SUPPLEMENTARY (FIGURES AND TABLES)

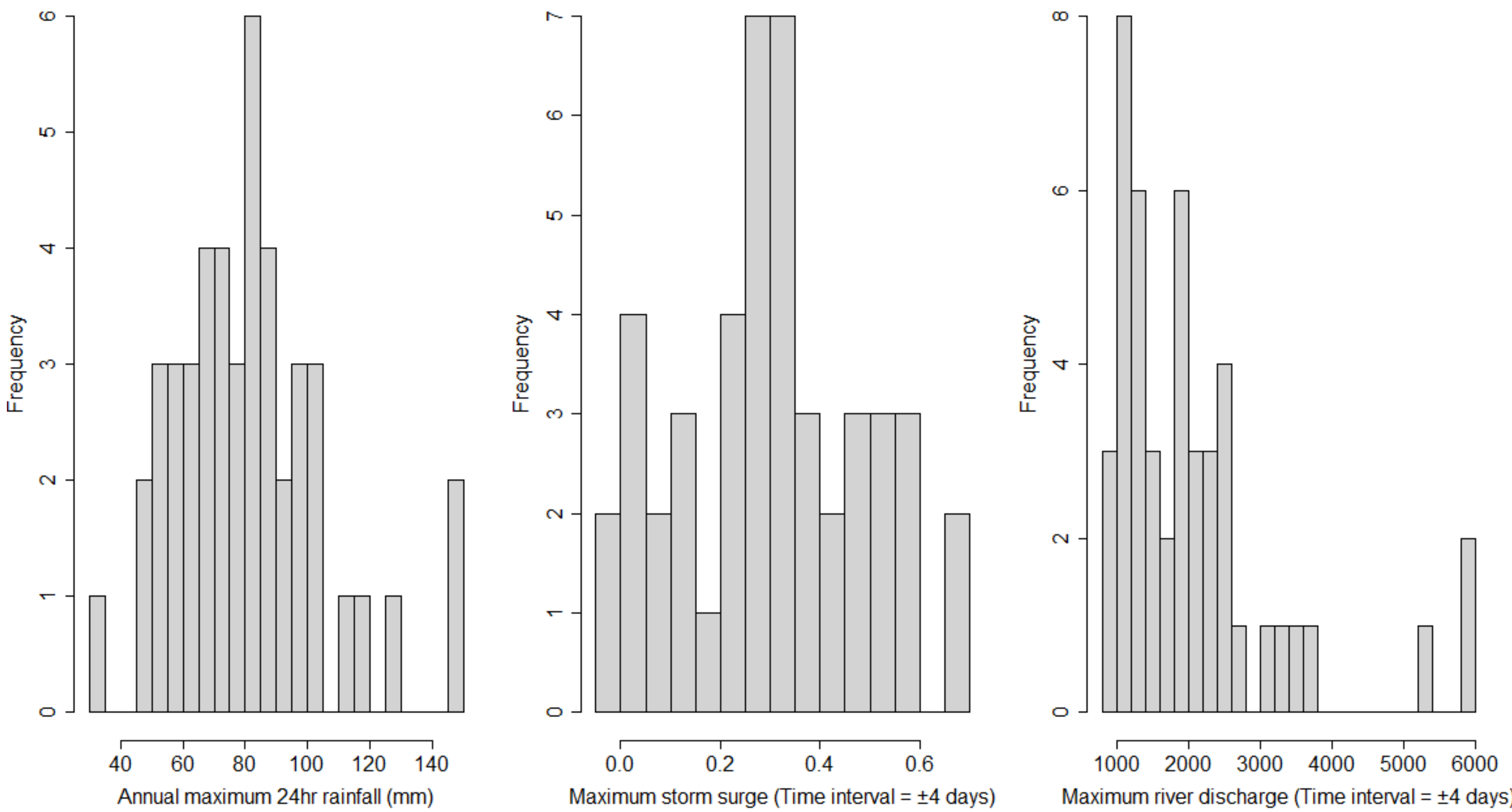
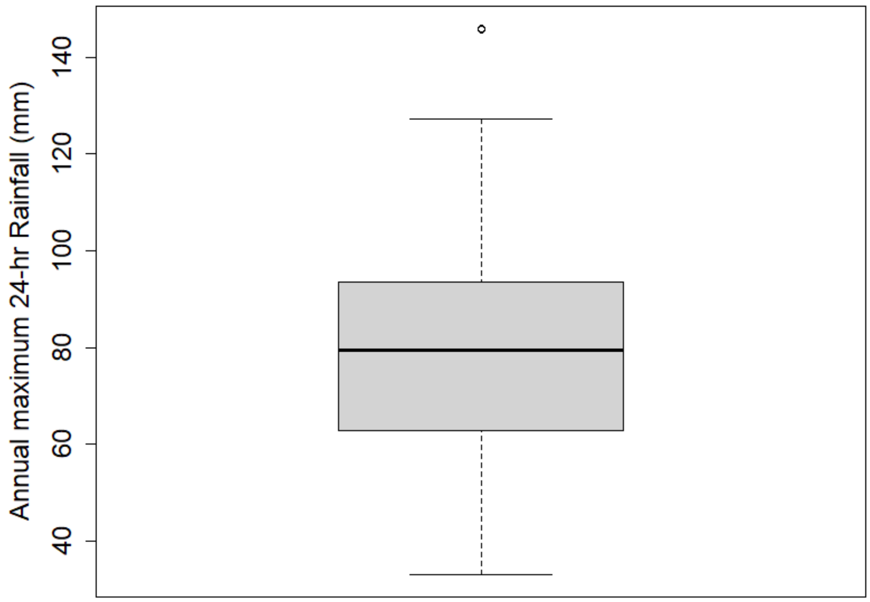
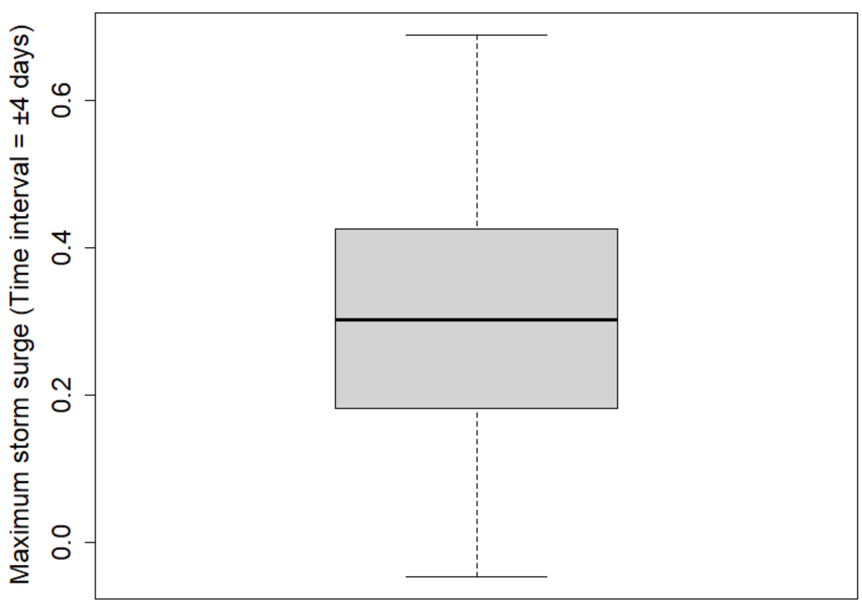


