

ENHANCING MULTI-DURATION EXTREME RAINFALL CHARACTERIZATION THROUGH BIVARIATE REGIONAL FREQUENCY ANALYSIS: INTEGRATING R-LARGEST AND ANNUAL MAXIMA

AMÉLIORER LA CARACTÉRISATION DES PRÉCIPITATIONS EXTRÊMES À DURÉES MULTIPLES GRÂCE À UNE ANALYSE BIDIMENSIONNELLE DE LA FRÉQUENCE RÉGIONALE BIVARIÉE: INTÉGRATION DES MAXIMA R-LES PLUS GRANDS ET ANNUELS

Adisa Hammed Akinsoji¹ and Kyung Sook Choi²

ABSTRACT

Intensifying extreme rainfall events under a changing climate necessitate improved frequency analysis methods for flood risk assessment and hydrological design. This study develops a comprehensive bivariate regional frequency analysis (BRFA) framework jointly modeling rainfall volume and mean intensity for 6-hour and 12-hour durations across South Korea. Independent storm events were extracted from 41 years (1984–2024) of hourly precipitation data at 61 Korea Meteorological Administration ASOS stations using the Inter-Event Time Definition (IETD) methodology, incorporating both annual maxima and r-largest peak-over-threshold events to enhance sample size and capture extreme event characteristics. K-means clustering applied to multivariate summary statistics delineated six homogeneous regions, validated through bivariate L-comoment heterogeneity measures and refined by simulated annealing optimization. Combined descriptive–predictive ranking selected the optimal marginal distributions among Gumbel, Generalized Normal, Generalized Extreme Value, Pearson Type III, Weibull, Exponential, and Generalized Pareto candidates, while copula selection evaluated eight families using maximum likelihood estimation and information criteria. Design quantiles were estimated via Monte Carlo simulation for return periods $T = 2$ –200 years and validated against empirical Cunnane plotting positions; 1,000 bootstrap iterations provided 90 % confidence intervals quantifying parametric uncertainty. Regional spatial patterns reveal distinct hydroclimatic characteristics: orographic enhancement on the Taebaek east coast, intensification effects in the Seoul metropolitan corridor, and maritime moderation along the southern coast. Comparison with current Korean Design Standard (KDS) values indicates substantial regional heterogeneity at the 100-year return period, with several regions exceeding the published KDS midpoint by 18–66 % and others falling within or slightly below the KDS band, depending on duration. The framework is directly applicable to the design of agricultural drainage and irrigation infrastructure, providing region-specific bivariate design rainfall pairs (volume and intensity) that univariate intensity–duration–frequency curves cannot provide.

Keywords: bivariate regional frequency analysis; copula; L-moments; r-largest; design rainfall; agricultural drainage; South Korea.

RESUME

L'intensification des événements de précipitations extrêmes dans le contexte du changement climatique exige une amélioration des méthodes d'analyse de fréquence pour l'évaluation des risques d'inondation et la conception hydrologique. Cette étude développe un cadre complet d'analyse de fréquence

1 Department of Agricultural Civil Engineering, Kyungpook National University, Daegu 41566, South Korea, adisaakinsoji@gmail.com

2 Institute of Agricultural Science & Technology, Kyungpook National University, Daegu 41566, South Korea, *Corresponding author: Kyung Sook Choi Email addresses: ks.choi@knu.ac.kr

