 sub-reaches

Sub-reach	R01	R02	R03	R04	R05	R06	R07	R08	R09	R10	R11	R12	R13
Drainage area (km^2)	1,514.2	1,505.4	1,490.1	1,451	1,313.9	1,160.7	1,149	1,124.4	1,104.1	1,019.3	914.6	901.5	879.4
Channel slope (%)	0.090	0.085	0.110	0.109	0.114	0.102	0.107	0.115	0.130	0.146	0.128	0.132	0.168
Sinuosity	1.31	2.53	1.01	1.03	1.10	1.75	1.23	1.35	1.09	1.19	1.29	1.49	1.88
Width (m)	335.2	216.7	381.8	473.8	434.3	344.2	345.4	327.4	209.4	253.2	184.2	179.1	213.1

Table 2. Topographic maps, aerial photos, and satellite images collected from various sources. Abbreviated sources are as follows: National Geographic Information Institute of Korea (NGII), Korea Forestry Promotion Institute (KOFPI), Samah Aerial Survey Co. (SAS)

Year	Year interval	Type	Pieces	Scale or ground resolution	Source
1970/71		Analog panchromatic	13	1/37,500	NGII
1974	3/4	〃	35	1/15,000	KOFPI
1979	5	〃	45	〃	〃
1980	1	〃	12	1/20,000	NGII
1986/87	6/7	〃	35	1/15,000	KOFPI
1988	1/2	〃	19	〃	NGII
1991	3	〃	11	1/20,000	〃
1995	4	〃	22	〃	〃
1996	1	〃	31	1/15,000	KOFPI
2005	9	〃	11	1/20,000	NGII
2008	3	Digital ortho-rectified	47	0.25 m/px	SAS
2010	2	〃	47	〃	〃
2013	3	〃	47	〃	〃
2016	3	〃	47	〃	〃

separate the downstream from upstream segments based on rather topographic differences than longitudinal ones. In this study, R01–R08 were belonged to the downstream segment, while R09–R13 to the upstream one.

3. Method

3.1 Aerial photograph collection and processing

The aerial photographs from various sources were used to determine the temporal changes in the vegetated areas of the Naeseong stream (Table 2). Past aerial photographs are widely used in geographic and environmental research (Clery et al. 2014) as they are useful for quantitative measurement of stream channel characteristics, such as change of land surface cover, sinuosity, and channel width. The aerial photographs collected were orthographically rectified and geographically referenced via image-to-image correction method in a GIS program, using the orthorectified aerial photos from 2013, according to the orthographic correction procedure described by Park et al. (2005). The ground resolution of the resampled orthoimage was 0.5 m per pixel.

The position accuracy of the orthographically rectified aerial photographs influences the accuracy of the land surface cover map because it is estimated based on the position accuracy itself. In this study, it was important to calculate the change in area as per the

Table 3. Types of land surface cover. HUP represents both Plantation[1], which includes Italian Poplar tree cultivation before the year 2000, and Pasture[2], which means areas used for repetitive herb raising/cutting after 2000, as identified from field investigations

	Type				
Natural	Open water (OWN)	Bare bar (BAN)	Initial herb (BAV)	Herbaceous (VGH)	Tree (VGT)
Man-induced	Cropland (HUC)	Plantation[1] Pasture[2] (HUP)	Disturbed land (BAC)	Engineered open water (OWE)	

land surface cover before and after the years being compared, so the position accuracy of the orthographically rectified aerial photographs was evaluated. The subjects were aerial photographs from 1970 to 2005. Aerial photographs from 2008 to 2016 were excluded because they were already corrected ortho-images. Accuracy was evaluated using about 20 reference points that were uniformly distributed throughout the study reach of the Naeseong stream. In terms of the calculated position error, root mean square error was 2.33 - 6.16 m, which is similar to the range of the orthographic correction errors of aerial photographs reported in previous studies (Wang and Ellis 2005, Hughes et al. 2006).

3.2 Land surface cover classification

To analyze the increase and decrease in the vegetated area, land surface cover was classified for the channel area of the Naeseong stream. There were 9 categories that it was classified into (Table 3), 5 of which were natural land surface cover, including open water, bare bar, incipient vegetation, herbaceous vegetation, and woody vegetation. The incipient vegetation represents sporadically established vegetation in bare bars, while herbaceous vegetation represents a densely populated area. In terms of woody vegetation, the size of the crown was considered as the area. There were 4 types of artificial land surface covers: cultivated land, disturbed land, disturbed open water, and plantations or pastures. Disturbed land refers to the land denuded by river construction, collection of aggregate, temporary road, and artificial removal of vegetation. Disturbed open water is the place, where open water is temporarily present due to construction work, such as the cofferdam and aggregate collection. Plantation is a poplar planting site that existed in sand bars from 1970 to the 1990s. It was pointed out as a factor that reduced the conveyance capacity so it had existed only until the 1990s and disappeared thereafter (Gu et al. 2010). A pasture is defined as an area where herbaceous vegetation is periodically mown; such land has existed mainly in the high water channel of the stream since the 2000s. Plantations and pastures are distinct from one another and do not overlap.

