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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 and economic development or changes in rainfall pattern as a result of climate change is likely to alter the duration and magnitude of droughts. To establish sustainable water resource management based on changes in future drought risk, understanding the relationship between low-flow conditions and controlling factors relative to drought magnitude is important. This study is the first attempt at revealing the relationship between low-flow and controlling factors at differing drought severities. I calculated the drought runoff coefficient for six types of occurrence probability based on past observation data of minimum flow and precipitation. Furthermore, I investigated the pattern of change in the drought runoff coefficient in accordance with the occurrence probability and relationship between the coefficient and geological, land use, and topographical factors. The drought runoff coefficient for multiple drought magnitudes exhibited three behaviour types corresponding to precipitation pattern. The results from a generalized linear model (GLM) revealed that the controlling factors differ depending on drought magnitude. 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 differences in the runoff component, which dominates stream discharge according to drought magnitude. Therefore, for effective water resource management, estimation of the drought runoff volume needs to consider precipitation pattern, geology, land use, and topography.

1 Introduction

The causes of, and adaptations to, droughts as natural disaster have been researched from the perspective of hydrology, environmentology, geology, meteorology, and agronomy (Mishra & Singh, 2010). The causes of droughts have been investigated in various regions, by focusing on rainfall pattern (Verschuren et al., 2000; Tabari, et al., 2012; Tfwala et al., 2018), temperature (Nicholls, 2004; Hein et al., 2019), wind (Namias, 1989), and humidity (Behrangi et al., 2015). In addition to the impacts of natural factors, aggravation of the drought hazard is expected to occur because of growing water demand associated with population growth and economic development (Frederiksen, 1996; Xiao-jun et al., 2012; El Kharraz et al., 2012) and changes in the hydrological cycle associated with anthropogenic impacts such as land use change (Liu et al., 2017; Deo et al., 2009; Lee et al., 2011).

Droughts are generally categorized into four types (Wilhite & Glantz, 1985). First, drought resulting from precipitation shortage is defined as meteorological drought (Mishra & Singh, 2010; Smakhtin & Hughes, 2007). In addition, the relationship between monthly rainfall and cumulative precipitation amount was investigated (Eltahir, 1992). 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 (Tallaksen & Van Lanen, 2004; Nalbantis & Tsakiris, 2009). Stream water discharge is often used as an indicator of the management and analysis of hydrological drought (Clausen & Pearson, 1995). Third, agricultural drought indicates declining soil moisture, regardless of surface water resources, causing crop failure (Rickard, 1960; Nieuwolt, 1986). Finally, socio-economic drought occurs in cases of defectiveness and incompatibility of the water resource system in relation to water demand (Eklund & Seaquist, 2015; Mehran et al., 2015).

Prolonged droughts cause severe socio-economic loss (Carrão et al., 2018; Ahmadalipour et al., 2019). Research results on the evaluation of the economic loss of droughts indicate that damage of $6–8 billion per year occurs in the United States (Smith & Katz, 2013; Smith & Matthews, 2015), with the EU suffering damages of €100 billion over the last 30 years (Carrão et al., 2016). 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 (Vicente-Serrano et al., 2012).

In addition, changes in the hydrological cycle as a result of climate change are expected to increase extreme drought events (Mishra & Singh, 2010). Unlike flood disasters, the influence of climate change on drought is not yet fully understood. However, future prediction of drought aggravation due to population growth in central Africa (Ahmadalipour et al., 2019) and increasing drought duration and severity in the interior southwest of the United States (Andreadis & Lettenmaier, 2006) have been reported. Furthermore, forecasts of drought using soil moisture as an indicator have indicated increasingly frequent drought events in Europe regardless of emission scenario (Grillakis, 2019).

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 flow regime alteration on ecosystems have been studied (Sparks, 1995; Bunn & Arthington, 2002; Taylor et al., 2008), and the natural flow regime has been elucidated (Poff et al., 1997; Lytle & Poff, 2004; Naiman et al., 2008; Kennard et al., 2010). Research on the factors that influence flow discharge have focused on rainfall amount or pattern (Obled et al., 1994; Montgomery et al., 1997), land use (Kashaigili, 2008; McIntyre & Marshall, 2010), and watershed geology (Meijerink, 1985). For research on flow regime, the factors influencing low flows strongly related to drought have been investigated, through focusing on watershed area, watershed elevation, ratio of urban area or forest cover, and geology (Mushiake et al., 1981; Zecharias & Brutsaert, 1988; Vogel & Kroll, 1992). However, these studies mainly focused on mountainous watersheds or a single factor. In addition, the low flows prevalent in the above research were not probabilistically evaluated. Therefore, the relationship between the appearance frequency of low flow and its controlling factors remain unknown.

Increasing water demand due to population growth and economic development and/or changes in rainfall pattern due to climate change alter the duration and magnitude of droughts. To establish sustainable water resource management based on

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changes in future drought risk, understanding the relationship between low flow and its controlling factors in relation to the magnitude of drought is important. Based on the above, I formulated the hypothesis that the controlling factors of low surface flow vary according to drought severity. The present study is a first attempt at revealing this relationship. The surface water volume of each drought occurrence probability was calculated based on long-term observation data. The relationship between the drought water volume of each occurrence probability and the controlling factors was analyzed. Multiple controlling factors related to geology, land use, and topography were introduced. Since the research results identify the controlling factor of drought for each occurrence probability, they may contribute to the development of effective water resource management through prediction of drought water volumes or impacts of climate change on the surface water runoff.