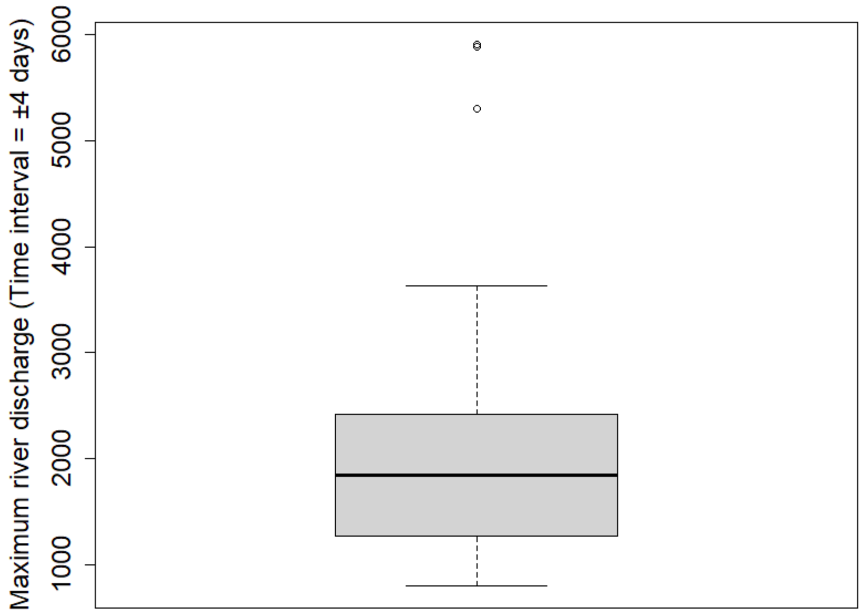

Figure S1: Histogram plot of selected compound flood (CF) drivers


Annual maximum 24-hr Rainfall (mm)
40
60
80
100
120
140

(a)

