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Characteristics and Controlling Factors of the Drought Runoff Coefficient

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Abstract: Increasing water demand due to population growth, economic development, and changes in rainfall patterns due to climate change are likely to alter the duration and magnitude of droughts. Understanding the relationship between low-flow conditions and controlling factors relative to the magnitude of a drought is important for establishing sustainable water resource management based on changes in future drought risk. This study demonstrates the relationship between low-flow and controlling factors under different severities of drought. I calculated the drought runoff coefficient for six types of occurrence probability, using past observation data of annual total discharge and precipitation in the Japanese archipelago, where multiple climate zones exist. Furthermore, I investigated the pattern of change in the drought runoff coefficient in accordance with the probability of occurrence of drought, and relationships among the coefficient and geological, land use, and topographical factors. The drought runoff coefficient for multiple drought magnitudes exhibited three behaviors, corresponding to the pattern of precipitation. Results from a generalized linear model (GLM) revealed that the controlling factors differed depending on the magnitude of the drought. During high-frequency droughts, the drought runoff coefficient was influenced by geological and vegetation factors, whereas land use and topographical factors influenced the drought runoff coefficient during low-frequency droughts. These differences were caused by differences in runoff, which dominated stream discharge, depending on the magnitude of the drought. Therefore, for effective water resource management, estimation of the volume of drought runoff needs to consider the pattern of precipitation, geology, land use, and topography.

Keywords: drought; geology; land use; topography; occurrence probability; water resource management

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1. Introduction

The causes of droughts and adaptations to natural disasters have been studied from the perspectives of hydrology, environmental science, geology, meteorology, and agronomy [1]. The causes of droughts have been investigated in various regions by focusing on rainfall patterns [2–4], temperature [5,6], wind [7], and humidity [8]. In addition to the impacts of natural factors, intensification of drought is expected to occur because of growing water demand associated with population growth, economic development [9–11], and changes in the hydrological cycle associated with anthropogenic impacts, such as land-use-change [12–14].

Droughts are generally categorized into four types [15]. First, drought resulting from a lack of precipitation is defined as a meteorological drought [1,16]. Second, a shortage of surface or subsurface water in relation to water utilization, as determined by established water resource management, is defined as hydrological drought [17,18]. Stream water discharge is often used as an indicator hydrological droughts and is used in management and analyses of such droughts [19]. Third, agricultural drought indicates declining soil moisture, regardless of surface water resources, causing crop failure [20,21]. Finally, socio-economic drought occurs in cases of defectiveness and incompatibility of the water resource system in relation to water demand [22,23].

Prolonged droughts cause severe socio-economic losses [24,25]. Economic loss arising from droughts has been estimated at USD 6–8 billion per year in the United States [26,27], with the EU suffering loss of 100 billion over the past 30 years [28]. The human damage caused by drought is even more serious. Droughts in Ethiopia/Sudan (1984) and the Sahel region (1974) killed 450,000 and 325,000 people, respectively [29].

Changes in the hydrological cycle resulting from climate change are expected to increase extreme drought events [1]. Unlike flood disasters, the influence of climate change on drought remains poorly understood. However, predictions of an intensification of drought due to climate change and population growth in central Africa [25] and increasing drought duration and severity in the interior southwest of the United States [30] have been reported. Furthermore, forecasts of drought using soil moisture as an indicator have indicated increasingly frequent drought events in Europe, regardless of the emission scenario applied [31].

Stream-flow discharge is an important indicator of hydrological drought because in many regions, water resources are obtained from surface water. Previous studies of stream discharge have focused on water resources, ecosystems, river channel formation, and flood management. In particular, the effects of alterations to flow regime on ecosystems have been studied [32–34], and the natural flow regime has been elucidated [35–38]. Research on the factors that influence flow discharge has focused on rainfall amount or pattern [39,40], land use [41,42], and watershed geology [43]. For research on flow regimes, the factors influencing low flows that are strongly related to drought have been investigated by focusing on watershed area, watershed elevation, ratio of urban area or forest cover, and geology [44–48]. However, these studies mainly focused on mountainous watersheds or a single factor. In addition, the low flows prevalent in these studies were not evaluated probabilistically. Therefore, the relationship between the frequency of low flow and its controlling factors remains unknown.

Increasing water demand, due to population growth and economic development and/or changes in rainfall patterns due to climate change, alters the duration and magnitude of droughts. To establish sustainable water resource management based on changes in future drought risk, it is important to understand the relationship between low flow and its controlling factors, in relation to the magnitude of drought. Consequently, I formulated the hypothesis that the factors controlling low surface flow vary according to the severity of the drought. This study is a first attempt at revealing this relationship. The surface water volume of each drought-occurrence probability was calculated based on long-term observational data. The relationships among the drought water volume of each occurrence probability and the controlling factors were analyzed. Multiple controlling factors related to geology, land use, and topography were introduced. Since my results identified the controlling factor of drought for each occurrence probability, they may contribute to the development of effective water resource management strategies through prediction of drought water volumes or the impact of climate change on surface water runoff.

2. Materials and Methods

2.1. Location of the Study Area

In this study, 44 watersheds across the Japanese archipelago, where discharge observations have been conducted over 30 years, were used. Only stations where the impact of flow regime regulation is small due to a dam were used in this study. Thus, observation stations whose watershed included a sub-catchment in which a dam is located were excluded if the sub-catchment exceeded 10% of the total area of the watershed. (Figure 1). Information about the sub-catchment areas of dams was obtained from the Japan Dam Foundation [49]. Watershed areas ranged from 47 to 8208 km^2.

2.2. Calculation of the Hydrological Data

The runoff coefficient (calculated by dividing the depth of runoff by the amount of rainfall) has a clear relationship with controlling factors, including topography, land use, and geology [50,51]. Therefore, various analyses were conducted in this study, using the runoff coefficient during drought conditions.