For all aerial photographs, the land surface cover was classified manually. In this process, we obtained the cooperation of vegetation experts and aerial photograph specialists, when necessary, to improve the accuracy of vegetation readings. The classified land surface cover was made of ArcGIS polygons and was saved as a .shp file.

Area change per land surface cover before and after the compared year was calculated by the intersection tool for polygons in ArcGIS. Table 2 shows that the time interval between the years was 1 to 9. The change in the land surface cover between 1996 and 2005, which was the longest time interval, was excluded from the analysis because it was difficult to determine the disturbance in the stream channel that probably occurred during this period. In contrast, while the time interval between 1980 and 1986/87 is long (six-seven years), the data during this period were included in the analysis because it was the time period before major disturbances, such as river construction, occurred, thereby reflecting only natural changes. Therefore,

Table 4. Definition of dependent variables

Variable	Prior land cover	Posterior land cover
ENCR	OWN, BAN, BAV	VGH, VGT
RECV	VGH, VGT, HUC, HUP	OWN, BAN, BAV
AC	ENCR-RECV	

there were 12 pairs of years in which the change in land surface cover could be analyzed.

3.3 Statistical analysis

Multiple regression analysis was used to analyze the underlying causes of changes in the vegetated area. The dependent variable was the change in the vegetated area before and after the year of comparison. A change to a positive value implies that the vegetated area was enlarged due to natural causes, and the area that used to be open water, bare bars, or incipient vegetation in the year before comparison was vegetated with herbaceous and woody vegetation. The variable representing such a change was named encroachment (ENCR). The change to a negative value appeared when the vegetated area disappeared and changed reversely to open water, bare bars, or incipient vegetation. The fluvial erosion is the main drivers of reduction of vegetated area, along with the burial of vegetation caused by sedimentation of the bed load. We also included cases, where man-induced surface land cover, such as cultivated land and plantation/pasture, had been converted into open water and bare bars by the same processes of flowing water. This was because most of the cultivated land, plantation or pasture is the land surface cover mostly derived from the vegetated area, is located at the periphery of the active stream channel where the frequency of flooding is relatively low among the naturally formed vegetated areas. However, when the vegetation is removed and bed load is deposited during flooding, the cultivated land, plantation or pasture can be recovered to bare bars. The variable representing the change from vegetated and the man-induced area to recovered land surface cover, such as open water and bare bars was named recovery (RECV). The difference between ENCR and RECV is the change in the vegetated area expressed as area change (AC) (Table 4). If the AC is positive for the pair of years compared, it indicates an increase in the vegetated area, while a negative value a reduction.

Independent variables that represent environmental variables are considered to be capable of affecting vegetated area changes. A hydrological variable, discharge, reflects the climate and land surface cover of the watershed, and the drainage network structure; it is the most dominant factor that directly affects the morphology of a stream channel. Considering the concentration of more than 50% of the annual rainfall during summer in Korea, monthly or periodic discharge values from June to September were set as independent variables. The discharge value was divided into the mean and the peak flows. In addition, the discharge from May to December was added as a variable to reflect the floods that occurred during the periods other than June to September. Climate variables considered here were air temperature and rainfall. To reflect the survival, establishment, and growth period of riparian vegetation, temperature from winter to early summer (January to June) and annual average temperatures were considered as variables. Rainfall is a variable that can be used as a substitute for discharge, and it was applied only in the whole-reach analysis. In terms of the geomorphic variables, sinuosity, which reflects the geometrical shape of the stream channel, and channel width, which reflects the spatial limit where fluvial processes can occur, were applied as independent variables. The value of the year 1965 was used as the reference value because there was no

Table 5. Independent variables used for sub-reach analysis. Units of discharge, width, rainfall, and temperature are m^3/s, m, mm, and °C, respectively