2 Materials and Methods

2.1 Location of the study area

In this study, 44 watersheds belonging to the Japanese archipelago where discharge observations have been conducted over 30 years were used. To extract stations where the impact of flow regime regulation due to a dam is small, observation stations whose watershed was subject to over 10% occupancy by a dam watershed were excluded (Fig. 1). The watershed areas ranged from 47 to 8,208 km2.

2.2 Calculation of the hydrological data

Annual total discharge of each watershed was obtained from the Water Information System (http://www1.river.go.jp/). A sample of annual total discharge of each observation point was statistically calculated to estimate the total discharge for occurrence probabilities of 2, 10, 30, 50, 100, and 400 years. 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). Among the 13 probability distributions, the estimated design magnitude was selected based on standard least squares criteria (Takasao et al., 1986).

Annual precipitation data were obtained from the database of the Japan Meteorological Agency (http://www.jma.go.jp/jma/index.html). Data from observation stations with an observation period of over 30 years were used. A sample of the average depth of rainfall over the watershed area was calculated using a Voronoi diagram. The estimated

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annual precipitation for occurrence probabilities of 2, 10, 30, 50, 100, and 400 years was calculated using the same method used for annual total discharge.

The drought runoff coefficient of each occurrence probability for the 44 watersheds was calculated by dividing the annual total discharge by annual precipitation.

2.3 Collecting data for controlling factors

I assessed 11 indicators, 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. I classified the surface geology into four groups (volcanic rock, plutonic rock, metamorphic rock, and sedimentary rock) based on geological creation processes using a subsurface geological map with a scale of 1:200,000 (http://nrb-www.mlit.go.jp/kokjo/inspect/landclassification/download/). 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% in all target watersheds.

The land use data were obtained from the National Survey on the Natural Environment by the Japan Ministry of Environment (http://www.vegetation.biodic.go.jp/legend.html). Classification of land use was based on five categories (coniferous forest, broadleaf forest, mixed coniferous–broadleaf forest, cropland, and urban areas); each class was considered to have different effects on runoff phenomena. The ratio of each land use for the 44 watersheds was calculated by GIS.

I calculated the inverse of channel slope and topographical gradient, form ratio, and roundness as topographic factors. Channel slope was defined as the division of the difference in elevation between the observation station and the headwater by the length of the stream channel. The form ratio was calculated by dividing the watershed area by the square of the length of the stream channel (Horton, 1932). The form ratio approaches 1.0 if the shape of the basin is almost square or circular. The roundness was calculated as the division of the circumference of the same area of a watershed by the boundary length of the watershed (Miller, 1953). Topography data were obtained from Global 3D Map Service (ALOS World 3D-30 m).

2.4 Statistical analysis

To investigate the characteristics of the drought runoff coefficient and its relationship with the controlling factors, an analysis by non-metric multi-dimensional scaling (NMDS) (Kruskal, 1964) was conducted. NMDS refers to a family of related ordination techniques, all of which use rank order information in a (dis)similarities matrix (Coxon, 1982; Gauch, 1982; Whittaker, 1987). Similarity in the drought runoff coefficient between watersheds was calculated by Bray–Curtis similarity (Bray & Curtis, 1957). As a result of the permutation test, controlling factors closely related to the classification of the drought runoff coefficient ($p < 0.01$) were presented as vectors. Of the 11 indicators used as controlling factors, the 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

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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.

Next, a generalized linear model (GLM) was developed to formulate a prediction model for the drought runoff coefficient for each occurrence probability. As the explanatory variables, 10 controlling factors were selected, same of the NMDS. The GLM is an extinction model of a linear model, which allows the incorporation of non-normal distributions of the response variables and linear transformations of the dependent variables (McCullagh and Nelder, 1989). I compared the obtained Akaike information criteria (AIC) (Burnham & Anderson, 2002) of each model by increasing and decreasing the variables. Finally, I adopted the lowest AIC model as the best model for each of the 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 calculation results for annual precipitation, drought runoff volume, and drought water volume per unit drainage area for each occurrence probability are presented in Table 1. The precipitation amount 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 precipitation amount and drought water volume per unit drainage area between observation stations tended to decrease, corresponding with the increasing occurrence probability. Eight types of probability distribution were selected for the calculation of drought water volume. The probability distributions indicated highest adaptability for Gev, which was selected at 23 stations. LN3Q had the second highest adaptability, being selected at seven stations. In the calculation of the precipitation amount, 10 types of probability distribution were selected. Adaptability followed was in the order: Gev (16 stations) > Gumbel (7 stations) > LN3Q (6 stations).

3.2 Classification of the drought runoff coefficient and controlling factors

As a result of seriation and clustering using the drought runoff coefficient for each occurrence probability based on NMDS, the 44 stations were classified into three groups. Furthermore, SR and PR (geological factors) and CF, MCBF, UA, and CL (land use factors) were selected as the controlling factors strongly related to the classification of the drought runoff coefficient based on the permutation test ($p < 0.01$). The selected controlling factors were placed in the positive direction of the first axis for PR and UA. MCBF was placed in the negative direction of the first axis. CL was placed in the positive direction of the second axis. CF and SR were placed in the negative direction of the second axis (Fig. 2).

Group A (N = 16) was located in the second and third quadrats, 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 rock. Group B (N = 16) was located in the first and fourth quadrats, composed of watersheds dominated by urban area or cropland. The surface geology of watersheds belonging to Group B was dominated by plutonic rock. Group C (N = 12) was located in the third and fourth quadrats, composed of watersheds characterized by a high ratio of the coniferous forest.