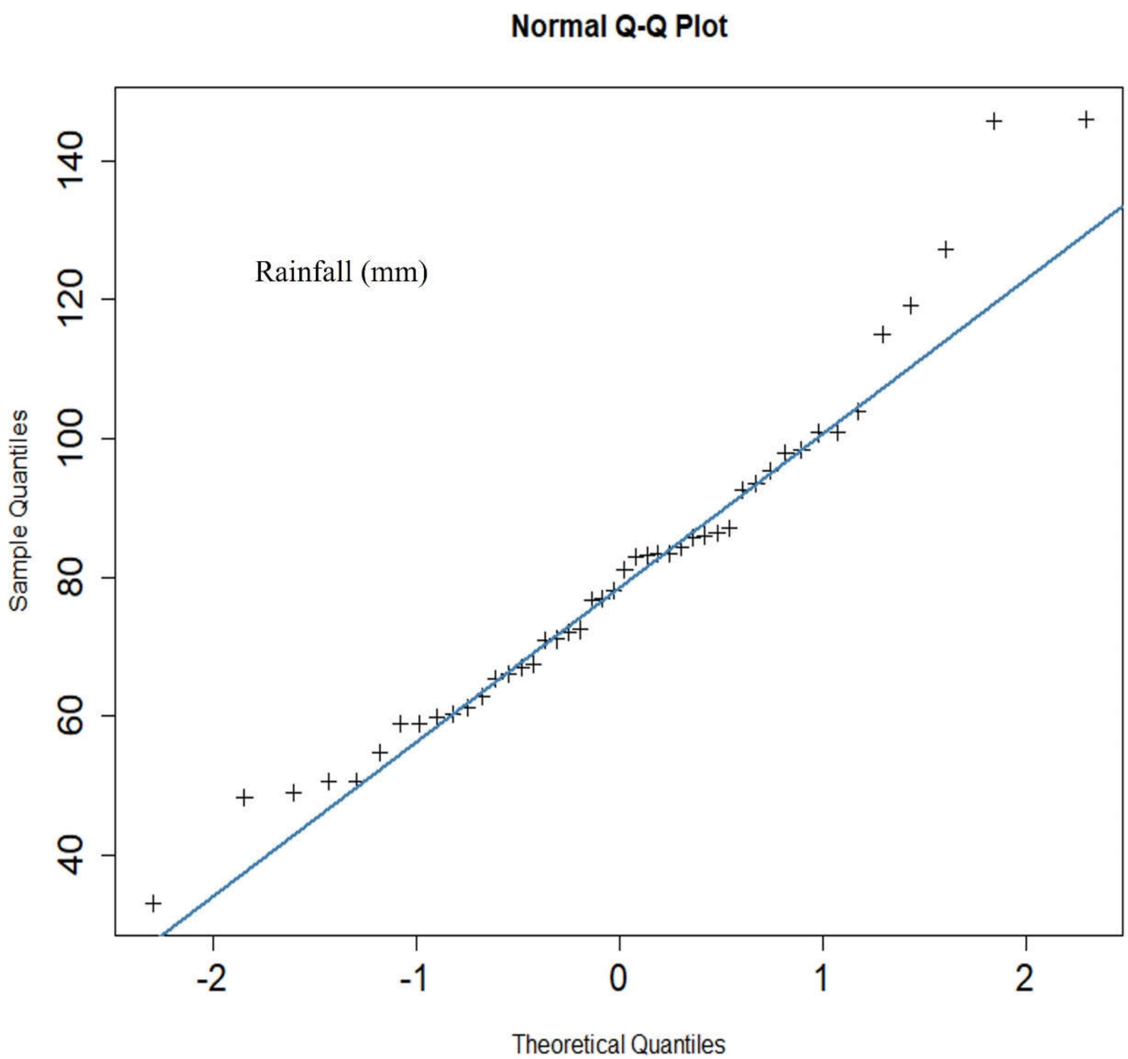

Maximum storm surge (Time interval = ±4 days)
0.0
0.2
0.4
0.6

(b)