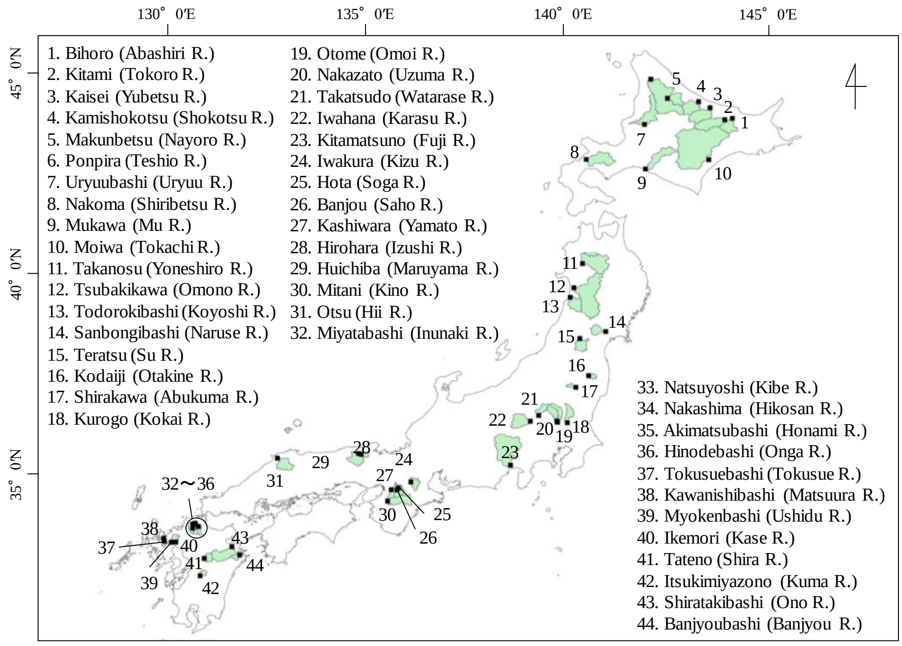

Figure 1. Location of the study site. In this study, I included watershed areas of 44 observation stations across the Japanese archipelago.

Although various time-scale indices have been used in the assessment of drought, propagation of a precipitation anomaly to streamflow was explained at the annual time-scale [52,53], and annual discharge was frequently used as an evaluation indicator of drought [54–57]. Therefore, I used annual total discharge as an indicator to calculate the drought runoff coefficient. To investigate the relationship between the various frequencies of droughts (from low to high) and the controlling factors, the drought runoff coefficients for six different probability years of occurrence (1/2, 1/10, 1/30, 1/50, 1/100, and 1/400) were calculated. Further, I defined the runoff coefficient for six different probability of years of occurrence as the drought runoff coefficient.

The drought runoff coefficient of each occurrence probability for the 44 watersheds was calculated using the following equation:

$$Qn / (Pn * A) (1) \qquad (1)$$

where Qn is the estimated total discharge of each occurrence probability, Pn is the estimated precipitation amount of each occurrence probability, n = 2, 10, 30, 50, 100, and 400; and A is the watershed area. The annual total discharge of each watershed was obtained from the Water Information System (http://www1.river.go.jp/ access on 10 April 2019). Annual precipitation data were obtained from the database of the Japan Meteorological Agency (http://www.jma.go.jp/jma/index.html access on 10 April 2019). Data from observation stations with an observation period exceeding 30 years were used based on the research results, which indicates that the stability of reproduction statistics increases if the samples exceed approximately 30 [58]. A sample of the average depth of rainfall over the watershed area was calculated using a Voronoi diagram to objectively consider the effect of area on the amount of rainfall at the watersheds.

A sample of annual total discharge and the average depth of rainfall over the watershed of each observation point were calculated to estimate the total discharge and annual precipitation for occurrence probabilities of 2, 10, 30, 50, 100, and 400 years. The hydrological statistics utility (ver. 1.5.) was used for the statistical analysis. I calculated the estimated design magnitude using 13 probability distributions, including the exponential distribution

(EXP), Gumbel distribution (Gumbel), exponential-type distribution of maximum (SqrtEt), generalized extreme value distribution (Gev), log-Pearson type III distribution (real coordinate space) (LP3Rs), log-Pearson type III distribution (log coordinate space) (LogP3), Iwai method (Iwai), Ishihara Takase method (IshiTaka), the logarithmic normal distribution with three parameters (quantile method) (LN3Q), the logarithmic normal distribution with three parameters (Slade II) (LN3PM), the logarithmic normal distribution with two parameters (Slade I, L-moments method) (LN2LM), the logarithmic normal distribution with two parameters (Slade I, moments method) (LN2PM), and the logarithmic normal distribution with four parameters (Slade IV, moments method) (LN4PM) [59–68]. Among the 13 probability distributions, the estimated design magnitude was selected based on the standard least-squares criteria [69].

Numerous definitions of hydrological droughts have been proposed [15,70]. In this study, with reference to Whipple [71] and Changnon [72], low flow discharge was defined as being less than the average annual total discharge, and drought was defined as being less than 75% of the average annual total discharge. Furthermore, a discharge of 50%–75% of the average annual total discharge was defined as high-frequency drought, and a discharge of less than 50% was defined as low-frequency drought.

2.3. Collecting Data for Controlling Factors

Twelve indicators were assessed and classified into three categories (geological, land-use, and topographic factors) as controlling factors of the drought runoff coefficient.

As a geological factor, I focused on surface geology. Surface geology was classified into four groups (volcanic rock, plutonic rock, metamorphic rock, and sedimentary rock), based on geological creation processes, using a subsurface geological map at a scale of 1:200,000 (http://nrb-www.mlit.go.jp/kokjo/inspect/landclassification/download/ access on 12 April 2019). The ratio of each surface geology was calculated using a geographic information system (GIS). In addition, metamorphic rock was excluded from the analysis because the composition ratio was less than 5% for all target watersheds.

Land-use data were obtained from the National Survey on the Natural Environment, conducted by the Japan Ministry of Environment (http://www.vegetation.biodic.go.jp/legend.html access on 12 April 2019). Five classes of land use were recognized in this study (coniferous forest, broadleaf forest, mixed coniferous–broadleaf forest, cropland, and urban areas), and each class was considered to have different effects on runoff. The proportion of land use for each of the 44 watersheds was calculated using GIS.