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The average value of the drought runoff coefficient for each occurrence probability was large, with Group A > B > C. In addition, the difference in the drought runoff coefficient between occurrence probabilities was smaller in Group A than other groups, exhibiting a little difference between the occurrence probabilities of 2 and 400 years. However, in Group C, the drought runoff coefficient tended to decrease in accordance with the increasing occurrence probability. In Group B, the change in drought runoff coefficient with occurrence probability indicated behavior intermediate between Groups A and C. Although the drought runoff coefficient decreased up to an occurrence probability of 30 years, it had an almost constant value at occurrence probabilities exceeding 30 years (Fig. 3).

3.3 Characteristics of controlling factors in each group

Fig. 4 presents a boxplot of the controlling factors for each group. The bold line in the center of the boxplot depicts the median of the data. The top and bottom of the box indicate the third and first quartiles, respectively. In addition, the line located at the top of the box indicates the largest value over than the value, calculated by (first quartile − 1.5 × (third quartile − first quartile)). The line located at the bottom of the box indicates the smallest value less than the value, calculated by (third quartile − 1.5 × (third quartile − first quartile)).

Geological factors VR and SR had similar results. The highest values for both indicators were observed in Group A, followed by those in Group C and Group B. One-way analysis of variance indicated a significant difference among the three groups ($p < 0.01$). The Tukey's HSD test revealed a significant difference between Group B and the other two groups ($p < 0.01$) for both factors. However, PR had an opposite trend. The average value for PR was highest in Group B (41%), followed by those in Group C (7.2%) and Group A (2.7%). Results of 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 Group A ($p < 0.01$) and Group C ($p < 0.01$).

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

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

3.4 Relationship between the drought runoff coefficient for each occurrence probability and the controlling factor

Analysis of the relationship between the drought runoff coefficient for each occurrence probability and the controlling factor by the GLM revealed that PR, SR, CF, and CL are decreasing factors for the drought runoff coefficient, whereas BF, MCBF, and Gr are increasing factors. The influence of these controlling factors on the drought runoff coefficient differed among the occurrence probabilities. Indicators of the forest classification were selected as controlling factors for occurrence probabilities of 2 and 10 years, whereas the land use factor, CF, and UA were selected as decreasing factors for the drought runoff coefficient for occurrence probabilities of over 30 years. Goodness of fit was highest for the occurrence probability of 50 years (R^2 = 0.444), and it was lowest for the occurrence probability of two years (R^2 = 0.377). VR (geological factor) and FR and CLR (topographical factors) were not selected as controlling factors of the drought runoff coefficient (Table 2).

4 Discussion

4.1 Difference in drought runoff coefficient between areas

As a result of drought runoff coefficient classification, observation stations belonging to the Japanese archipelago were classified into three groups: Groups A, B, and C. The drought runoff coefficient of Group A was characterized by high values regardless of changes in occurrence probability. However, the drought runoff coefficient of Group C decreased with increasing occurrence probability. The change in the drought runoff coefficient with increasing occurrence probability for Group B had an intermediate trend between Groups A and C. The stable and high drought runoff coefficient of Group A, which was composed of watersheds belonging to the heavy snow area, can be attributed to its more particular precipitation pattern compared to those of other areas. Takahashi et al. (1978) investigated the drought water volume of this water source area and explained that the large drought water volume of north Japan results from the stable water supply induced by spring snowmelt runoff and intermittent rainwater in fall. This water supply contributes to maintaining the groundwater in the drought season. In addition, the drought risk of the area influenced by spring snowmelt runoff will increase owing to the decreasing precipitation amounts in winter and spring as caused by climate change. This suggests the importance of snowmelt runoff to water resource recharge (Wada et al., 2005).

A trend of decreasing drought runoff coefficient with increasing occurrence probability was found in Group C, which is composed of the southwest Japanese archipelago. In these watersheds, the precipitation amount largely depends on the concentrated rainfall of a typhoon or a rainy season (Arao & Kaneko, 1985). Therefore, the low supply of water into the ground during drought results in a low drought runoff coefficient in the case of a high occurrence probability. In addition to the precipitation pattern, the geology of the watersheds belonging to Group C also seemed to influence the low drought runoff coefficient. Group C was composed of watersheds with a high ratio of sedimentary rock (Figure 4). Further, the geological age of the sedimentary rock of these watersheds (the Mesozoic and Paleozoic age) is older than that in other areas (Sudo, 2006). The low drought runoff coefficient was thought to be caused by the high agglomeration degree of the rock, which is a result of the high geological age influencing the deep percolation of precipitation.

4.2 Controlling factors and the drought runoff coefficient

4.2.1 Occurrence probability of drought and controlling factors

Based on the GLM, which investigated the relationship between the drought runoff coefficient and controlling factors, geological factors and land use factors (vegetation) influenced the drought runoff coefficient in high-frequency drought, whereas land use factors and topographic factors were selected as influencing factors in low-frequency drought. This is considered to be due to the fact that the runoff components that control flow discharge differ depending on drought frequency. In the case of high-frequency drought, the factors closely related to surface runoff or subsurface flow were selected, and factors related to the water-table stream with a larger time scale seemed to be selected for low-frequency drought. Previous research investigating the relationship between flood discharge and controlling factors for multiple occurrence probabilities revealed that a coniferous forest increases discharge in low-frequency floods, whereas topographical factors increase discharge in high-frequency floods (Itsukushima et al., 2016). In addition, it is reported that the controlling factor for stream discharge changes from rainfall to geological factors with threshold of ordinary water discharge (Mushiake et al., 1981). From these research 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 research has revealed that geology is one of the controlling factors of flow regime (Peters et al., 2003, 2005; Salinas et al., 2013). The reasons for differences in drought runoff or base flow as a result of geology are that (i) the retention capacity of groundwater differs based on geology, and (ii) the infiltration capacity of soils differs based on geology (Lacey & Grayson, 1998; Bloomfield et al., 2009). From the GLM, PR and SR (among the geological factors) were selected as controlling factors that decrease the drought runoff coefficient in high-frequency drought (Table 2). This result is incompatible with the research result of Mushiake et al. (1981), who noted that granite (classified as a plutonic rock) is a factor in increasing drought discharge. This difference was caused by the location of the study area and the observation period of the data. Mushiake et al. (1981) used the average drought value based on a relatively short-term period. In addition, their research focused on a mountainous river, the drought discharge of which was dominated by surface runoff or subsurface flow. By contrast, Yokoo & Oki (2010) revealed that geological age has a relation with drought runoff; in particular, based on an investigation of watersheds with an area of more than 100 km2, quaternary geology was found to be an increasing factor for drought runoff. Therefore, it is necessary for one to consider both geology type and geological age as indicators when one predicts drought runoff.