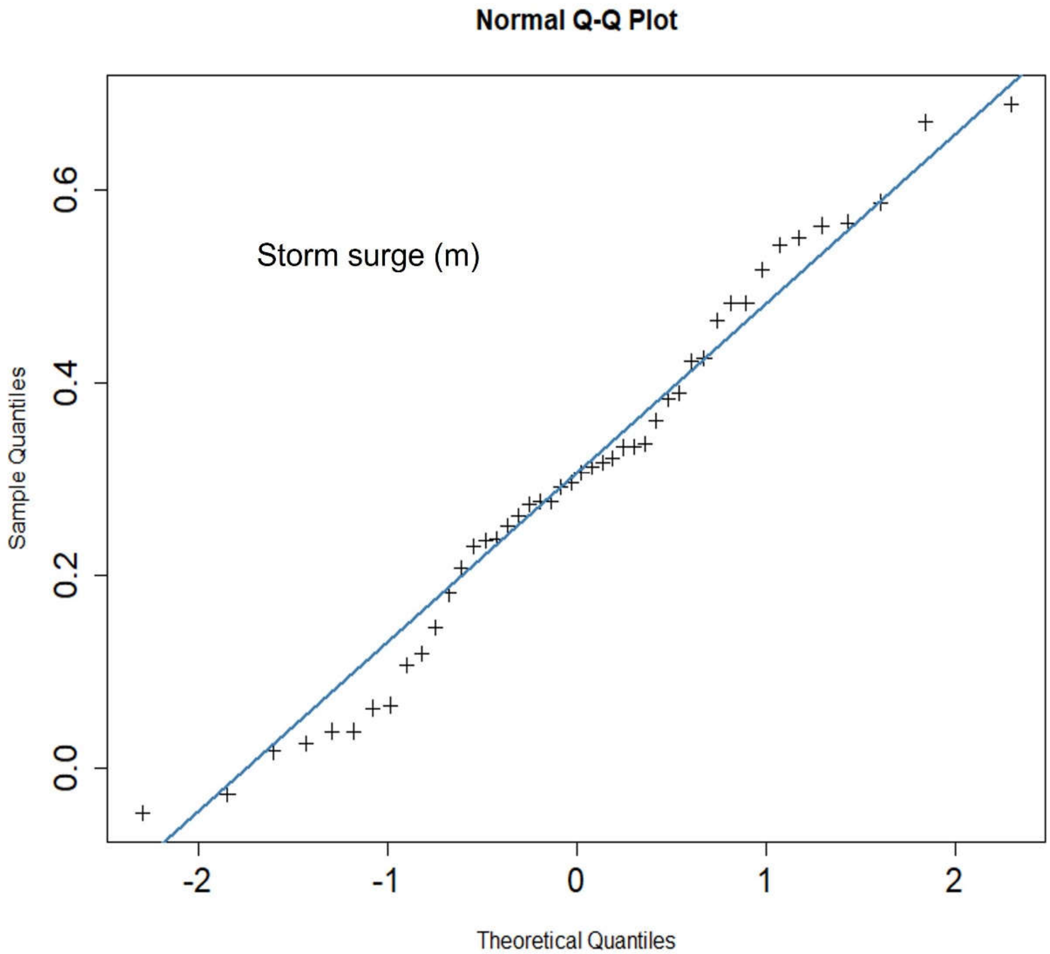

(c)

Figure S2: Box whisker plot of CF drivers (a) Annual maximum 24-hr Rainfall (mm) (b) Maximum Storm surge (Time interval = $\pm$ 4 days) (m) (c) Maximum River discharge (Time interval = $\pm$ 4 days) ($m^3sec^{-1}$)