I calculated the inverse of the channel slope and topographical gradient, form ratio, and roundness, as topographic factors. Channel slope was defined as the difference in elevation between the observation station and headwater divided by the length of the stream channel. Topographic gradient was obtained by averaging the slope angles calculated using the average maximum method in the watershed [73]. The form ratio was calculated by dividing the watershed area by the square of the length of the stream channel [74]. The form ratio approaches 1.0 if the shape of the basin is almost square or circular. Roundness was calculated by dividing the circumference of the watershed area by the watershed boundary length [75]. Topography data were obtained from the Global 3D Map Service (ALOS World 3D-30 m).

2.4. Statistical Analyses

To investigate the characteristics of the drought runoff coefficient and its relationship with the controlling factors, an analysis using nonmetric multidimensional scaling (NMDS) [76] was conducted. NMDS refers to a family of related ordination techniques, all of which use rank order information in a (dis) similarity matrix [77–79]. Similarity in the drought runoff coefficient between watersheds was calculated using the Bray–Curtis similarity [80]. From the permutation test (n = 999), controlling factors closely related to the classification of the drought runoff coefficient ($p < 0.01$) were presented as vectors. Of the indicators used as controlling factors, topographical gradient was excluded from the analysis because of the strong positive correlation (r > 0.07) between it and cropland. In addition, to investigate the difference in controlling factors among groups classified by similarity of the drought runoff coefficient, the controlling factors of each group were analyzed using one-way analysis of variance and the Kruskal–Wallis test. Further, Tukey's honestly significant difference (Tukey's HSD) and the Steel–Dwass test were conducted to reveal differences between groups if a significant difference was confirmed among groups.

A generalized linear model (GLM) was subsequently developed to formulate a predictive model for the drought runoff coefficient for each occurrence probability. Ten controlling factors were used as explanatory variables, similar to the NMDS. The GLM is an extinction model of a linear model that allows the incorporation of non-normal distributions of the response variables and linear transformations of the dependent variables [81]. I compared the obtained Akaike information criteria (AIC) [82] for each model using the stepwise selection method [83]. Finally, the lowest AIC model was adopted as the best model for each species. GLM was conducted using MASS (version 7.3-50).

3. Results

3.1. Annual Precipitation and Drought Water Volume for Each Occurrence Probability

The results for annual precipitation, volume of drought runoff, and drought water volume per unit drainage area for each occurrence probability are presented in Tables 1 and 2. The depth of precipitation and drought water volume per unit drainage area tended to be high in southwest Japan and low in north Japan. In addition, the differences in depth of precipitation and drought water volume per unit drainage area between observation stations decreased with an increasing probability of occurrence. Eight types of probability distributions were selected to calculate the drought water volume. The probability distributions indicated the highest adaptability for Gev, which was selected at 23 stations. LN3Q had the second highest adaptability and was selected at seven stations. In the calculation of precipitation depth, 10 types of probability distributions were selected. Adaptability followed the order: Gev (16 stations) > Gumbel (7 stations) > LN3Q (6 stations). From the calculation of the total discharge of each probability of occurrence, the percentages of the average annual discharge were 96%, 67%, 56%, 53%, 48%, and 42% for probability of occurrences of 2, 10, 30, 50, 100, and 400 years, respectively. Therefore, the total discharge of the occurrence probability of 2 years corresponded to low-flow; 10, 30, and 50 years corresponded to the high-frequency drought; and 100 and 400 years corresponded to the low-frequency drought.

Table 1. The calculation result of precipitation amount for each occurrence probability.

No	Observation Station	Basin Area (km^2)	Precipitation Amount for Each Occurrence Probability (mm)						N	Model
			1/2	1/10	1/30	1/50	1/100	1/400		
1	Bihoro	824	925	731	659	633	602	554	31	Gev
2	Kitami	1394	794	601	515	481	439	370	31	Gev
3	Kaisei	1335	832	646	569	539	504	445	31	Gev
4	Kamishokotsu	1051	929	701	595	552	500	411	31	Gev
5	Makunbetsu	695	961	781	702	672	634	570	31	Gumbel
6	Ponpira	4029	1161	964	864	822	769	673	31	Gev
7	Uryuubashi	1661	1439	1199	1085	1038	980	880	31	Gev
8	Nakoma	1402	1245	1035	936	897	847	762	31	LN3Q
9	Mukawa	1228	1192	907	767	711	641	520	31	Gev
10	Moiwa	8208	1041	813	709	668	617	532	31	LN3Q
11	Takanosu	2109	1595	1285	1164	1120	1067	982	31	Gev
12	Tsubakikawa	4305	1957	1642	1522	1477	1422	1332	31	LN2LM
13	Todorokibashi	937	2155	1815	1684	1634	1575	1477	31	LN2LM
14	Sanbongibashi	551	1387	1147	1054	1018	977	906	31	Iwai
15	Teratsu	661	1195	972	890	861	826	772	31	Gev
16	Kodaiji	180	1199	913	793	747	691	598	31	Gev
17	Shirakawa	172	1957	1447	1200	1101	978	772	31	Gev
18	Kurogo	580	977	774	685	651	608	536	31	LN3Q
19	Otome	760	1381	1117	988	935	870	756	31	Gev
20	Nakazato	205	1629	1285	1103	1026	929	755	31	Gev
21	Takatsudo	472	1684	1323	1149	1080	994	847	31	LN3Q
22	Iwahana	1228	1282	970	845	799	743	653	31	Gumbel