In addition to plutonic rock, sedimentary rock was selected as a decreasing factor for the drought runoff coefficient for occurrence probabilities of 2 and 10 years. The infiltration capacity of sedimentary rock seems to be changed by the degree of agglomeration. However, flysch (classified as sedimentary rock) has been revealed as a factor for increasing drought or flood (Gaál et al., 2012). 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 (Condon & Maxwell, 2015). 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 agglomeration degree of the rock is closely related to runoff phenomena, as mentioned 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 of the rainfall–runoff relationship caused by vegetation changes have long been recognized (Andréassian, 2004). In addition, runoff volume differs between a coniferous forest and a broadleaf forest owing to dissimilarities in evapotranspiration (Calder 1990; Zhang et al., 2001; Hirano et al., 2009). My research results also indicate the different functions of the coniferous forest and the broadleaf forest. Based on the GLM, the broadleaf forest is selected as an increasing factor for the drought runoff coefficient for high-frequency drought, whereas the coniferous forest is a decreasing factor for low-frequency drought (Table 2). This is thought to be due to the difference in evapotranspiration. 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 (Bosch & Hewlett, 1982). Further, the drought runoff volume increases due to the clearing of the coniferous forest (Andreassin, 2004; Brown et al., 2005; Maita & Suzuki, 2007, 2008). These research results support the results of the GLM. Moreover, I presume that the reason for the coniferous forest decreasing the drought coefficient in low-frequency drought is as follows: Since evapotranspiration and canopy interception occur constantly regardless of drought magnitude, the amount of precipitation for surface runoff decreases as the precipitation amount decreases, and the effects of coniferous forests become dominant. By contrast, the evapotranspiration amount and the runoff volume are altered by the management condition of the forest, the condition of the forest floor, and tree age (Scott & Lesch, 1997; Sakai et al., 2009; Rasoulzadeh & Homapoor Ghoorabjiri, 2014). This research examined the relationship between the runoff coefficient and vegetation type as land use factors for relatively large watersheds. Therefore, the difference between broadleaf and coniferous forests became clear. However, it should be noted that the runoff coefficient could change even within the same forest type if the targeted watershed is smaller.

Moreover, land use change significantly alters runoff mechanisms (Fohrer et al., 2001). Among land use changes, urbanization increases flood peak discharge (Brown et al., 2009) and decrease the minimum flow (Poff et al., 2006). 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 (Simmons & Reynolds, 1982; Leopold, 1968). The GLM results indicate that urban areas are a decreasing factor for the drought runoff coefficient in low-frequency drought. 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 drought. By contrast, the surface water from the upstream area is decreased in low-frequency drought; therefore, the influence of urbanization, such as limitation of rainfall infiltration or supply of surface water from groundwater, is assumed to be dominant.

4.2.4 Topographic factors and the drought runoff coefficient

For the relationship between topographic factors and drought runoff, river length, watershed gradient, average watershed width, and altitude were studied as topographic factors influencing base flow (Yokoo & Oki, 2010; Moliere et al., 2009; Engeland & Hisdal, 2009; Castellarin et al., 2004; Abebe & Foerch, 2006). The GLM indicated that channel slope is an

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increasing factor for the drought runoff coefficient at occurrence probabilities of 10 years or more (Table 2). This result supports the research of Moliere et al. (2009) who revealed that zero flow days increase in high-gradient rivers. However, the 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 drought is mainly governed by surface runoff. Therefore, the geological or land use factors closely related to surface runoff were dominant, rather than topographical factors. On the other hand, the ratio of groundwater seemed to increase with river discharge in low-frequency drought. Therefore, the topographic factor most closely related to the groundwater is thought to be selected. Moreover, this study focused on observation stations with various basin areas, including both mountainous regions and alluvial areas. Interaction between groundwater and surface water is considered to be more active in alluvial channels; therefore, the drought runoff coefficient is higher in the low-gradient watershed.

5 Conclusions

This manuscript reports a first attempt at revealing the relationship between drought runoff and controlling factors (geological, land use, and topographical factors) in relation to drought magnitude.

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 had intermediate behavior between the aforementioned two groups. In addition, this classification result indicated a significant relationship between the ratio of plutonic rock, sedimentary rock (geological factors), urban areas, and a mixed coniferous–broadleaved forest (land use factors).

The GLM revealed that the controlling factor differs depending on drought magnitude. 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 dominates 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 precipitation pattern or climatic zone, and the controlling factors of the drought runoff coefficient changed in accordance with occurrence probability. Therefore, for effective water resource management, estimation of the drought runoff volume needs to consider precipitation pattern, geology, land use, and topography. Since 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.