Type	Item	Variable
Discharge	June	Q_{JN}, Q_{JNK}
	July	Q_{JY}, Q_{JYK}
	August	Q_{AU}, Q_{AUK}
	June–July	Q_{JJ}, Q_{JJK}
	June–August	Q_{JA}, Q_{JAK}
	June–September	Q_{JS}, Q_{JSK}
	August–September	Q_{AS}, Q_{ASK}
	May–December	Q_{MD}, Q_{MDK}
Temperature	Mean in January	T_{JA}
	Mean in February	T_{FE}
	Mean in March	T_{MA}
	Mean in April	T_{AP}
	Mean in May	T_{MY}
	Mean in June	T_{JN}
	Mean in April–June	T_{AJ}
	Annual mean	T_{YR}
Rainfall	April	R_{AP}
	May	R_{MY}
	June	R_{JN}
	July	R_{JY}
	August	R_{JJ}
	June–July	R_{AU}
	June–August	R_{JA}
	June–September	R_{AS}
	August–September	R_{JS}
	Annual	R_{YR}
Geomorphology	Sinuosity	SIN
	Inter-levee width of 1965	W_L

significant difference in the channel width of the Naeseong stream over the years. Table 5 only shows the independent variables representing arithmetic values, but for every variable, log-transformed variables which are expressed with prefix 'L' attached before the name of the arithmetic variables were separately used as independent variables. The variables representing discharge, temperature, and rainfall were used either as average values during the year before and after comparison or single values from the specific year showing the maximum or minimum during the same period.

Multiple regression analysis was performed in two different ways. One was the sub-reach analysis using the data obtained from sub-reaches from R01 to R13 in which the watershed area and the discharge were different, and the other was a whole-reach analysis in which the entire study reach was treated as one. For application in the sub-reach analysis, the discharge of each sub-reach was calculated proportionally to a ratio of the watershed area of each reach (Table 1) to the watershed area of the Wolpo station. For the whole-reach analysis, only the discharge of Wolpo station was used. Since the geomorphic variables depend on the characteristics of each sub-reach, it was only applied to the sub-reach analysis. Only the data from Yeongju station was used for temperature and rainfall, therefore, it was applied only to the whole-reach analysis.

In the sub-reach analysis, the effective number of observations were 146. Among the total 156 data points (13 sub-reaches × 12 pairs of years), 10 data points that were considered to distort the analysis due to man-induced disturbances, such as vegetation removal, aggregate collection, riverbed maintenance, and levee construction, were excluded after examination of the aerial photographs. On the other hand, the total number of data points was 12 in the whole-reach analysis.

The statistical packages used here were the open source software R (R Development Core Team 2017) and the MS Excel^{TM} statistics toolbox. Independent variables were applied by the forward stepwise method. After the results of the forward stepwise method were reviewed, manual combination of independent variables were also applied with the trial and error method to perform regression analysis. The correlation coefficient between the independent variables and variance inflation factor were calculated to examine the multicollinearity problem that could occur when similar independent variables were involved in multiple regression analysis. When the correlation coefficient was less than 0.7, both variables were selected. When the variance inflation factor was less than 10, it was determined that there was no collinearity. For calculation of variance inflation factor, the “car (small letter)” library package in R was used.

4. Results

4.1 Change of the vegetated area over time

Fig. 5 shows changes, including increase in the vegetated area (ENCR) and decrease (RECV) in it as well, according to the years of comparison. However, the sub-reaches marked with 0 as the change in an area was partially affected by man-induced disturbance, which indicated that the natural change could not be determined. Fig. 6 shows a series of the aerial photographs of the sub-reach R07~R08 overlaid with visualization of land surface cover of the vegetation (VGH, VGT) and the cultivated and plantation or pasture area. From the perspective of the increase and decrease in the vegetated area, Fig. 5 can be divided into 6 periods. The first is from 1971 to 1980, where both ENCR and RECV show low values. This is the so-called white river period when the almost the entire channel area was stayed unvegetated. During the second period (1980 - 1986), the vegetated area increased sharply around some sub-reaches present downstream (R04~R05, R07). However, RECV increased in the following period, 1986 - 1988. These two periods coincide with the drought period in around 1982 and the flood season in 1987, respectively (Fig. 3, 4).

The fourth period is from 1988 to 2008, when man-induced disturbance and an increase in vegetation downstream occurred simultaneously. In the early part of this period (1988 - 1995), river construction and riverbed maintenance were frequent in the downstream sub-reaches. From 1991 to 1995, the vegetated area increased at the R03, R04, and R07 sub-reaches, which had been disturbed in 1988 - 1991. No quantitative analysis was conducted during 1996 - 2005, without aerial photographs. However, in the satellite images with low resolution, the vegetated area did not change significantly. In 2005 - 2008, riverbed maintenance was carried out in the downstream R05~R08 sub-reaches. During this period, disturbance caused or maintained riverbed denudation; vegetation was established when there was no disturbance or disturbance had stopped. In the fifth period from 2008 to 2013, the vegetated area continued to increase in the downstream sub-reaches. The sixth period is from 2013 to 2016, when vegetated area increased sharply in almost all of the reach, which may have been influenced by the drought that occurred from 2014 to 2016. Fig. 7 shows the increase and decrease in the vegetated area according to the period.