Table 1. *Cont.*

No	Observation Station	Basin Area (km^2)	Precipitation Amount for Each Occurrence Probability (mm)						N	Model
			1/2	1/10	1/30	1/50	1/100	1/400		
23	Kitamatsuno	3540	1488	1107	973	923	865	772	31	Iwai
24	Iwakura	501	1634	1266	1117	1060	992	877	31	Iwai
25	Hota	163	1337	907	717	646	564	434	31	LN3Q
26	Banjou	105	1372	1037	862	790	700	544	31	Gev
27	Kashiwara	962	1397	1035	866	800	720	589	31	LN3Q
28	Hirohara	195	1869	1616	1520	1484	1443	1381	31	Gev
29	Huichiba	837	1721	1412	1287	1239	1181	1082	31	LogP3
30	Mitani	1049	1818	1435	1307	1261	1208	1122	31	LP3Rs
31	Otsu	911	1866	1536	1401	1348	1282	1172	31	LogP3
32	Miyatabashi	123	1475	1112	950	886	808	677	31	Gev
33	Natsuyoshi	47	1890	1404	1178	1087	977	791	31	Gev
34	Nakashima	326	2262	1664	1379	1264	1125	891	31	Gev
35	Akimatsubashi	113	1835	1368	1144	1055	944	756	31	Gev
36	Hinodebashi	695	1751	1309	1101	1018	917	745	31	Gev
37	Tokusuebashi	71	2252	1531	1256	1159	1049	883	31	Exp
38	Kawanishibashi	120	2252	1618	1323	1205	1063	824	31	Gev
39	Myokenbashi	95	1825	1342	1115	1024	912	725	31	Gev
40	Ikemori	231	1748	1271	1037	943	826	632	31	Gev
41	Tateno	386	2688	1992	1727	1629	1511	1316	31	LogP3
42	Itsukimiyazono	227	2217	1639	1414	1330	1232	1068	31	LN3Q
43	Shiratakibashi	1381	1942	1441	1247	1174	1087	943	31	LogP3
44	Banjyoubashi	278	2165	1548	1321	1238	1142	989	31	Gumbel

Table 2. The calculation result of drought runoff volume, and drought water volume per unit drainage area for each occurrence probability.

No	Drought Water Volume for Each Occurrence Probability (10^6 M^3)						N	Model	Drought Water Volume Per Unit Drainage Area for Each Occurrence Probability					
	1/2	1/10	1/30	1/50	1/100	1/400			1/2	1/10	1/30	1/50	1/100	1/400
1	435	299	254	240	222	196	60	Gev	0.53	0.36	0.31	0.29	0.27	0.24
2	699	521	461	441	415	373	60	LN3PM	0.50	0.37	0.33	0.32	0.30	0.27
3	962	709	637	613	585	541	52	LogP3	0.72	0.53	0.48	0.46	0.44	0.40
4	909	680	610	588	565	532	60	Gev	0.86	0.65	0.58	0.56	0.54	0.51
5	833	588	500	476	435	385	49	LN3Q	1.20	0.85	0.72	0.69	0.63	0.55
6	5882	4762	4348	4167	4000	3704	46	Gev	1.46	1.18	1.08	1.03	0.99	0.92
7	2326	1852	1667	1587	1515	1370	40	LN3Q	1.40	1.11	1.00	0.96	0.91	0.82
8	2082	1724	1613	1563	1515	1449	52	Gev	1.49	1.23	1.15	1.11	1.08	1.03
9	1250	833	667	625	556	438	42	LogP3	1.02	0.68	0.54	0.51	0.45	0.35
10	7143	5263	4545	4348	4000	3448	47	LogP3	0.87	0.64	0.55	0.53	0.49	0.42
11	3226	2632	2381	2283	2174	2000	55	Iwai	1.53	1.25	1.13	1.08	1.03	0.95
12	8333	6667	5882	5882	5556	5263	71	Gev	2.07	1.65	1.46	1.46	1.38	1.30
13	1961	1538	1389	1333	1266	1149	43	LN3PM	2.09	1.64	1.48	1.42	1.35	1.23
14	877	676	610	585	559	513	41	Iwai	1.59	1.23	1.11	1.06	1.01	0.93
15	833	625	526	500	476	400	42	Gumbel	1.26	0.95	0.80	0.76	0.72	0.61
16	137	95	83	78	72	65	36	Gev	0.76	0.53	0.46	0.43	0.40	0.36
17	196	137	116	110	101	88	48	Gev	1.14	0.80	0.68	0.64	0.59	0.51
18	714	526	455	435	400	357	55	Gumbel	1.23	0.91	0.78	0.75	0.69	0.62
19	1064	690	524	461	388	274	36	Gev	1.40	0.91	0.69	0.61	0.51	0.36
20	217	141	110	98	84	62	37	Gev	1.06	0.69	0.53	0.48	0.41	0.30
21	588	370	286	263	227	182	51	LN3Q	1.25	0.78	0.61	0.56	0.48	0.39
22	901	592	478	439	392	318	42	Gev	0.73	0.48	0.39	0.36	0.32	0.26
23	2174	1163	885	794	699	552	49	LN3Q	0.61	0.33	0.25	0.22	0.20	0.16
24	500	314	240	214	182	133	42	Gev	1.00	0.63	0.48	0.43	0.36	0.27
25	200	118	94	86	78	65	24	Gumbel	1.23	0.72	0.58	0.53	0.48	0.40
26	102	64	52	48	43	36	29	Gumbel	0.97	0.61	0.49	0.46	0.41	0.35
27	840	552	446	410	369	308	29	Exp	0.87	0.57	0.46	0.43	0.38	0.32
28	278	213	189	180	169	154	35	Iwai	1.42	1.09	0.97	0.93	0.87	0.79
29	1205	943	855	820	781	719	32	LP3Rs	1.44	1.13	1.02	0.98	0.93	0.86
30	1282	862	704	649	581	474	28	Gev	1.22	0.82	0.67	0.62	0.55	0.45
31	1389	1064	935	885	826	730	23	Gumbel	1.52	1.17	1.03	0.97	0.91	0.80
32	141	93	79	74	68	60	58	LogP3	1.15	0.76	0.64	0.60	0.56	0.49
33	76	46	35	31	26	19	30	Gev	1.61	0.98	0.74	0.65	0.55	0.39
34	412	260	207	188	167	134	62	SqrtEt	1.26	0.80	0.64	0.58	0.51	0.41
35	156	102	84	78	71	60	38	Gumbel	1.38	0.90	0.74	0.69	0.63	0.53
36	952	595	469	426	376	300	55	SqrtEt	1.37	0.86	0.68	0.61	0.54	0.43
37	96	58	45	41	36	28	41	SqrtEt	1.35	0.82	0.64	0.57	0.50	0.40
38	185	106	81	71	61	46	38	Gev	1.54	0.89	0.67	0.60	0.51	0.38
39	133	78	56	48	38	25	27	Gev	1.40	0.82	0.59	0.50	0.40	0.26
40	222	133	109	101	93	80	25	Gev	0.96	0.58	0.47	0.44	0.40	0.35
41	714	500	435	400	370	323	24	Gumbel	1.85	1.30	1.13	1.04	0.96	0.84
42	526	345	278	256	233	192	35	LN3Q	2.32	1.52	1.22	1.13	1.02	0.85
43	1818	1282	1124	1064	1000	893	66	LN3PM	1.32	0.93	0.81	0.77	0.72	0.65
44	357	209	165	150	133	108	57	LN3Q	1.28	0.75	0.59	0.54	0.48	0.39