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Competing Interests

The author declares that he has no conflicts of interest.

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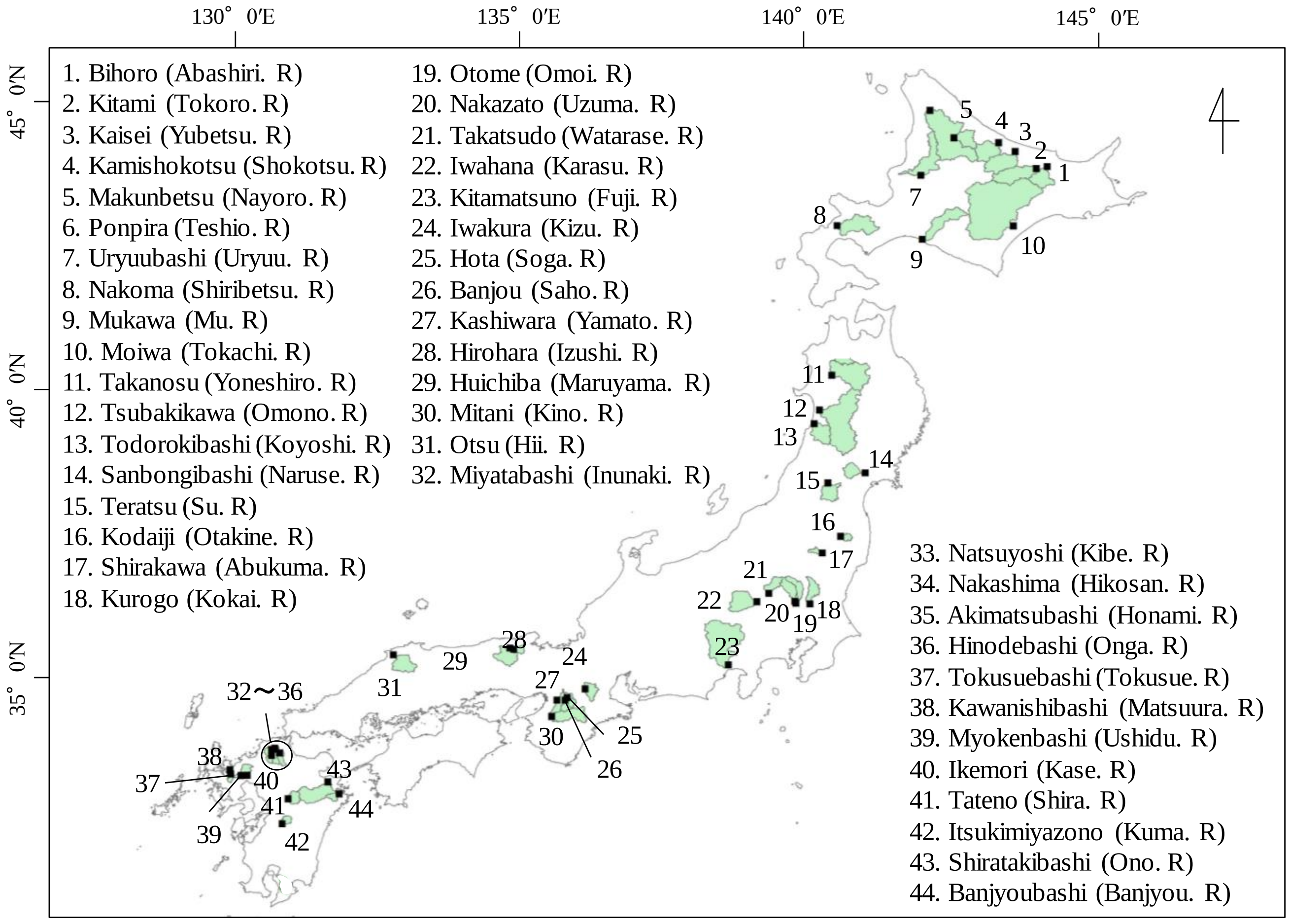

Figure 1: Location of the study site. The 44 observation stations in the Japanese archipelago were considered.