régionale bivariée (BRFA) modélisant conjointement le volume et l'intensité moyenne des précipitations pour des durées de 6 heures et 12 heures à travers la Corée du Sud. Les événements de tempête indépendants ont été extraits à partir de 41 années (1984–2024) de données horaires de précipitations dans 61 stations ASOS de l'Administration météorologique de la Corée, en utilisant la méthodologie Inter-Event Time Definition (IETD), intégrant à la fois les maxima annuels et r-les événements de pointe au-dessus du seuil les plus importants afin d'améliorer la taille de l'échantillon et de capturer les caractéristiques des événements extrêmes. Le clustering K-moyens appliqué à des statistiques récapitulatives multivariées a délimité six régions homogènes, validé par des mesures d'hétérogénéité L-comoments bivariées et affiné par une optimisation de recuit simulée. Le classement combiné descriptif-prédictif a sélectionné les distributions marginales optimales parmi les candidats Gumbel, Normal généralisé, Valeur extrême généralisée, Pearson Type III, Weibull, Exponentielle et Pareto généralisé. Alors que la sélection de copules a évalué huit familles en utilisant l'estimation du maximum de vraisemblance et des critères d'information. Les quantiles de conception ont été estimés via la simulation Monte Carlo pour des périodes de retour $T = 2\text{--}200$ ans et validés par rapport aux positions empiriques de tracé de Cunnane ; 1 000 itérations bootstrap ont fourni des intervalles de confiance à 90% quantifiant l'incertitude paramétrique. Les modèles spatiaux régionaux révèlent des caractéristiques hydroclimatiques distinctes : amélioration orographique sur la côte orientale du Taebaek, effets d'intensification dans le corridor métropolitain de Séoul et modération maritime tout au long de la côte sud. La comparaison avec les valeurs actuelles de la norme coréenne de conception (KDS) indique une hétérogénéité régionale substantielle sur la période de retour à 100 ans, plusieurs régions dépassant le point médian publié par KDS de 18-66% et d'autres se situant dans ou légèrement en dessous de la bande KDS, selon la durée. Le cadre est directement applicable à la conception d'infrastructures de drainage et d'irrigation agricoles, fournissant des paires de précipitations théoriques bivariées spécifiques à une région (volume et intensité) que les courbes de fréquence-durée-d'intensité univariées (KDS) ne peuvent pas fournir.

Mots clés : Analyse de fréquence régionale bivariée; Copule; L- moments; r-plus grand; précipitation théorique; Drainage agricole; Corée du Sud.

INTRODUCTION

Extreme rainfall is the dominant trigger of flood damage to agricultural infrastructure in South Korea. Approximately 60–70 % of annual precipitation falls during the June–August Changma monsoon, generating intense convective episodes that overwhelm rural drainage networks, paddy field protection works, and small reservoirs (Adelodun et al., 2023). The August 2020 monsoon caused damage exceeding USD 1.8 billion, and the July 2023 floods inundated tens of thousands of hectares of farmland and resulted in the loss of more than half a million livestock. Reliable estimation of design rainfall at sub-daily durations — particularly 6 and 12 hours, the peak-flow design windows for agricultural drainage — underpins the sizing of rural drainage channels, pump stations, and detention reservoirs, and is therefore central to ICID member countries' adaptation agendas.

The prevailing univariate intensity–duration–frequency (IDF) approach treats rainfall volume and intensity as independent variables. This decomposition misrepresents the joint probability structure of extreme storms, in which high volume and high mean intensity tend to co-occur (De Michele and Salvadori, 2003; Tootoonchi et al., 2022). For a fixed return period, the joint exceedance probability of simultaneously high volume and high intensity is systematically larger than the product of the marginal exceedance probabilities, leading to undersized infrastructure when independence is assumed (Hsiao et al., 2021). Copula-based bivariate frequency analysis resolves this through Sklar's theorem: each marginal is modelled optimally and joint dependence is encoded by a copula function (Nelsen, 2006).

Regional frequency analysis (RFA) increases effective sample size by pooling hydrologically homogeneous stations, multiplying the information available for long return-period quantiles (Hosking and Wallis, 1997). Combining RFA with copula modelling — bivariate regional frequency analysis (BRFA) — has been demonstrated for floods (Requena et al., 2013) and droughts (Pashaie et al., 2024) but applications to agricultural rainfall design remain limited. Korean precipitation studies have examined Gumbel and

Generalized Extreme Value univariate fits (Kim et al., 2019, 2020) and bivariate non-stationary modeling (An et al., 2025), yet a regional bivariate framework targeted at agricultural drainage durations of 6 and 12 hours has not been reported.

This paper presents a BRFA tailored to agricultural drainage design at 6 and 12 hour durations across South Korea, using r -largest peak-over-threshold sampling drawn from independent IETD events. Six homogeneous regions are delineated by K-means clustering and refined by simulated annealing optimization of the bivariate L-comoment H_1 statistic. Bivariate design quantiles are derived for return periods up to 200 years and contrasted with the published Korean Design Standard (KDS) bands.