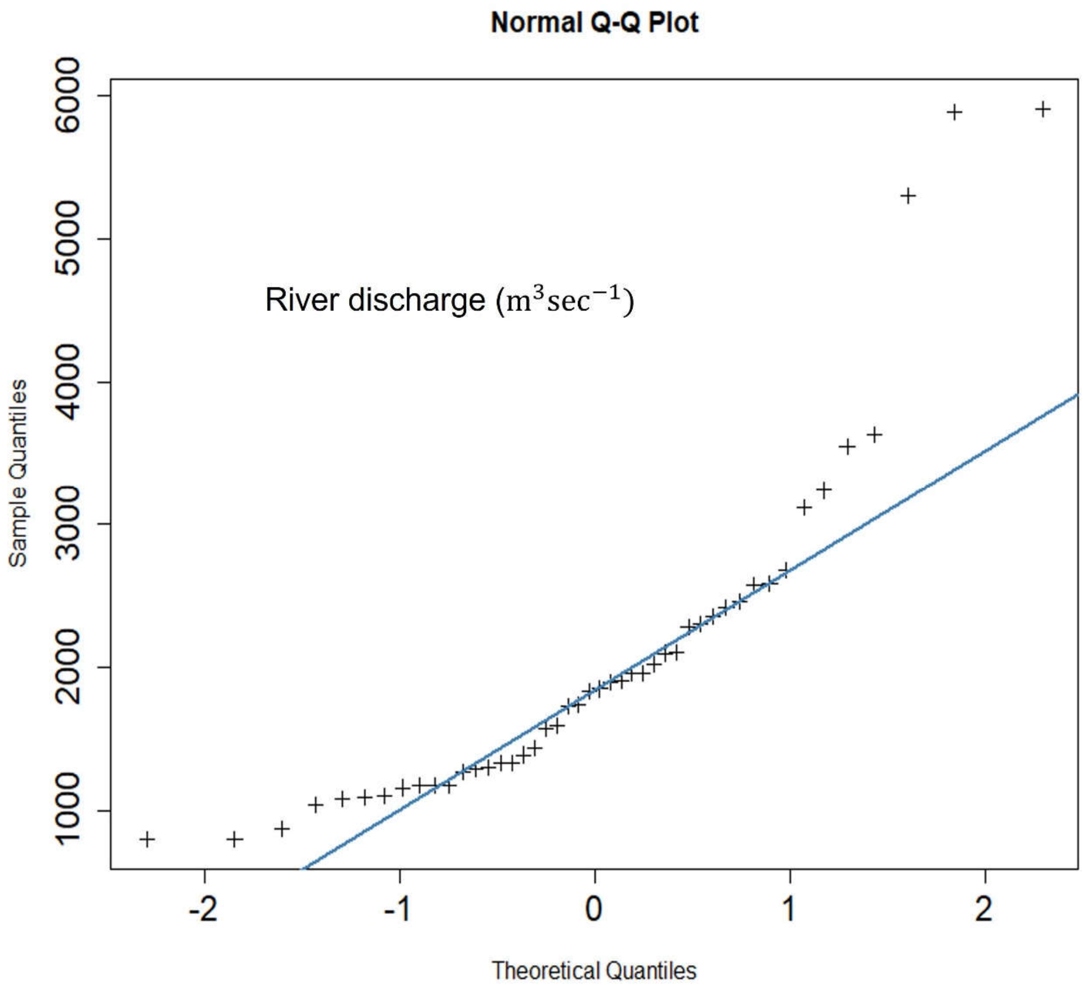
Normal Q-Q Plot
Rainfall (mm)
Sample Quantiles
Theoretical Quantiles
40
60
80
100
120
140
-2
-1
0
1
2

(a)



Normal Q-Q Plot
Storm surge (m)
Sample Quantiles
Theoretical Quantiles
0.0
0.2
0.4
0.6
-2
-1
0
1
2

(b)




(c)