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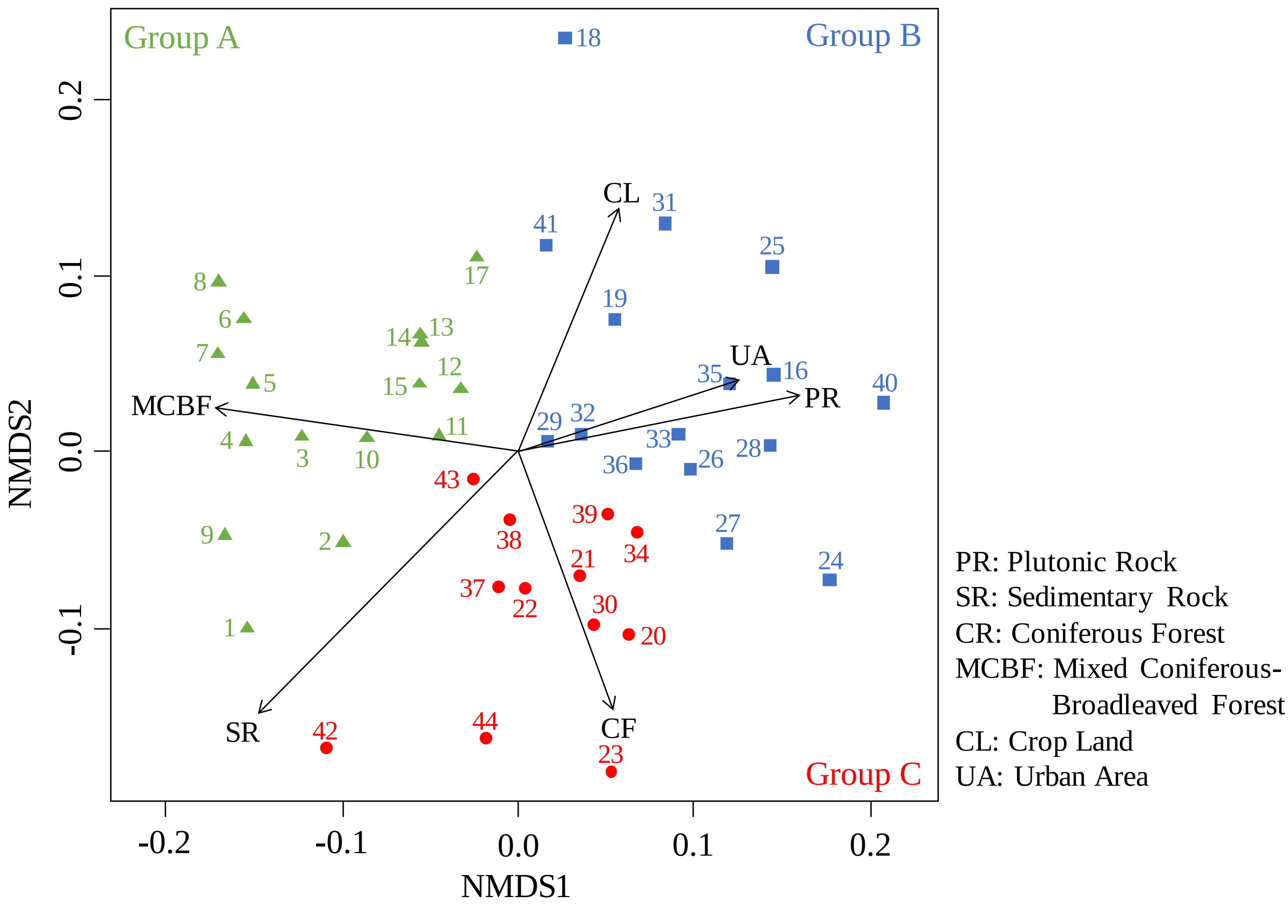

Figure 2: Results of NMDS using the drought runoff coefficient for each occurrence probability. NMDS: non-metric multi-dimensional scaling

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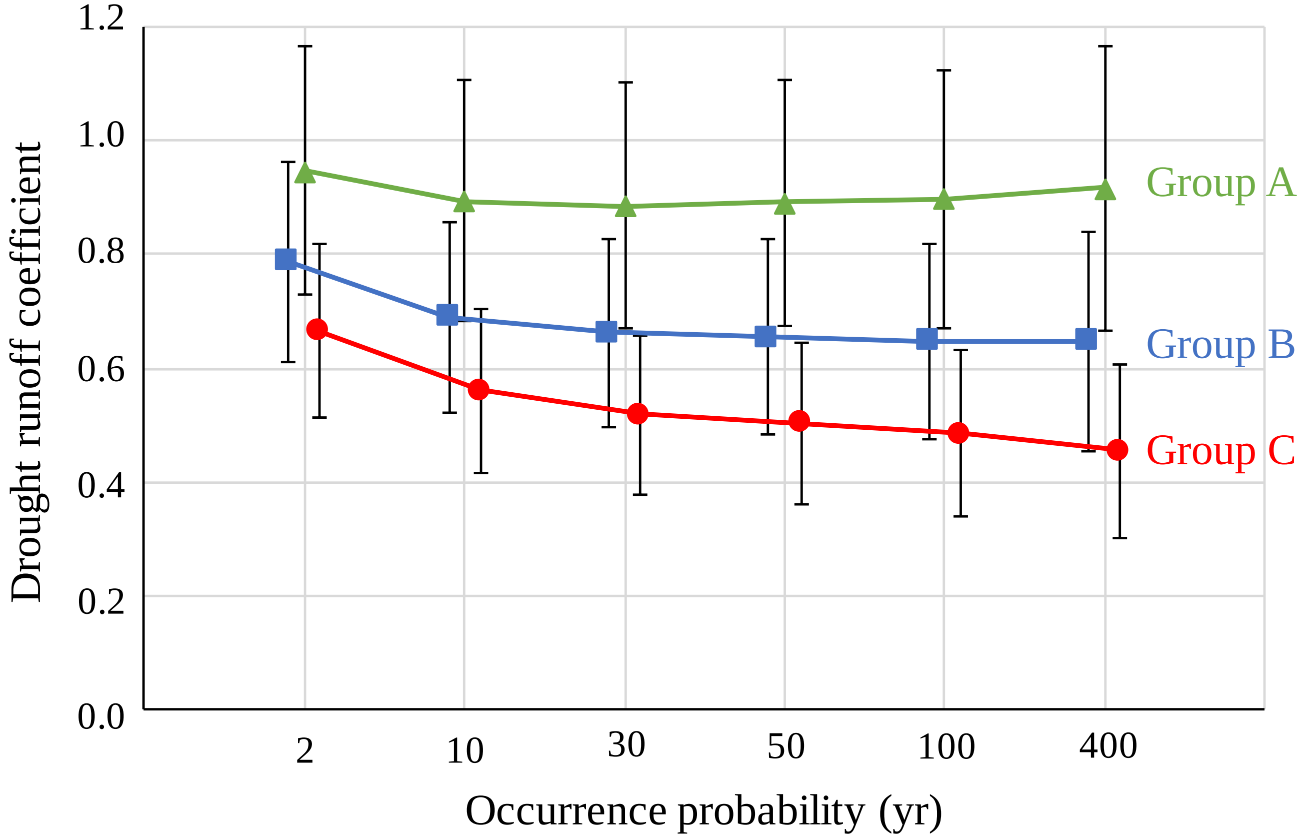