4.2 Sub-reach analysis

Table 6 shows some of the multiple linear regression models in which the increase and decrease in the vegetated areas in each sub-reach shown in Fig. 5 is the dependent variable, and the hydrology, climate, and geomorphic variables are independent variables. The independent variables were separately applied either as arithmetic or log-transformed values. Since the dependent variable, AC, has both positive and

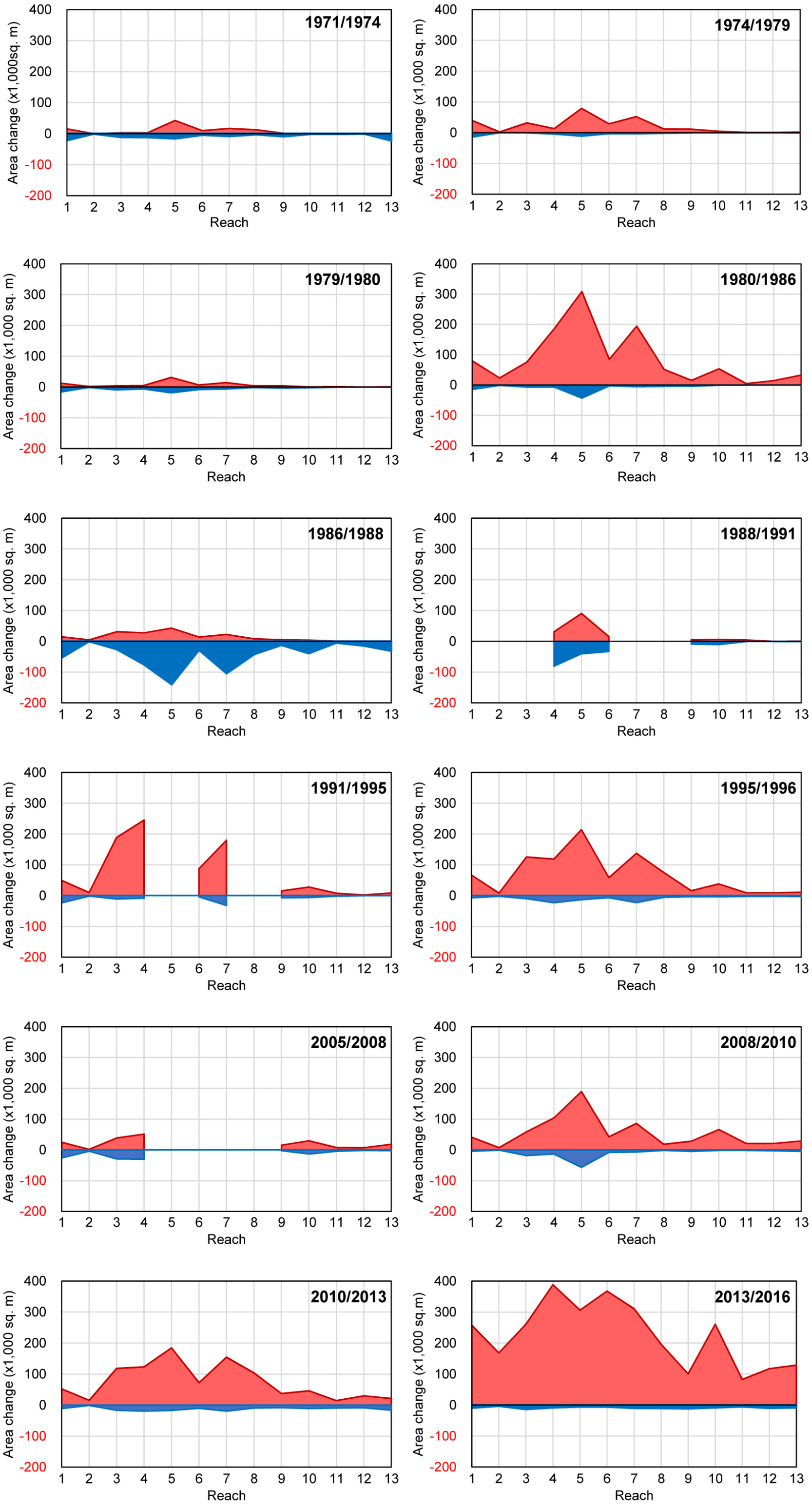

Fig. 5. Change in ENCR (red) and RECV (blue) according to year along the sub-reaches. Sub-reaches of no value indicate exclusion due to human disturbance.