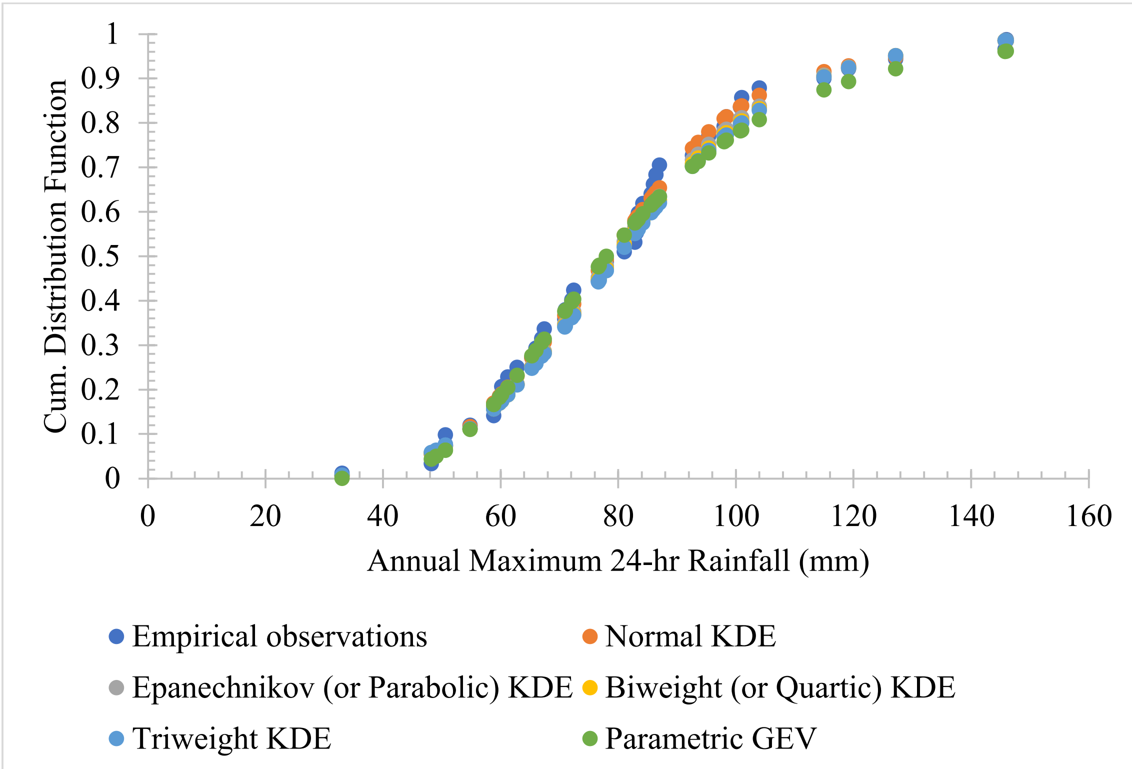
Figure S3: Normal Quantile-Quantile (Q-Q) plots for (a) Annual maximum 24-hr Rainfall (mm) (b) Maximum Storm surge (Time interval = ± 4 days) (m) (c) Maximum River discharge (Time interval = ± 4 days) $(m^3 sec^{-1})$

Table S1: Basic summary statistics of the selected compound flooding (CF) drivers

| Annual Maximum 24-hr Rainfall (mm) | Maximum Storm surge (Time interval = ±4days) (m) | Maximum River discharge (Time interval = ±4 days) ($m^3 sec^{-1}$) |
|---|---|---|
| Min. : 33.00 | Min. :-0.0470 | Min. : 800 |
| 1st Qu.: 63.42 | 1st Qu.: 0.1875 | 1st Qu.:1275 |
| Median : 79.50 | Median : 0.3015 | Median :1840 |
| Mean : 80.68 | Mean : 0.3025 | Mean :2074 |
| 3rd Qu.: 93.35 | 3rd Qu.: 0.4243 | 3rd Qu.:2405 |
| Max. :146.00 | Max. : 0.6890 | Max. :5910 |
| Var: 589.0201 | Var: 0.03544252 | Var: 1438211 |

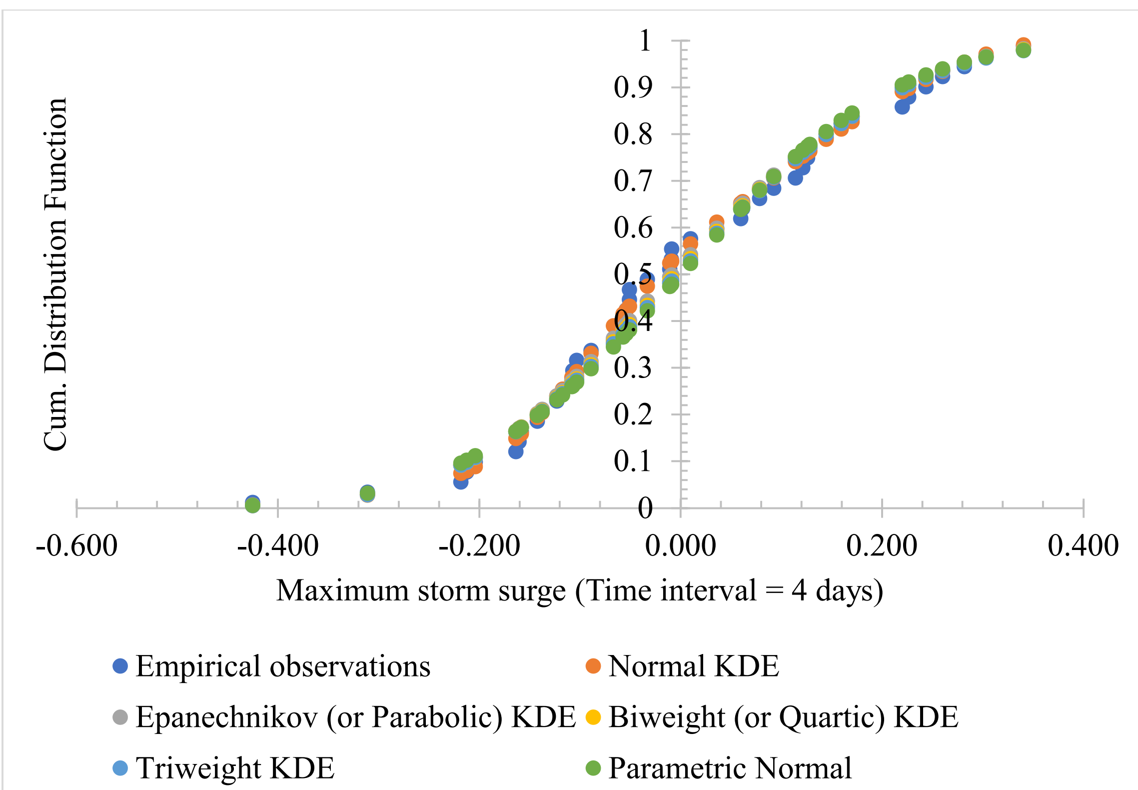
Table S2: Test for homogeneity within individual time series of CF drivers