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Figure 3: Average value of the drought runoff coefficient for each occurrence probability across three groups

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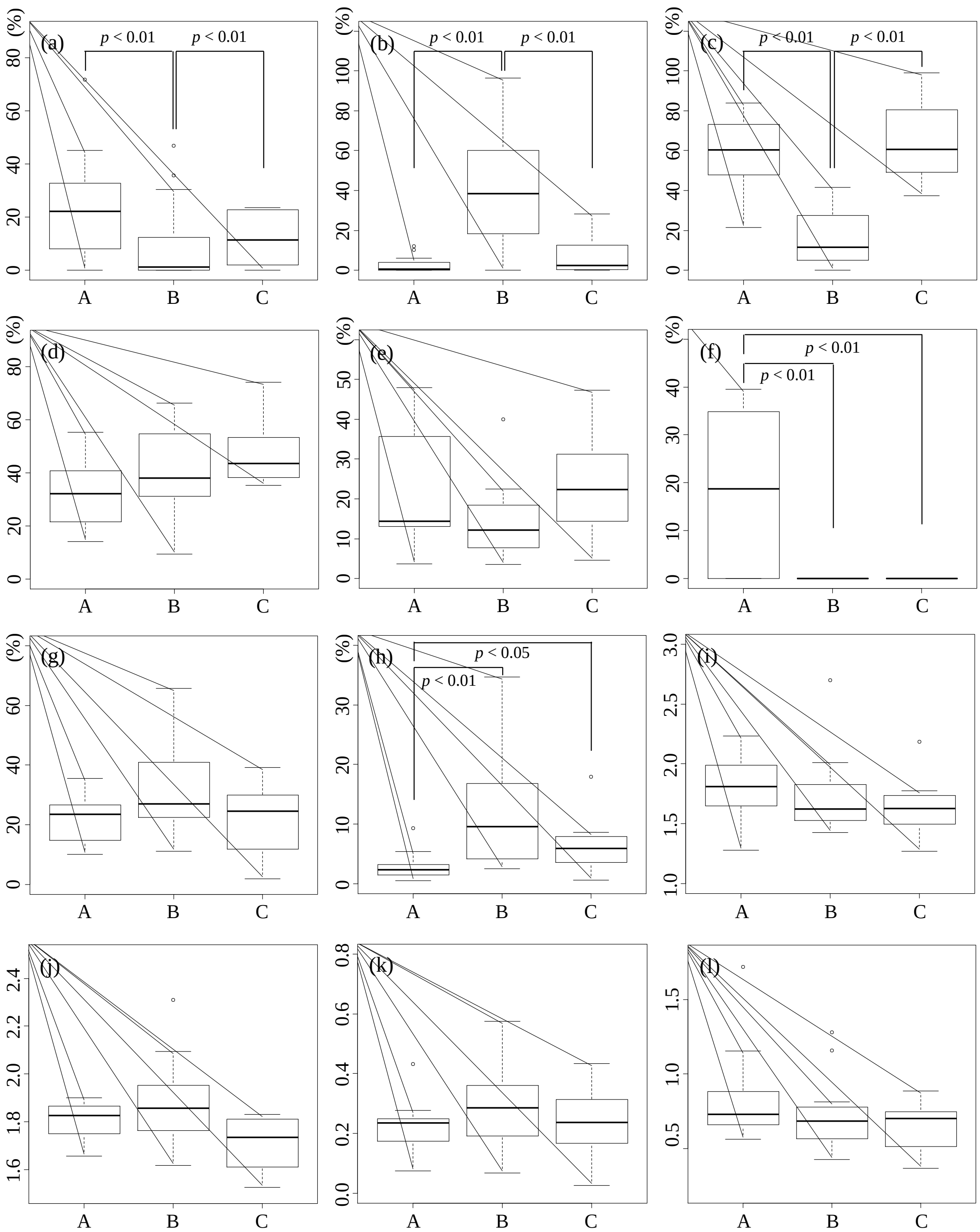

530 **Figure 4: Comparison of controlling factors between groups: (a) VR: volcanic rock, (b) PR: plutonic rock, (c) SR: sedimentary rock, (d) CF: coniferous forest, (e) BF: broadleaf forest, (f) MCBF: mixed coniferous–broadleaved forest, (g) CL: crop land, (h) UA: urban area, (i) CS: channel slope, (j) TGr: topographical gradient, (k) FR: form ratio, (l) Ro: roundness**

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Table 1: The calculation result of annual precipitation, drought runoff volume, and drought water volume per unit drainage area