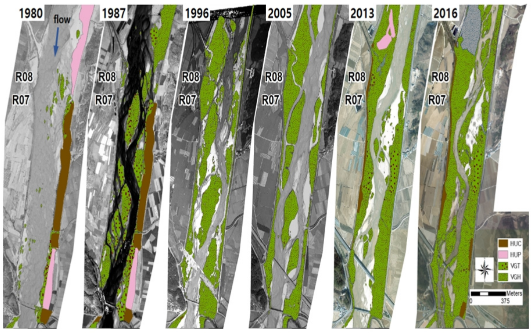

Fig. 6. A series of orthorectified aerial photos with layers of classified land surface cover of vegetation (VGH, VGT), cultivated land (HUC) and plantation or pasture (HUP) along sub-reach R07 - R08 during 1980 - 2016.

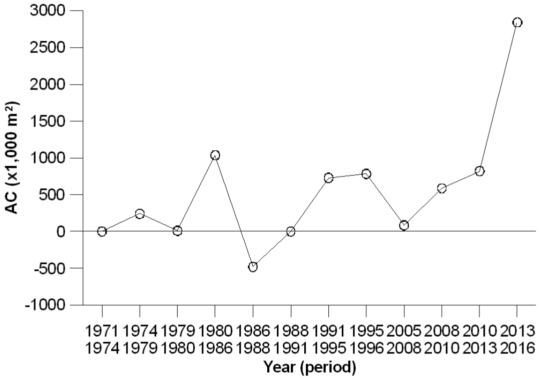

Fig. 7. Temporal changes in the vegetated area for the whole study reach.

negative values, it was treated as an arithmetic variable only. The temperature also did not show as large variation as the other independent variables did; hence, the arithmetic value was used.

In this study, a forward stepwise method was applied to derive a linear regression model with high determination coefficients among many independent variables. Additionally, the second variable was examined for each step, and the cases where the multiple regression equations had higher determination coefficients than the forward stepwise method were compared to develop a regression model. In addition, the model with the highest explanatory power among all the regression models, including the peak discharge variables for each condition, was included. Table 6 shows only three variables because in the case of a regression model with more than 4 variables, hydrology, geomorphology, and climate were selected evenly as the first 3 variables. As a result, in the case of the fourth variable, any variable with a high correlation coefficient with the former variables was added, but the increment of the determination coefficient remained relatively small. The correlation coefficient between independent variables was in the range of -0.61 to 0.38. The variance inflation factor was in the range of 1.01 to 1.71, i.e., it was significantly lower than 10, which is the standard criterion of collinearity.

The first characteristic shown in Table 6 is the difference between arithmetic and log-transformed variable models. The log-transformed model (Eq. 2), which showed the highest determination coefficient when considering up to 3 variables, had higher determination coefficient than the arithmetic regression model did (Eq. 1). This phenomenon was similarly observed when applying other variables or by analyzing upstream and downstream regions separately. This was due to the exponential nature that is inherent to the results observed for natural phenomena, indicating that the log-transformed regression model was more appropriate. Therefore, only the log-transformed result was presented in a single variable model or in the models separately for the downstream and the upstream sub-reaches, respectively.

In the case when all of the observation points (146) for 13 sub-reaches was used, the multiple regression model with the highest explanatory power used the mean discharge of July (LQ_{JY}) with channel width and temperature from April to June (T_{AJ}) as variables (Eq. 2); the adjusted coefficient of determination (hereinafter coefficient of determination) was 0.753 . The second highest regression model used the peak discharge of June to July (LQ_{JJK}) instead of the mean discharge of July (Eq. 3). These two variables had higher explanatory power than any other variables representing the summer discharge. Eq. 2 and Eq. 3 show that the major factor affecting the increase and decrease in the vegetated area in the entire sub-reaches of the Naeseong stream

Table 6. Regression models for sub-reach-based analysis. *p*-values of all the models were below 0.01. The prefix L means that the variable is log-transformed

Model condition		Regression model		df	Adjusted R^2
Arithmetic	All	$AC = 78.43TAJ + 0.457W - 0.942Q_{JJ} – 1,308$	(1)	142	0.685
Log-transformed	All	$AC = -56.64LQ_{JY} + 112.99LW + 56.7T_{AJ} – 1,275.89$ $AC = -50.55LQ_{JJK} + 108.13LW + 51.34T_{AJ} – 1,086.60$	(2) (3)	142 142	0.753 0.729
	All (1 variable)	$AC = -63.08LQ_{JJK} + 436.06$ $AC = -69.42L(Q_{JJK}/W) + 90.20$	(4) (5)	144 144	0.512 0.647
	Downstream (1 variable)	$AC = -80.18LQ_{JJK} + 571.84$	(6)	73	0.730
	Upstream (1 variable)	$AC = 38.83T_{AJ} – 2,374.0$	(7)	69	0.586

Table 7. Relative importance (RI) of regressors in the all sub-reach models (Eq. 2)

All sub-reach (Eq. 2)	Variables	LQJY	LW	TAJ
	RI (R^2)	0.5020 (0.5155)	0.1802 (0.1055)	0.3178 (0.3980)

was the discharge during the rainy season from June to July, followed by channel width and spring temperature. They showed negative, positive, and positive correlations, respectively, exhibiting that an increase of the vegetated area occurred in condition to decrease in discharge, a large channel width, and high temperatures. When the regression model was built with a single variable of peak discharge, the discharge from June to July accounted for about 50% of the change in the vegetated area (Eq. 4).