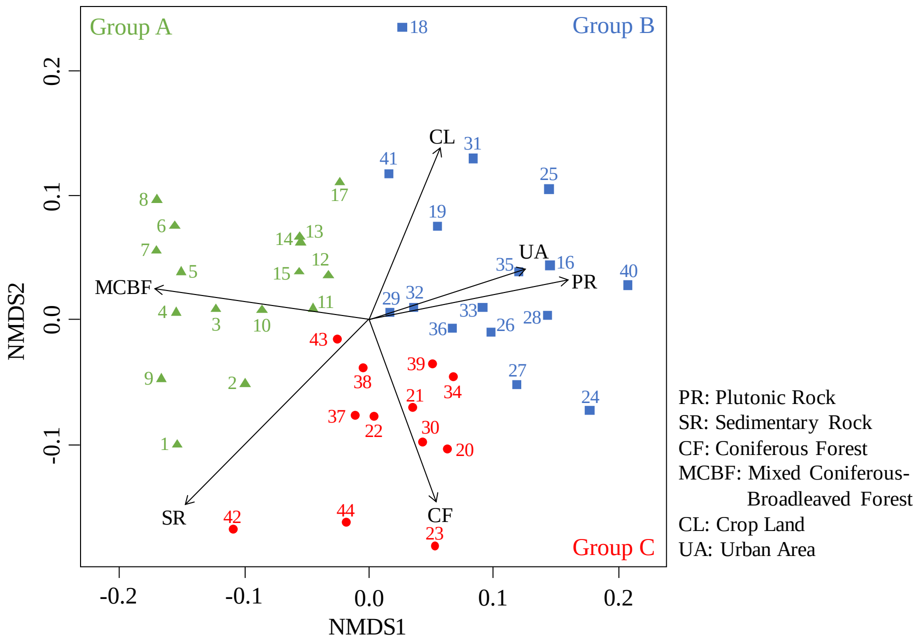

Figure 2. Result of NMDS using drought runoff coefficient of each occurrence probability. NMDS, nonmetric multidimensional scaling.

Group A (N = 16) was located in the second and third quadrats and was composed of watersheds dominated by a mixed coniferous and broadleaf forest. The watersheds belonging to Group A were also characterized by low ratios of urban area and plutonic rocks. Group B (N = 16) was located in the first and fourth quadrats, composed of watersheds dominated by urban areas or croplands. The surface geology of the watersheds belonging to Group B was dominated by plutonic rocks. Group C (N = 12) was located in the third and fourth quadrats, and was composed of watersheds characterized by a high proportion of coniferous forest.

The average runoff coefficient was largest in group A and smallest in group C in all occurrence probabilities. In addition, the difference in the drought runoff coefficient between occurrence probabilities was smaller in Group A than in the other groups, exhibiting a slight difference between the occurrence probabilities of 2 and 400 years. However, in Group C, the drought runoff coefficient tended to decrease with increasing occurrence probability. In Group B, the change in drought runoff coefficient with occurrence probability indicated an intermediate behavior between Groups A and C. Although the drought runoff coefficient decreased to an occurrence probability of 30 years, it had an almost constant value at occurrence probabilities exceeding 30 years (Figure 3). A significant difference between groups A and C was confirmed in all occurrence probabilities ($p < 0.01$). In addition, a significant difference between groups A and B was confirmed in the occurrence probabilities of 10, 30, 50, 100, and 400 years ($p < 0.01$).

3.2. Characteristics of Controlling Factors in Each Group

Figure 4 presents a boxplot of the controlling factors for each group. The geological factors VR and SR yielded similar results. The highest values for both indicators were observed in group A, followed by those in groups C and B. One-way analysis of variance indicated a significant difference among the three groups ($p < 0.01$). Tukey's HSD test revealed a significant difference between Group B and the other two groups ($p < 0.01$) for both factors. However, the PR exhibited the opposite trend. The average value for PR was highest in group B (41%), followed by those in groups C (7.2%) and A (2.7%). The Kruskal–Wallis test revealed significant differences among the groups ($p < 0.01$). In addition, the Steel–Dwass test revealed that the PR of group B was significantly higher than that of groups A ($p < 0.01$) and C ($p < 0.01$).

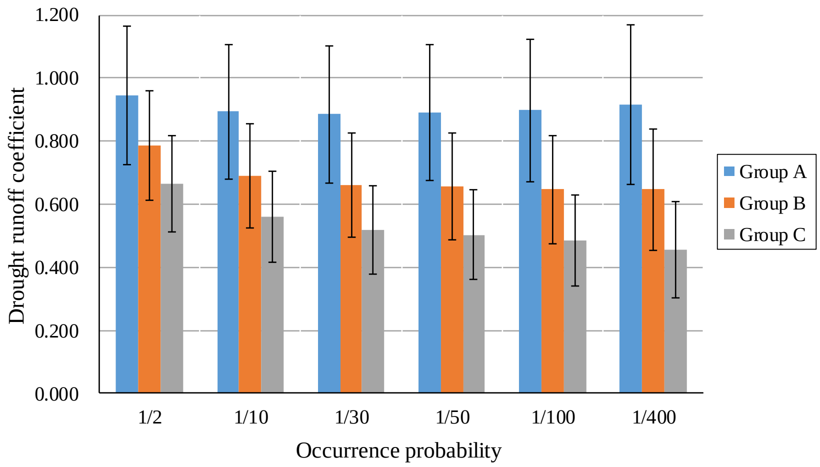

Figure 3. Characteristics of the average value of drought runoff coefficient for each occurrence probability in three groups.