| Flood variables | Pettitt (Estimated p-value) | SNHT test (Estimated p-value) | Buishand (Estimated p-value) | Overall conclusion |
|---|---|---|---|---|
| Annual Maximum 24-hr Rainfall (mm) | 1 > 0.05 (significance level) | 0.7764 > 0.05 (significance level) | 0.8316 > 0.05 (significance level) | Time series is homogenous |
| **Storm Surge (Time interval = ±4days) (m)*** | **0.02541 < 0.05 (significance level)** | **0.02755 < 0.05 (significance level)** | **0.09325 > 0.05 (significance level)** | **Time series is not homogenous** |
| River Discharge (Time interval = ±4 days) ($m^3 sec^{-1}$) | 0.5625 > 0.05 (significance level) | 0.8773 > 0.05 (significance level) | 0.5616 > 0.05 (significance level) | Time series is homogenous |
| Note: The p-value has been computed using 20000 Monte Carlo simulations.<br>*Storm surge events (bold letter with an asterisk) exhibited non-homogenous behaviour, their estimated p-value for the Pettit and SNHT tests is less than p = 0.05 | | | | |



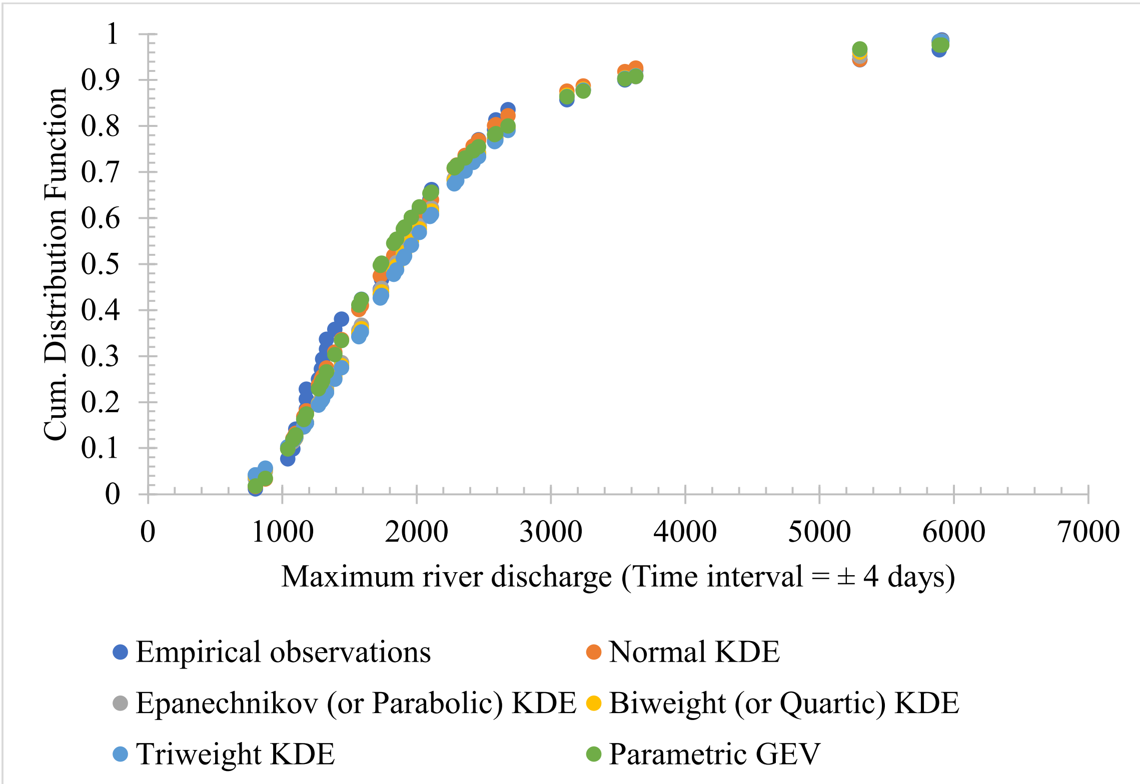
Cum. Distribution Function
Annual Maximum 24-hr Rainfall (mm)
Empirical observations
Normal KDE
Epanechnikov (or Parabolic) KDE
Biweight (or Quartic) KDE
Triweight KDE
Parametric GEV