The paper aims to (i) demonstrate the regional heterogeneity of design rainfall across Korea's monsoon-dominated farming basins, (ii) provide bivariate volume–intensity design pairs at the durations most relevant to drainage peak-flow design, and (iii) quantify the gap between BRFA-derived quantiles and current Korean standards, supporting evidence-based revision of design rainfall tables for agricultural infrastructure.

1. STUDY AREA AND DATA

South Korea spans 33°–38° N and 124°–132° E, with a total land area of approximately 100,000 km² and elevations ranging from coastal lowlands to the Taebaek Mountain Range (maximum elevation 1,708 m). Mean annual precipitation increases from approximately 1,000 mm in interior valleys to over 1,800 mm along the southern and eastern coasts. Agriculture occupies approximately 17 % of the national land area, concentrated in alluvial plains where paddy rice and irrigated upland crops depend on managed drainage and flood protection infrastructure operated principally by the Korea Rural Community Corporation (KRC). Hourly precipitation data were obtained from the KMA Automated Surface Observing System (ASOS) network for January 1984 to December 2024 (41 years), providing approximately 21.9 million station-hours across 61 stations after quality screening. Stations with gaps exceeding 30 consecutive days or short records were excluded; all 61 retained stations satisfy the bivariate discordancy criterion $D_i < 2.6049$ (Chebana and Ouada, 2007).

The bivariate response variables are event rainfall volume V (mm) and mean event intensity I (mm h⁻¹). Independent rainfall events were extracted using the Inter-Event Time Definition (IETD) criterion (Restrepo-Posada and Eagleson, 1982): the rolling cumulative rainfall series at each duration was scanned hour by hour, with consecutive events required to be separated by a dry period at least equal to the duration window and to exceed a minimum volume threshold $v_0 = 1$ mm. The procedure yielded 58,892 events at 6 h and 45,073 events at 12 h pooled across all stations. The five largest monsoon-season events per station per year were retained, yielding pooled regional samples of 358–1,290 observations per region—an order of magnitude larger than annual maxima sampling and sufficient for stable bivariate copula estimation (Smith, 1986; Wright et al., 2022).

2. METHODOLOGY

2.1 Feature engineering and clustering

Nine station-level attributes — mean annual maximum rainfall, mean monsoon and autumn rainfall, month of the annual maximum, monsoon-to-annual and autumn-to-annual ratios, longitude, latitude, and elevation — were standardized by z-score normalization. Principal component analysis retained seven components, accounting for at least 99% of the variance. K-means clustering was applied for $k \in \{2, 3, 4, 5, 6\}$; $k = 6$ maximized the silhouette coefficient and was retained.

2.2 Bivariate L-comoments and homogeneity

Bivariate L-comoment matrices of order 2, 3, and 4 were computed for each station's (V , I) record (Chebana and Ouada, 2007; Serfling and Xiao, 2007). The 12-element vectors of vectorized ratio matrices form the basis for the bivariate discordancy statistic D_i and the heterogeneity statistic H_1 (Hosking and Wallis, 1997). Regions are acceptably homogeneous when $H_1 < 1.0$.

2.3 Simulated annealing refinement

Initial K-means assignments produced regions with H_1 values exceeding 1.0 at both 6 h and 12 h, indicating residual heterogeneity. Simulated annealing (SA) was used to refine cluster boundaries by minimizing $\max(H_1)$ across the six regions, subject to a minimum cluster size of five stations. The cooling schedule was geometric with $T_0 = 20.0$ and $\alpha = 0.98$, and uphill moves were accepted with the Metropolis probability $\exp(-\Delta J / T)$. SA converged to fully homogeneous configurations at both durations.

2.4 Marginal distribution and copula selection

The marginal distributions of V and I were modeled by selecting the best fit from eight candidates (Exponential, Weibull, Generalized Normal, Generalized Extreme Value, Generalized Logistic, Generalized Pareto, Gumbel, and Pearson Type III). Empirical quantiles were obtained from the Cunnane plotting position $F_i = (i - 0.4)/(n + 0.2)$. The combined descriptive–predictive ranking of T. H. Nguyen et al. (2017) was applied: descriptive metrics include RMSE, RRMSE, MAE, AICc, and BIC; predictive performance was assessed through 1,000 bootstrap half-sample iterations evaluating coverage and bias. The distribution minimizing the rank sum was retained.