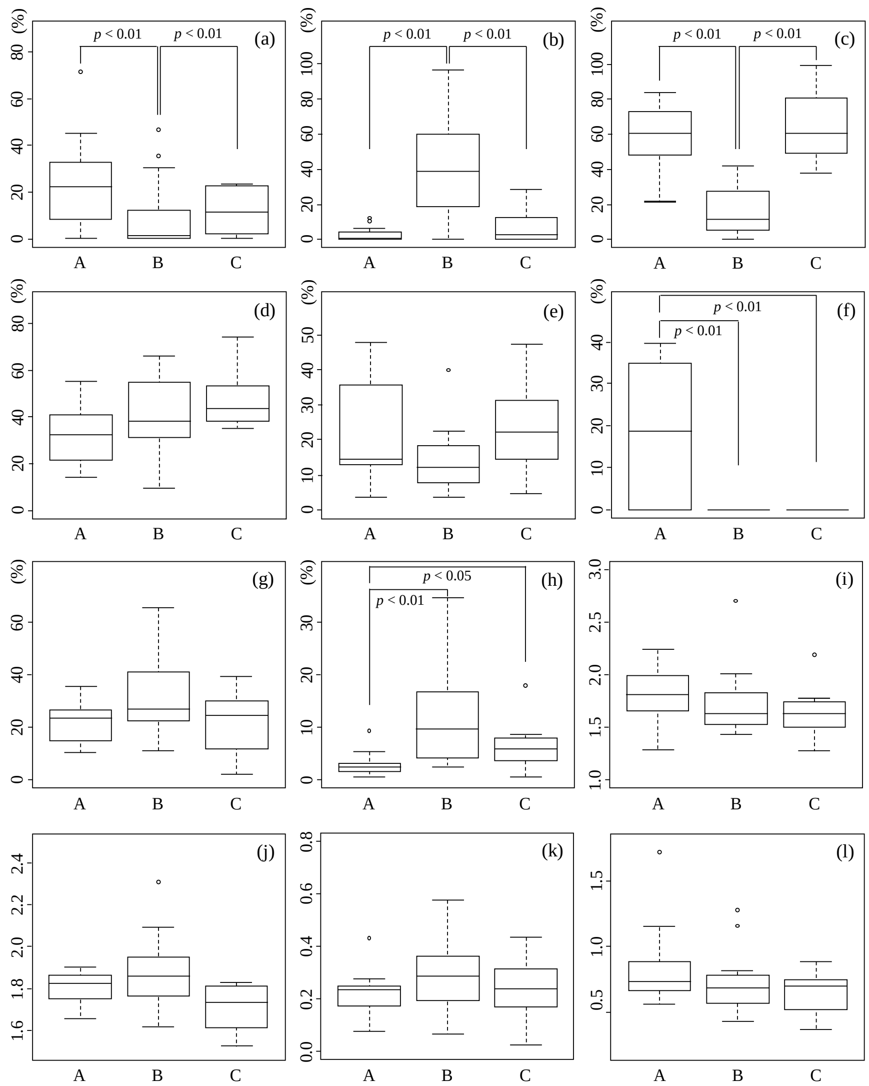

Figure 4. Comparison of controlling factors between groups: (**a**) VR: Volcanic Rock, (**b**)PR: Plutonic Rock, (**c**) SR: Sedimentary Rock, (**d**) CF: Coniferous Forest, (**e**)BF: Broadleaf Forest, (**f**) MCBF: Mixed Coniferous–Broadleaved Forest, (**g**) CL: Crop Land, (**h**) UA: Urban Area, (**i**) CS: Channel Slope (**j**) TGr Topographical Gradient (**k**) FR: Form Ratio, (**l**) Ro: Roundness.

MCBF was the only land-use factor confirmed in watersheds belonging to Group A. The average value for UA was highest in group B (12%), followed by groups C (6.4%) and A (2.9%). The Kruskal–Wallis test revealed significant differences among groups ($p < 0.01$). In addition, the Steel–Dwass test revealed that the UA of group A was significantly lower than that of groups B ($p < 0.01$) and C ($p < 0.05$).

By contrast, one-way analysis of variance and the Kruskal–Wallis test indicated no significant difference for land-use factors BF, CF, and CL, and all topographical factors.

4. Discussion

4.1. Difference in Drought Runoff Coefficient between Areas

Observation stations located on the Japanese archipelago were classified into three groups, A, B, and C, on the basis of their drought runoff coefficient. Furthermore, as a result of this classification, geographically close rivers tend to be classified into similar groups. The tendency of geographically adjacent rivers to show similar hydrological characteristics has been confirmed in previous studies [84]. Sawicz et al. [85] explained that this tendency was caused by climatic and landscape characteristics changing slowly in space. The drought runoff coefficient of Group A exhibited high values, regardless of changes in occurrence probability. However, the drought runoff coefficient of Group C decreased with increasing occurrence probability. Catchment classification using runoff characteristics is important from the standpoint of prediction in ungauged basins or the creation of a common language [86]. Carely et al. [87] analyzed the runoff coefficient of rivers in Sweden, Scotland, Canada, and the United States, and divided rivers into two groups (catchments that rapidly generate precipitation runoff and catchments that more readily store water and exhibit a more delayed release). In addition, Laaha and Blosch [48] demonstrated that seasonality of rainfall was the optimal parameter for the classification of watersheds using low-flow data. The change in the drought runoff coefficient with increasing probability of occurrence for Group B exhibited a trend intermediate between Groups A and C. In this study, I used the drought runoff coefficient as the indicator, which was calculated by dividing total river runoff by total rainfall in each area. The drought runoff coefficient was calculated annually and therefore, the difference in the trend of the drought runoff coefficient of occurrence probability among groups was thought to be partly caused by the seasonality of rainfall across different time-scales. However, it is clear that watershed factors exerted a strong influence on the drought runoff coefficient because the characteristics of the watershed indicator differed for each classification, based on the NMDS results. The stable and high drought runoff coefficient of Group A, which was composed of watersheds in regions experiencing heavy snow, can be attributed to its specific pattern of precipitation, compared to those of other areas. This is also due to low evapotranspiration in high-latitude areas [88,89]. Takahashi et al. [90] investigated the drought water volume of this water source area and concluded that the large drought water volume of north Japan results from the stable water supply induced by spring snowmelt, and associated runoff and intermittent rainfall in fall. This water supply contributes to the maintenance of groundwater during the drought season. In addition, the drought risk of the area influenced by spring snowmelt runoff will increase owing to the decreasing depth of precipitation in winter and spring as a result of climate change. This confirms the importance of snowmelt runoff in water resource recharge [91].