Eq. 2 and Eq. 3 used channel width (LW), a geomorphic variable, as the second independent variable, indicating that this geomorphic variable affected the increase and decrease in the vegetated area. This is consistent with the expectation that at the same discharge, mean flow velocity and tractive force decreases as the channel width increases, which would be advantageous for vegetation establishment. In this sense, the coefficient of determination increased to 0.647 when the discharge per unit width ($L(Q_{JJK}/W)$), which was calculated by dividing the discharge by the channel width, was used as a single variable (Eq. 5).

The mean temperature from April to June (T_{AJ}) was selected as the third independent variable in Eq. 2 and Eq. 3. This suggests that the increase in the air temperature at the growth stage of riparian vegetation can contribute to the increase in the vegetated area by promoting plant growth. However, as shown in the single-variable regression model (Eq. 7, Fig. 8), built on the data from R02 and the upstream reaches (R09–R13), the data collected for the period from 2013–2016, when a remarkably high T_{AJ} and rapid vegetation increase was recorded simultaneously, significantly affected the results of this study.

To investigate the relative importance of the first to third independent variables included in Eq. 3, “relaimpo” package (Grömping, 2006) in the R software was used. The “lmg” method was applied, in which the influence of additional regression variables is calculated by subtracting the part of existing regression variables from the union of all the regression variables with considering the order of input of regression variables.

Table 7 shows that the discharge during June to July, channel width, and temperature from April to June had relative importance of 50 %, 18 %, and 32 %, respectively, in Eq. 2, which is a multiple regression model for the entire sub-reaches of the Naeseong stream. These results are related to the single-variable model for the downstream sub-reaches excluding R02 (Eq. 6), and the single-variable model for the upstream

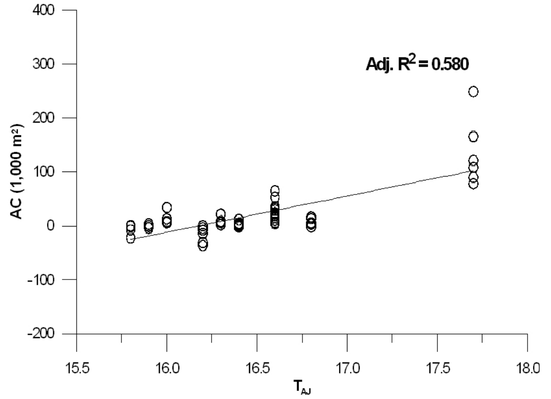

Fig. 8. A uni-variable regression model plot between AC and TAJ for upstream sub-reaches, together with R02.

reaches including R02 (Eq. 7), in Table 6. In other words, the discharge from June to July is a variable of high explanatory power for the downstream sub-reaches, and the temperature from April to June is a variable having high explanatory power for the upstream sub-reaches. The channel width is an independent variable that reflects the differences between the upstream and downstream reaches (Table 1). The reason why R02 belongs to the upstream group is that R02 is more consistent with what appears in the upstream sub-reaches. The channel width of R02 is only 52 % of the mean (377.4 m) of the other sub-reaches belonging to the downstream group but is almost equal to the mean channel width (207.8 m) of the upstream sub-reaches. Mean annual rate of increase in the vegetated area of R02 (0.12 %) is much less than that of the downstream group (0.62 %), but similar with the upstream group (0.10 %).

4.3 Whole-reach analysis

In the case of the whole-reach analysis, the number of observation points was as small as 12; the geomorphic variable was excluded, and thus, only the two-variable model was used. In addition, rainfall was used along with discharge as a climate variable. Table 8 shows two models with the highest coefficient of determination and a statistically significant P value less than 0.01, when discharge and rainfall were applied as independent variables, respectively. All variables were log-transformed values. When discharge at the Wolpo station, a hydrological variable, was used, the combination of the mean discharge from June to July and the average temperature in May (adjusted R^2= 0.859) showed the highest explanatory power. When the rainfall in Yeongju was used as a substitute variable for discharge, the combination of the rainfall from June to July and the temperature from April to June also had a high adjusted coefficient of determination (R^2=0.831). These results are well consistent with the results of the sub-reach analysis.