Following Sklar’s theorem, the joint distribution $F_{h,I}(v, i)$ was modeled as $C(F_h(v), F_I(i); \theta)$. Eight copula families (Gaussian, Student-t, Clayton, Gumbel, Frank, Joe, BB1, BB7) were evaluated using the same dual-criterion ranking. An intelligent pre-selection step restricted candidates based on Kendall’s τ : upper-tail-dependent families were prioritized when $\tau > 0.05$, and two-parameter families (BB1, BB7) were considered only when $\tau > 0.3$. Parameters were estimated by maximum pseudo-likelihood with margins clipped to $(10^{-6}, 1-10^{-6})$.

2.5 Regional bivariate quantile estimation

Regional bivariate quantiles were estimated by Monte Carlo simulation with 100,000 draws per region and duration. For each draw, the copula was sampled, and the volume marginal CDF was inverted to obtain V ; intensity was obtained directly from its marginal CDF without back-transformation, taking advantage of the fact that r -largest events extracted from independent storm episodes do not exhibit the deterministic V/D constraint that arises in fixed-window annual maxima sampling. Site-specific quantiles were derived through the index flood ratio $q_i(T) = q_r(T) \cdot \mu_i / \mu_r$. Bootstrap 90 % confidence intervals were obtained from 1,000 resampling iterations.

3. RESULTS

Results are presented for the four primary outputs of the BRFA pipeline: regional delineation (Figure 1), regional growth curves (Figure 2), bivariate joint design quantiles in the (V, I) plane (Figure 3), and comparison of 100-year regional volumes against current Korean Design Standard bands (Figure 4).

3.1 Regional delineation at 6 h and 12 h

At 6 h, simulated annealing refinement of the K-means partition produced six homogeneous regions with final H_1 ranging from 0.45 (R3) to 0.91 (R5), all below the 1.0 acceptability threshold (Figure 1a). Region 0 captures four stations along the central east coast where Taebaek orographic forcing dominates; Region 1 pools 13 inland-southern stations; Region 3 contains the Capital corridor (Seoul–Incheon) plus several mid-eastern stations; Regions 4 and 5 jointly cover the western and inland southern lowlands.

At 12 h, the SA-optimised partition differs noticeably from the 6 h configuration (Figure 1b), with H_1 values from 0.57 (R1) to 0.98 (R5). The redistribution reflects the fact that synoptic-scale rainfall accumulating over 12 h is governed by larger-scale circulation features (Changma front orientation, frontal precipitation bands) than the convective-cell extremes characteristic of 6 h, leading the L-comoment-based optimisation to select different region boundaries. The Capital corridor stations (Seoul,

Incheon, Suwon) are grouped together with the western lowlands as Region 3 at 12 h, while the east coast (Daegwallyeong, Sokcho, Ulleungdo) forms Region 1, distinct from the southwestern coast (Region 0).

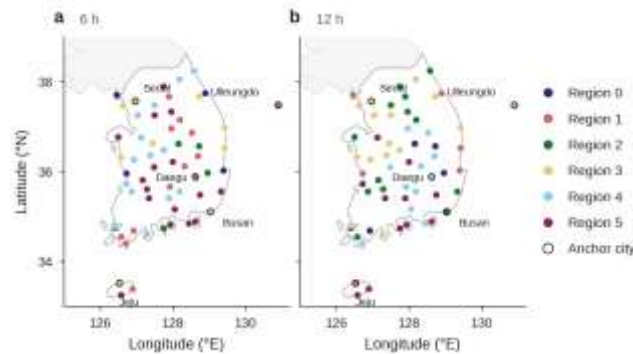


Figure 1. 61 KMA ASOS stations and SA-optimized regions at (a) 6 h and (b) 12 h durations. Final post-SA H_1 statistics: at 6 h, $R_0 = 0.77$, $R_1 = 0.88$, $R_2 = 0.72$, $R_3 = 0.45$, $R_4 = 0.78$, $R_5 = 0.91$; at 12 h, $R_0 = 0.79$, $R_1 = 0.58$, $R_2 = 0.64$, $R_3 = 0.60$, $R_4 = 0.88$, $R_5 = 0.98$ (all below the 1.0 acceptability threshold). The dashed brown line indicates the approximate Taebaek Mountain ridge.