A trend of decreasing drought runoff coefficient with increasing occurrence probability was found in Group C, which is composed of watersheds within the southwest Japanese archipelago. In these watersheds, the depth of precipitation largely depends on the intense rainfall of a typhoon or rainy season [92]. Therefore, the low supply of water into the ground during drought results in a low drought runoff coefficient when the probability of occurrence is high. In addition to the influence of the pattern of precipitation, the geology of the watersheds belonging to Group C also influenced the low drought runoff coefficient. Group C was composed of watersheds with a high proportion of sedimentary rock (Figure 4). Furthermore, the geological age of the sedimentary rock of these watersheds (the Mesozoic and Paleozoic ages) is older than that in other areas [93]. The low drought runoff coefficient was thought to be caused by the high degree of agglomeration of the rock, which is a result of the high geological age influencing the deep percolation of precipitation. Group A is also an area with a large proportion of sedimentary rock, but it is thought that the difference in geological age and the influence of rainfall patterns was dominant, resulting in a difference in the rate of drought outflow from Group C.

4.2. Controlling Factors and the Drought Runoff Coefficient

4.2.1. Occurrence Probability of Drought and Controlling Factors

Hydrologic units reflect the characteristics of climate, geology, topography, and land use of watersheds [86,94]. Therefore, in this section, I describe the relationship between the watershed characteristics (geology, land use, and topography) and the drought runoff coefficient for each occurrence probability. The GLM investigated the relationships between the drought runoff coefficient and controlling factors, and demonstrated that geological factors and land-use factors (vegetation) influenced the drought runoff coefficient in high-frequency drought. In contrast, land-use factors and topographic factors were selected as influencing factors in low-frequency drought. Comparing the standard partial regression coefficient obtained from the GLM as a function of the occurrence probability, the value of MCBF of land-use factors was higher than that of geological factors in the high-frequency drought. In the drought with an occurrence probability of 30 years, the value of land-use factor exceeded that of the geological factor, and CF was selected as the most influential indicator. Furthermore, CS was selected as an important factor in low-frequency drought, in addition to CF. This is considered to be due to the fact that the runoff components that control flow discharge differ, depending on drought frequency. Geological factors and land-use factors were selected as the controlling factors in the total discharge of occurrence probability of 2 and 10 years. These factors are closely related to surface runoff or subsurface flow. In contrast, for the low-frequency drought, factors related to a longer time-scale hydrological cycle, such as ground-water level, were selected. Previous research investigating the relationship between flood discharge and controlling factors for multiple occurrence probabilities demonstrated that a coniferous forest increases discharge in low-frequency floods, whereas topographical factors increase discharge in high-frequency floods [51]. In addition, the controlling factor for stream discharge changes from rainfall to geological factors with the threshold of ordinary water discharge [44]. From these results, it is clear that the controlling factors change according to the frequency of both flood and drought events.

4.2.2. Geological Factors and the Drought Runoff Coefficient

Some studies have demonstrated that geology is one of the factors controlling the flow regime [95–97]. The reasons for differences in drought runoff or base flow as a function of geology are that (i) the retention capacity of groundwater differs based on geology; and (ii) the infiltration capacity of soils differs as a function of geology [98,99]. From the GLM, PR and SR (among the geological factors) were selected as controlling factors that decreased the drought runoff coefficient in high-frequency drought (Table 3). This is incompatible with the results of Mushiake et al. [44], who noted that granite (classified as a plutonic rock) is a factor in increasing drought discharge. This contrast in results was caused by the location of the study area and the observation period of the data. Mushiake et al. [44] used the average drought value based on a relatively short-term period. In steep mountain rivers with a small watershed area, rainfall rapidly flows out, and the ratio of surface and intermediate runoff to drought discharge is thought to be larger. In addition, the influence of local deep percolation in bedrock cracks appears to be highly significant in small watersheds. Therefore, a minimum basin area is necessary to evaluate the effect of geological factors on the drought runoff coefficient. In contrast, Yokoo and Oki [100] demonstrated that geological age exerts an influence on drought runoff. In particular, based on an investigation of watersheds with an area exceeding 100 km^2, quaternary geology was found to be an increasing factor for drought runoff. Rocks of different geological ages differ in the degree of consolidation and result in a difference in the degree of deep percolation. Furthermore, as diagenesis progresses, water exchange between an aquifer and a river is less likely to occur. Therefore, geological age is an important factor for characterizing the drought runoff coefficient. Therefore, it is necessary to consider both geological type and geological age as indicators for predicting drought runoff.

Table 3. Analysis of the relationship between drought runoff coefficient of each occurrence probability and controlling factors by GLM

Controlling Factors	**Occurrence Probability**					
	1/2	**1/10**	**1/30**	**1/50**	**1/100**	**1/400**
Geological factor						
VR	−0.065					
PR	−0.135 **	−0.087 *	−0.072	−0.076	−0.068	
SR	−0.158 **	−0.107 **	−0.091	−0.097	−0.094	
Land use factor						
BF	0.098 *	0.087 **		−0.047	−0.047	−0.059
CF			−0.120 **	−0.159 ***	−0.155 **	−0.205 ***
MCBF	0.122 **	0.117 **				
CL			−0.078	−0.106 *	−0.103	−0.083
UA			−0.078 *	−0.079 *	−0.087 *	−0.084 *
Topographical factor						
CS	0.049	0.098 **	0.105**	0.105 **	0.073 *	0.118 *
FR		0.047	0.047			
RO				−0.052		−0.089
R^2	0.377	0.441	0.435	0.444	0.421	0.430
AIC	−23.013	−24.676	−20.005	−17.291	−12.615	−4.9517

p-value < 0.05 = *, *p*-value < 0.01 = **, *p*-value < 0.001 = ***.

In addition to plutonic rock, sedimentary rock was selected as a factor causing a decline of the drought runoff coefficient for occurrence probabilities of 2 and 10 years. The infiltration capacity of sedimentary rocks appears to change with the degree of agglomeration. However, flysch (classified as a sedimentary rock), is a factor for increasing drought or flood [101]. The GLM results support the finding that the low permeability of sedimentary rock is a controlling factor in high-frequency drought.