5. Discussion and conclusions

5.1 Importance of floods in the rainy season

The results of multiple regression analysis for sub-reaches and the whole reach show that the major variables affecting the increase and decrease of vegetated area were the discharge from June to July during the rainy season (the mean discharge in July and peak flood discharge from June to July), which corresponds to the first half of summer. This is consistent with the results of the whole-reach analysis with rainfall as a variable. In addition, these results were relatively more obvious in the downstream reach than in the whole reach of the Naeseong stream. On the contrary, the discharge in August or September or the discharge from June to August or June to

Table 8. Multiple regression models for whole-reach based analysis. p-values of all the models were below 0.01. The t in variables means a whole reach analysis was applied

Condition	Regression model for AC		df	Adjusted R2
Discharge	$AC = -840.6LQt_{JJ} + 599.6T_{MY} - 6,336.3$	(8)	9	0.859
Rainfall	$AC = -2028.9LR_{JJ} + 821.8T_{MY} - 1,084.8$	(9)	9	0.831

September, which corresponds to the latter half of summer, showed a relatively low correlation with the increase and decrease in the vegetated area. This suggests that the early summer flood, which is the seedling season, is more important for the increase and decrease of the vegetated area than the overall flood in the whole summer season. This result was also similar to that of an existing statistical study (Johnson 1994) on rivers in the semi-arid regions of the United States, in which the mean discharge in June was the main driving variable. However, it also reflects from the hydrological characteristics in Korea, where the flood in the rainy season was concentrated in late June-mid July.

When the regression model was considered as a quantitative relation, the discharge under the condition (AC=0), where there was no increase or decrease in the vegetated area, was calculated to be 1,005 m^3/s for the whole reach. This is equivalent to the discharge of 2.78-year frequency at the Wolpo station. According to the relation (Eq. 6), for the downstream group with a higher explanatory power of peak discharge in June to July, the discharge was 1,251.4 m^3/s, which was the frequency discharge for more than 3 years. This is larger than bank-full discharge which is equivalent to 1.5 to 2.33-year frequency. This could be one of the reasons why the vegetated area have been continuously increasing along the downstream sub-reaches during the period without man-induced disturbances since the 1980s (Fig. 5).

5.2 Effect of temperature

In contrast to the downstream reach, the temperature from April to June (or temperature in May) was the main variable for the increase and decrease in the vegetated area in the upstream reach. This was because the coefficient of determination of the T_{AJ} was somewhat low (0.58), but it was significantly higher than the coefficient of determination (0.369) of the discharge variable (LQ_{JY}). Nevertheless, the regression model in this study reflects the effects of simultaneous emergence of high temperature phenomenon and rapid vegetation increase during only one period (2013 - 2016), so additional data and analysis are needed for the effect of spring temperature.

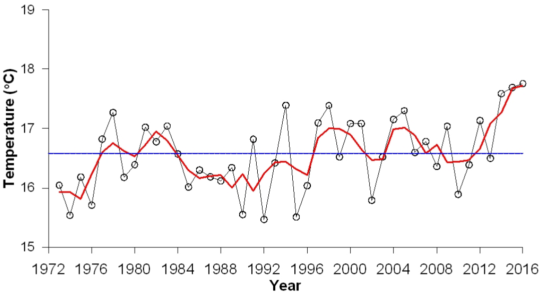

Fig. 9. Mean temperature during April to June in Youngju. The red line indicates a 3-year moving average.

Räpple et al. (2017) showed a positive correlation between the temperature in the growth season from April to September and the increased vegetated area based on the statistical analysis of vegetation monitoring data for several years in small-scale streams. They argued that a high temperature during the growth season would be able to accelerate the speed of vegetation establishment if the wet conditions were maintained. Thus, their results are in line with those of the present study. In general, rising temperatures in the spring accelerate the flowering of vegetation, while seed dispersal and growth of seedlings also begins early. According to the study of Choi et al. (2006), during the period from 1973 to 2004, spring had started 6 days earlier in Korea. In the Naeseong stream, the temperature in the spring is rising in the long term (Fig. 9). Therefore, if vegetation growth starts early in spring due to climate change, even if floods occur during the same period, the removal or burial of vegetation is relatively less, and the possibility of the survival of vegetation may increase, thereby increasing the vegetated area. Moreover, if floods during June to July are weak, or if the summer floods are delayed, vegetation may increase greatly, as observed for the Naeseong stream in 2014 - 2015. Therefore, this possibility should be considered for future river vegetation management.