3.2 Regional growth curves

Regional growth curves (Figure 2) show systematic increases of both V and I with return period across all regions and both durations. At 6 h, the predicted regional curves track the empirical Cunnane points closely up to $T = 100$ years, with regional Pearson correlation coefficients of 0.96–0.99 and relative RMSE values below 0.16 across the six regions. R_0 (east coast) exhibits the steepest growth in volume — the regional 100-year volume reaches 257.6 mm, more than 70 % above the regional $T = 2$ year value of 66.0 mm — reflecting the heavy-tailed behavior induced by orographic enhancement combined with episodic typhoon contributions.

At 12 h, R_1 (east coast) shows the most rapid quantile growth, with $V(T = 100) = 326.9$ mm versus $V(T = 2) = 83.7$ mm, a fourfold increase. The other five regions exhibit more moderate growth. Regional intensities at 12 h range from 6.5 to 10.8 mm h^{-1} at $T = 100$ years, with R_1 again the largest. The fit accuracy, indicated by the proximity of the observed and predicted curves at the 100-year point, supports the validity of the regional pooling and copula-based design quantile estimation procedure for both durations.

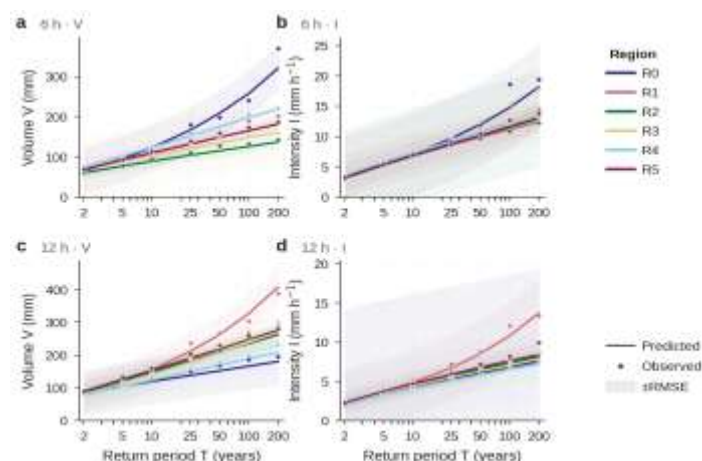


Figure 2. Regional growth curves of volume V (left column) and intensity I (right column) at (a, b) 6 h and (c, d) 12 h. Solid lines are predicted regional quantiles; markers are observed Cunnane plotting positions.

3.3 Bivariate joint design quantiles

The joint volume–intensity design pairs at $T = 10, 50, \text{ and } 100$ years (Figure 3) reveal clear regional separation in the bivariate design space. At 6 h, R0 (east coast orographic) sits in the upper-right region of the (V, I) plane with the 100-year design pair $(V, I) = (258 \text{ mm}, 14.8 \text{ mm h}^{-1})$, substantially separated from R2 ($148 \text{ mm}, 11.6 \text{ mm h}^{-1}$). At 12 h, R1 (east coast) again dominates with $(327 \text{ mm}, 10.8 \text{ mm h}^{-1})$, while R0 (southwestern coast) is the lowest ($166 \text{ mm}, 6.8 \text{ mm h}^{-1}$).

This bivariate representation provides design information that univariate IDF curves cannot supply. For agricultural drainage sizing, both the peak inflow rate (intensity-driven) and the total volume to be conveyed or stored (volume-driven) must be jointly specified for a given return period. The inter-region spread at fixed T (factor of 1.5–1.7 in volume and 1.3–1.6 in intensity) confirms that a single national IDF table cannot represent the regional heterogeneity of design rainfall, and that regionalized bivariate quantiles are necessary for context-appropriate drainage design.