While much research has revealed the relationship between geology and drought discharge, some researchers have claimed a stronger influence of topography than that of surface geology on groundwater level [102]. To clarify the more precise influence of geology, it is important to analyze the relationship between drought and geology under the same conditions of watershed area, topography, land use, and drought magnitude. In addition, the degree of agglomeration of the rock is closely related to runoff phenomena, as discussed above. Further research is needed to quantify the relationship between drought runoff discharge and geology in various regions.

4.2.3. Land Use Factors and the Drought Runoff Coefficient

Changes in the number of available water resources due to an alteration in the rainfall–runoff relationship caused by vegetation changes have long been recognized [103]. In addition, runoff volume differs between coniferous and broadleaf forests, owing to the dissimilarities in evapotranspiration (ET) [104–106]. My research results also indicate the different functions of coniferous and broadleaf forests. Based on the GLM, the broadleaf forest was selected as an increasing factor for the drought runoff coefficient for high-frequency drought, whereas coniferous forest was a decreasing factor for low-frequency drought (Table 3). This is thought to be due to differences in ET. Previous research has indicated that the change in runoff volume is larger for a coniferous forest when a coniferous forest and a broadleaf forest are cleared [107]. Furthermore, the drought runoff volume increases because of the clearing of the coniferous forest [103,108–110]. These results support the GLM results. Moreover, I presume that the reason for the coniferous forest decreasing the drought coefficient in low-frequency drought is as follows: Since ET and canopy interception occur constantly regardless of drought magnitude, the amount of precipitation available to generate surface runoff decreases as the depth of precipitation decreases, and the effects of coniferous forests become dominant. In contrast, ET and runoff volume are altered by the management status of the forest, the condition of the forest floor, and tree age [111–113]. This study examined the relationship between the runoff coefficient and vegetation type as land-use factors for relatively large watersheds. Therefore, the differences between broadleaf and coniferous forests have become clear. However, it should be noted that the runoff coefficient could change, even within the same forest type, if the targeted watershed is smaller.

Land use changes significantly alter the mechanism of runoff [114]. Among land-use changes, urbanization increases flood peak discharge [115] and decreases minimum flow [116]. The main cause of urbanization decreasing the minimum flow is a decrease in the infiltration area and a decline in the base flow due to the consolidation of pipe systems [117,118]. The GLM results indicate that urban areas are a decreasing factor for the drought runoff coefficient in low-frequency droughts. The composition of tree species in the forest is an important controlling factor for high-frequency drought because the source of surface water mainly depends on rainfall in the upstream area. Therefore, the impact of urbanization is assumed to be relatively low in high-frequency droughts. In contrast, surface water from the upstream area is decreased in low-frequency drought and therefore, the influence of urbanization, including the limitation of rainfall infiltration or supply of surface water from groundwater, is assumed to be dominant. In contrast to this study, Ralf and Bloschl [119] demonstrated that land use, soil type, and geology do not exert strong influences on the volume of runoff in the normal stage in 459 rivers in Austria. Based on the results of my analysis, the magnitude of the impact of land use on the runoff coefficient varied, depending on the scale of runoff.

4.2.4. Topographic Factors and the Drought Runoff Coefficient

To determine the relationship among topographic factors and drought runoff, the influence of river length, watershed gradient, average watershed width, and altitude on base flow were examined [100,120–123]. The GLM indicated that channel slope is an increasing factor for the drought runoff coefficient at occurrence probabilities of 10 years or more (Table 3). This result supports the research of Moliere et al. [120], who demonstrated that zero flow days increase in high-gradient rivers. However, topographic factors were not selected as controlling factors for the drought runoff coefficient at an occurrence probability of 2 years. Runoff discharge in high-frequency droughts is mainly governed by surface runoff. Therefore, the geological or land-use factors closely related to surface runoff were dominant, rather than topographical factors. However, the ratio of groundwater appeared to increase with increasing river discharge during low-frequency drought. Therefore, the topographic factor most closely related to groundwater was selected. Moreover, this study focused on observation stations in various basins, including both mountainous and alluvial areas. The interaction between groundwater and surface water is considered to be more active in alluvial channels; therefore, the drought runoff coefficient was higher in low-gradient watersheds.

5. Conclusions

This manuscript reports relationships among drought runoff and controlling factors (geological, land-use, and topographical factors) as a function of occurrence probability.

Classification results of the drought runoff coefficient across multiple drought magnitudes indicated three types of behavior for the drought runoff coefficient. The group with watersheds influenced by snowmelt runoff had a high drought runoff coefficient, regardless of drought magnitude. However, the drought runoff coefficient of the group influenced by rainfall intensity decreased with increasing drought magnitude. The drought runoff coefficient of the remaining group exhibited intermediate behavior between these two groups. In addition, this classification result indicated a significant relationship between the proportion of plutonic rock, sedimentary rock (geological factors), urban areas, and a mixed coniferous–broadleaved forest (land-use factors).

The GLM revealed that the controlling factors differed depending on the magnitude of drought. In high-frequency drought, the drought runoff coefficient was influenced by geological and vegetation factors, whereas land use and topographical factors influenced the drought runoff coefficient in low-frequency drought. These differences were caused by the differences in the runoff component, which dominated stream discharge in relation to drought magnitude.

This research clarified that a change in the drought runoff coefficient due to occurrence probability differs depending on the precipitation pattern or climatic zone, and the controlling factors of the drought runoff coefficient changed in accordance with the occurrence probability. Therefore, for effective water resource management, estimation of the drought runoff volume needs to consider precipitation pattern, geology, land use, and topography to correspond to the magnitude of the drought. Because the results clarify the controlling factors of drought runoff for each occurrence probability, this study contributes to effective water resource management by estimating the drought volume for climatic zones and by predicting changes in drought volume due to climate change. Further research is needed to investigate applicable climate zones and the influence of catchment scale on the relationship between drought and the controlling factors. Although not included in this study, dimensionless numbers describing the geomorphological characteristics of catchments, including stream order [124,125], bifurcation or ratio hillslope form [126], were revealed to explain the hydrogeomorphological characteristics of the catchment. Therefore, I can improve my model by using these factors.

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