5.3 Effect of channel width

The differences between the upstream and downstream reaches were confirmed from the time-series characteristics of the increase and decrease in the vegetated area (Fig. 5), the influence of the channel width in the whole-reach three-variable model, and the differences in the main variables used in the single-variable regression model. The differences resulted mainly from the differences in channel width. The R02 showed similar characteristics with the sub-reaches belonging to the upstream group. Fig. 10 illustrates the mean annual rate of increase in the vegetated area, cultivated land, and plantation or pasture with the channel width of every sub-reach. In this figure, except for R02, all the downstream sub-reaches show the channel width more than 300 m and the mean annual rate of increase of the vegetated area by 0.5% or more. On the other hand, the upstream sub-reaches and R02 had a channel width of less than 300 m, and the growth rate in the vegetated area was less than 0.2%. Thus, the difference between these two groups is remarkable.

Except for the so-called white river period before 1980, since the same year, the vegetated area has expanded in the downstream reach of the Naeseong stream. This phenomenon has continued despite temporary denudation due to the flood in 1987 and frequent disturbances since 1988. As a result, the vegetated area became either mid-channel fluvial islands or floodplains around the active main channel. In other parts, the vegetated area was changed into the man-induced area, such as the cultivated land and pasture. Consequently, the channel width decreased (Lee 2018). In other words, geomorphic differences are considered one of the main causes of spatial differences in the expansion of vegetated areas in the same river (Williams and Wolman 1984). The difference fundamentally resulted from the degree of confinement of a river valley. In a wide river valley, the river space is wide, and the embankment has sufficient width. Contrastingly, in a narrow river valley, the expansion of the vegetated area and the resulting formation of the floodplain are subject to restriction, therefore, only sand bars are formed in the stream channel (Alabyan and Chalov 1998).

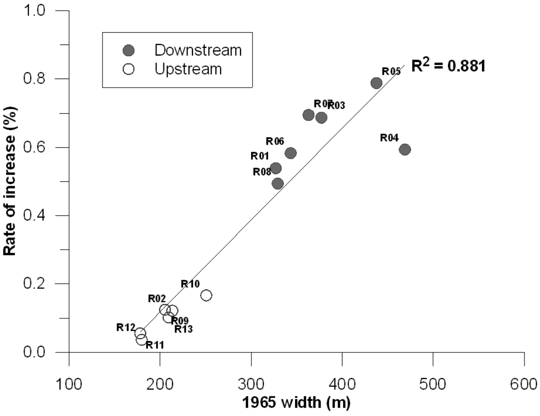

Fig. 10. Relationship between annual rate of increase in VGH/VGT/HUC/HUP area and width of 1965.

5.4 Implication of long-term increase of the vegetation area

From a long-term point of view, except for the large flood period, the Naeseong stream has undergone a continuous increase in the vegetation area (Fig. 1). This implies that even in the unregulated condition the discharge in the rainy season of the Naeseong stream was insufficient to maintain or reduce the vegetated area. If the current hydrological and climatic conditions continue, the unvegetated riverbed condition that existed in the Naeseong stream before the 1980s cannot be recovered, but instead it will be changed to the stream, where the channel area is covered by vegetation as shown in Fig. 6. This change will continue until the equilibrium between flowing water-vegetation-geomorphology is reached. In the aspect of river management, this means that management practices to recover and keep the riverbed as the so-called white river are difficult to achieve its goal. Instead, the equilibrium and sustainability of a stream channel should be considered and river management should be carried out based on an understanding of the interaction of flowing water-vegetation-geomorphology.

5.5 Conclusion

In this study, it was confirmed from the multiple regression analysis that the main variables affecting the change of the vegetation area in the Naeseong stream were the discharge of the rainy season, spring temperature, and the channel width. Considering that a river is a stage, where interaction between flowing water, vegetation, and geomorphology occurs, the three variables derived from multiple regression analysis (discharge, temperature, and channel width) represent environmental variables related to flowing water, vegetation, and geomorphology, respectively. Discharge carries sediment through the volume and velocity of flowing water passing through the stream channel, and thus, is involved in the channel forming processes by eroding and depositing the stream channel and vegetation. Temperature affects the periodic growth processes, such as plant flowering, seed spreading and germination, establishment and growth, and related physiological processes. Channel width is the space secured for flowing water and is involved in the area and spatial arrangements of flowing water that change throughout the year. It is related to wetness and dryness of the land surface, fast, slow, or stagnant flows of water, as well as differentiation and diversity in relative elevation as compared to the water level. Thereby, channel width is directly or indirectly involved in the variability of riparian vegetation establishment. Therefore, river management for riparian vegetation should be implemented based on a scientific understanding of the interaction between flowing water-vegetation-geomorphology. In addition, the effect of water quality and sediment discharge, which were not covered in this study, are related to flowing water and vegetation, respectively; therefore, follow-up studies on these elements should be carried out.

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