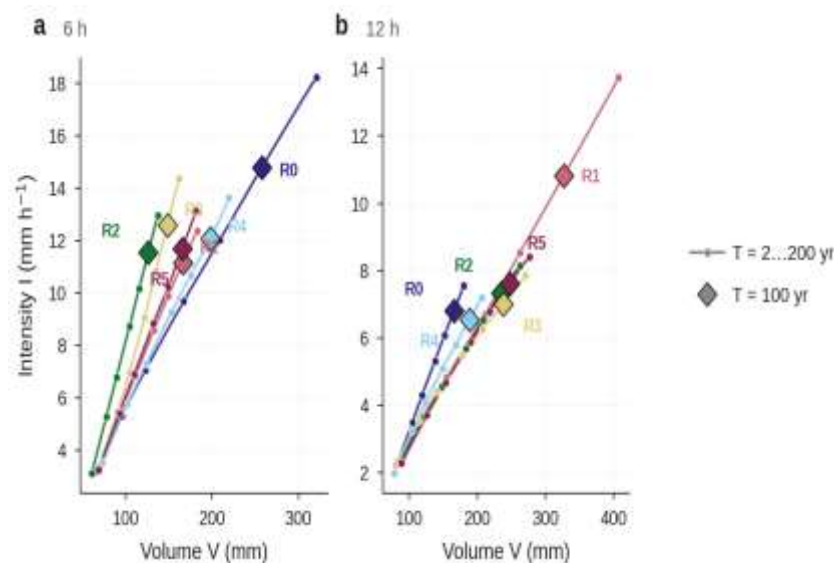


Figure 3. Bivariate (V, I) design pairs across return periods $T = 2$ to 200 years for all six regions at (a) 6 h and (b) 12 h. Each region traces a smooth path through the design plane across return periods $T = 2, 5, 10, 25, 50, 100, 200$ yr (small filled circles); the $T = 100$ yr design point is highlighted with a black-edged diamond. The East Coast regions R0 (at 6 h) and R1 (at 12 h) show the most extreme bivariate quantile growth.

3.4 Comparison with Korean Design Standards

Comparison of the 100-year regional volumes with the published KDS $T = 100$ -year design rainfall band (Figure 4) reveals substantial spatial heterogeneity. At 6 h, four of six regions equal or exceed the KDS midpoint of 155 mm by 7–66 %, while R2 falls 19 % below and R3 sits 4 % below the midpoint. At 12 h, four of six regions equal or exceed the KDS midpoint of 210 mm by 12–56 %, while R0 (southwestern coast) is 21 % below and R4 (inland south) is 10 % below.

Two regions stand out: R0 at 6 h (+66%, 258 mm vs 155 mm KDS midpoint) and R1 at 12 h (+56%, 327 mm vs 210 mm). Both correspond to the east coast orographic corridor, where Taebaek-driven enhancement of monsoon and typhoon-related precipitation produces the heaviest tails in the national network. These regions have likely been under-designed under uniform national standards and warrant priority revision of agricultural drainage infrastructure capacity. Conversely, regions falling below the KDS band suggest that applying the highest national values uniformly represents over-design in those areas, with potential for cost savings while maintaining adequate hydraulic safety.

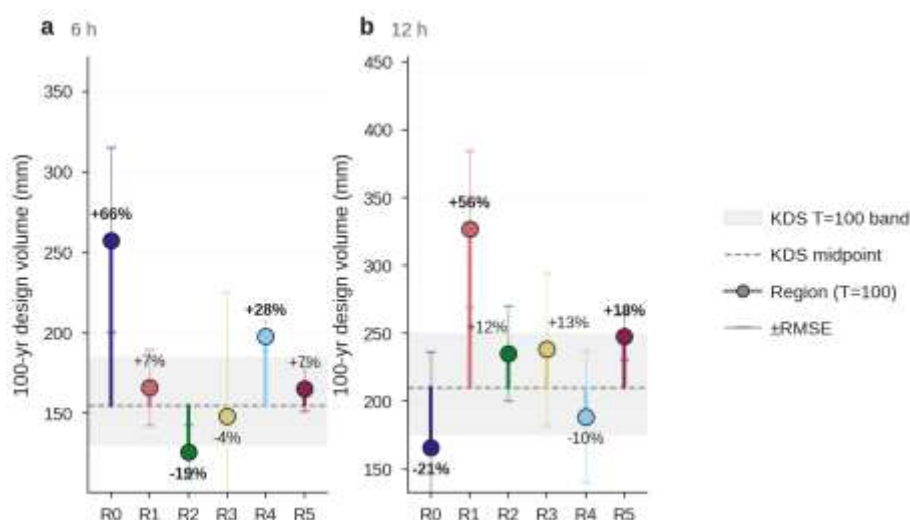


Figure 4. 100-year regional volume estimates relative to the published Korean Design Standard band at (a) 6 h and (b) 12 h. Grey shading shows the KDS T = 100 yr range; dashed line is the KDS midpoint. Annotations express each regional value as a percentage deviation from the KDS midpoint.