No	Observation station	Basin area (km^2)	Precipitation amount for each occurrence probability (mm)						N	Model
			2	10	30	50	100	400		
1	Bihoro	824	925	731	659	633	602	554	31	Gev
2	Kitami	1,394	794	601	515	481	439	370	31	Gev
3	Kaisei	1,335	832	646	569	539	504	445	31	Gev
4	Kamishokotsu	1,051	929	701	595	552	500	411	31	Gev
5	Makunbetsu	695	961	781	702	672	634	570	31	Gumbel
6	Ponpira	4,029	1,161	964	864	822	769	673	31	Gev
7	Uryuubashi	1,661	1,439	1,199	1,085	1,038	980	880	31	Gev
8	Nakoma	1,402	1,245	1,035	936	897	847	762	31	LN3Q
9	Mukawa	1,228	1,192	907	767	711	641	520	31	Gev
10	Moiwa	8,208	1,041	813	709	668	617	532	31	LN3Q
11	Takanosu	2,109	1,595	1,285	1,164	1,120	1,067	982	31	Gev
12	Tsubakikawa	4,305	1,957	1,642	1,522	1,477	1,422	1,332	31	LN2LM
13	Todorokibashi	937	2,155	1,815	1,684	1,634	1,575	1,477	31	LN2LM
14	Sanbongibashi	551	1,387	1,147	1,054	1,018	977	906	31	Iwai
15	Teratsu	661	1,195	972	890	861	826	772	31	Gev
16	Kodaiji	180	1,199	913	793	747	691	598	31	Gev
17	Shirakawa	172	1,957	1,447	1,200	1,101	978	772	31	Gev
18	Kurogo	580	977	774	685	651	608	536	31	LN3Q
19	Otome	760	1,381	1,117	988	935	870	756	31	Gev
20	Nakazato	205	1,629	1,285	1,103	1,026	929	755	31	Gev
21	Takatsudo	472	1,684	1,323	1,149	1,080	994	847	31	LN3Q
22	Iwahana	1,228	1,282	970	845	799	743	653	31	Gumbel
23	Kitamatsuno	3,540	1,488	1,107	973	923	865	772	31	Iwai
24	Iwakura	501	1,634	1,266	1,117	1,060	992	877	31	Iwai
25	Hota	163	1,337	907	717	646	564	434	31	LN3Q
26	Banjou	105	1,372	1,037	862	790	700	544	31	Gev
27	Kashiwara	962	1,397	1,035	866	800	720	589	31	LN3Q
28	Hirohara	195	1,869	1,616	1,520	1,484	1,443	1,381	31	Gev
29	Huichiba	837	1,721	1,412	1,287	1,239	1,181	1,082	31	LogP3
30	Mitani	1,049	1,818	1,435	1,307	1,261	1,208	1,122	31	LP3Rs
31	Otsu	911	1,866	1,536	1,401	1,348	1,282	1,172	31	LogP3
32	Miyatabashi	123	1,475	1,112	950	886	808	677	31	Gev
33	Natsuyoshi	47	1,890	1,404	1,178	1,087	977	791	31	Gev
34	Nakashima	326	2,262	1,664	1,379	1,264	1,125	891	31	Gev
35	Akimatsubashi	113	1,835	1,368	1,144	1,055	944	756	31	Gev
36	Hinodebashi	695	1,751	1,309	1,101	1,018	917	745	31	Gev
37	Tokusuebashi	71	2,252	1,531	1,256	1,159	1,049	883	31	Exp
38	Kawanishibashi	120	2,252	1,618	1,323	1,205	1,063	824	31	Gev
39	Myokenbashi	95	1,825	1,342	1,115	1,024	912	725	31	Gev
40	Ikemori	231	1,748	1,271	1,037	943	826	632	31	Gev
41	Tateno	386	2,688	1,992	1,727	1,629	1,511	1,316	31	LogP3
42	Itsukimiyazono	227	2,217	1,639	1,414	1,330	1,232	1,068	31	LN3Q
43	Shiratakibashi	1,381	1,942	1,441	1,247	1,174	1,087	943	31	LogP3
44	Banjyoubashi	278	2,165	1,548	1,321	1,238	1,142	989	31	Gumbel

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Table 1: (Continued)

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					
	2	10	30	50	100	400			2	10	30	50	100	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	5,882	4,762	4,348	4,167	4,000	3,704	46	Gev	1.46	1.18	1.08	1.03	0.99	0.92
7	2,326	1,852	1,667	1,587	1,515	1,370	40	LN3Q	1.40	1.11	1.00	0.96	0.91	0.82
8	2,082	1,724	1,613	1,563	1,515	1,449	52	Gev	1.49	1.23	1.15	1.11	1.08	1.03
9	1,250	833	667	625	556	438	42	LogP3	1.02	0.68	0.54	0.51	0.45	0.35
10	7,143	5,263	4,545	4,348	4,000	3,448	47	LogP3	0.87	0.64	0.55	0.53	0.49	0.42
11	3,226	2,632	2,381	2,283	2,174	2,000	55	Iwai	1.53	1.25	1.13	1.08	1.03	0.95
12	8,333	6,667	5,882	5,882	5,556	5,263	71	Gev	2.07	1.65	1.46	1.46	1.38	1.30
13	1,961	1,538	1,389	1,333	1,266	1,149	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	1,064	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	2,174	1,163	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	1,205	943	855	820	781	719	32	LP3Rs	1.44	1.13	1.02	0.98	0.93	0.86
30	1,282	862	704	649	581	474	28	Gev	1.22	0.82	0.67	0.62	0.55	0.45
31	1,389	1,064	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	1,818	1,282	1,124	1,064	1,000	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

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535 **Table 2: Analysis of the relationship between drought runoff coefficient of each occurrence probability and controlling factors by GLM**

	Occurrence probability					
	2	10	30	50	100	400
Geological factor						
VR						
PR	(−) **	(−) *				
SR	(−) **	(−) **				
Land use factor						
BF	(+) *	(+) **				
CF			(−) **	(−) ***	(−) **	(−) ***
MCBF	(+) **	(+) **				
CL				(−) *		
UA			(−) *	(−) *	(−) *	(−) *
Topographical factor						
CS		(+) **	(+) **	(+) **	(+) *	(+) *
FR						
RO						
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