4. IMPLICATIONS FOR AGRICULTURAL DRAINAGE

South Korea's agricultural infrastructure includes approximately 17,500 reservoirs and 90,000 km of irrigation and drainage channels managed by the KRC. Current design practice references univariate IDF tables that specify either volume or intensity independently. The bivariate design pairs derived in this study enable a fundamental upgrade: for any chosen return period, engineers can simultaneously establish the peak inflow rate (from the intensity quantile) and the total volume to be stored or conveyed (from the volume quantile), ensuring that infrastructure satisfies both capacity and conveyance criteria under compound extreme conditions.

The duration-specific design pairs are operationally useful in two distinct contexts. The 6 h pair governs short-duration peak-flow design — in particular, the sizing of small drainage channels, paddy field outlets, and detention basin spillways where convective extremes generate the limiting design event. The 12 h pair governs cumulative volume design relevant to detention basin storage, paddy field water level management during prolonged rainfall, and pump station operating cycles. The bivariate joint exceedance probability is materially higher than the product of the marginal exceedance probabilities whenever the residual dependence after IETD-based event extraction is positive (Kendall's τ in the range 0.10–0.20 across regions for the durations analyzed), implying that current designs based on independence assumptions are exposed to compound flooding more frequently than the nominal design return period would suggest.

The regional heterogeneity revealed in Figure 4 has direct policy implications. The R0 (6 h) and R1 (12 h) east coast results indicate that current uniform design rainfall tables under-specify the design event in the orographic corridor, where typhoon and monsoon contributions superimpose. Conversely, R0 (12 h) and R4 (12 h) results suggest that some inland regions could safely apply slightly lower design values than the upper bound of the current KDS band. A regionally differentiated revision — retaining the present KDS band as a national reference while introducing regional adjustment factors derived from BRFA — is recommended.

Climate adjustment factors of 1.10–1.30 may be applied as interim margins to account for projected intensification of extreme rainfall under SSP2-4.5 and SSP5-8.5 scenarios (Schlef et al., 2023). Combined with the BRFA-derived regional baselines, these factors provide a practical pathway to climate-resilient agricultural drainage standards. Future work will integrate non-stationary GEV/GLO marginals and time-varying copula parameters to formalize the climate adjustment within the BRFA

framework, and will extend the analysis to trivariate vine copula constructions of volume, intensity, and event duration.

5. CONCLUSIONS

A bivariate regional frequency analysis (BRFA) framework was applied to 41 years of hourly precipitation from 61 KMA ASOS stations across South Korea at 6 h and 12 h durations relevant to agricultural drainage design. Six homogeneous regions were delineated by K-means clustering and refined by simulated annealing optimization of the bivariate L-comoment H_1 statistic, with all regions satisfying $H_1 < 1.0$ at both durations. The combined descriptive–predictive ranking selected the optimal marginal distributions and copulas; bootstrap validation supported the stability of the resulting quantile estimates. The 100-year regional volumes show substantial spatial heterogeneity relative to the published Korean Design Standard band: at 6 h, R0 (east coast) exceeds the KDS midpoint by 66 %; at 12 h, R1 (east coast) exceeds by 56 %; whereas R0 (12 h) and R2 (6 h) fall 21 % and 19 % below the midpoint, respectively. Bivariate (V, I) design pairs at multiple return periods provide the joint information required for drainage sizing that univariate IDF tables cannot supply. Regionally differentiated revision of design rainfall tables, supplemented by climate adjustment factors of 1.1–1.3, is recommended for Korean agricultural drainage infrastructure, with priority on the east coast orographic corridor.

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