(a)



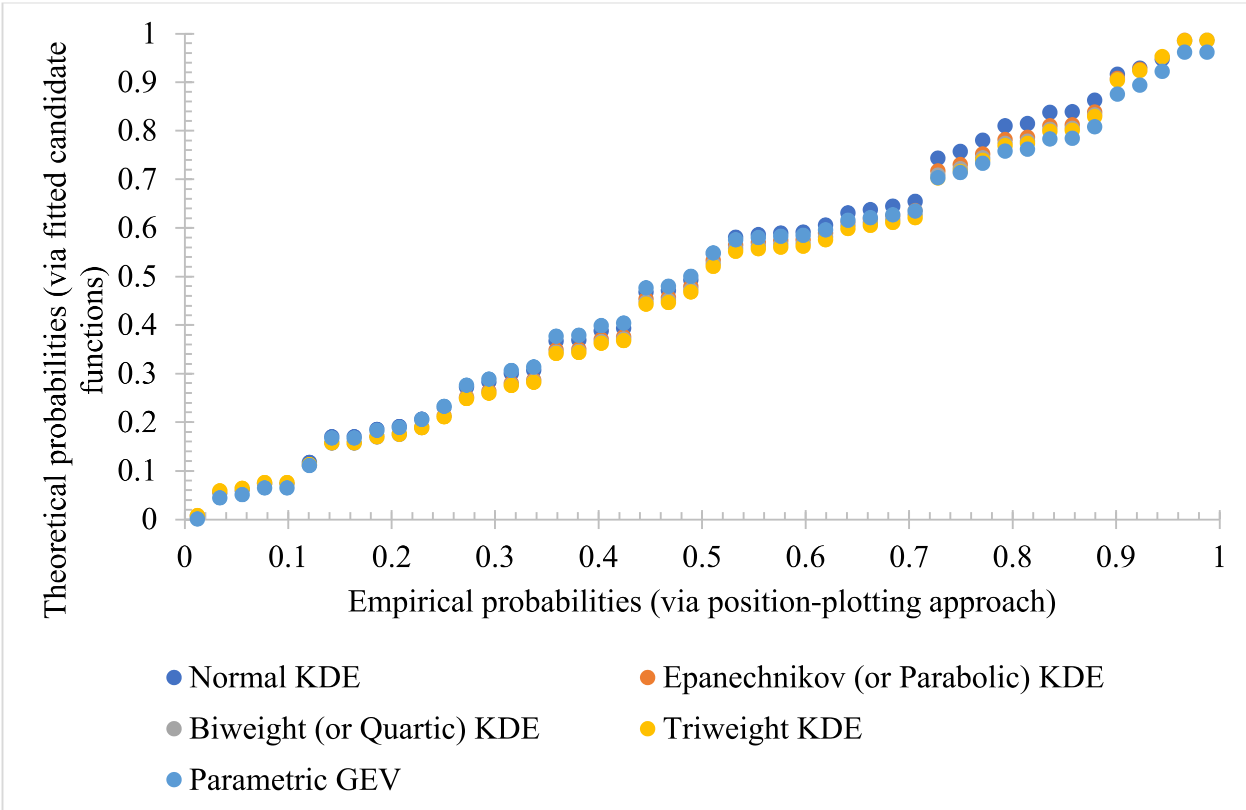
Cum. Distribution Function
Maximum storm surge (Time interval = 4 days)
Empirical observations
Normal KDE
Epanechnikov (or Parabolic) KDE
Biweight (or Quartic) KDE
Triweight KDE
Parametric Normal

(b)



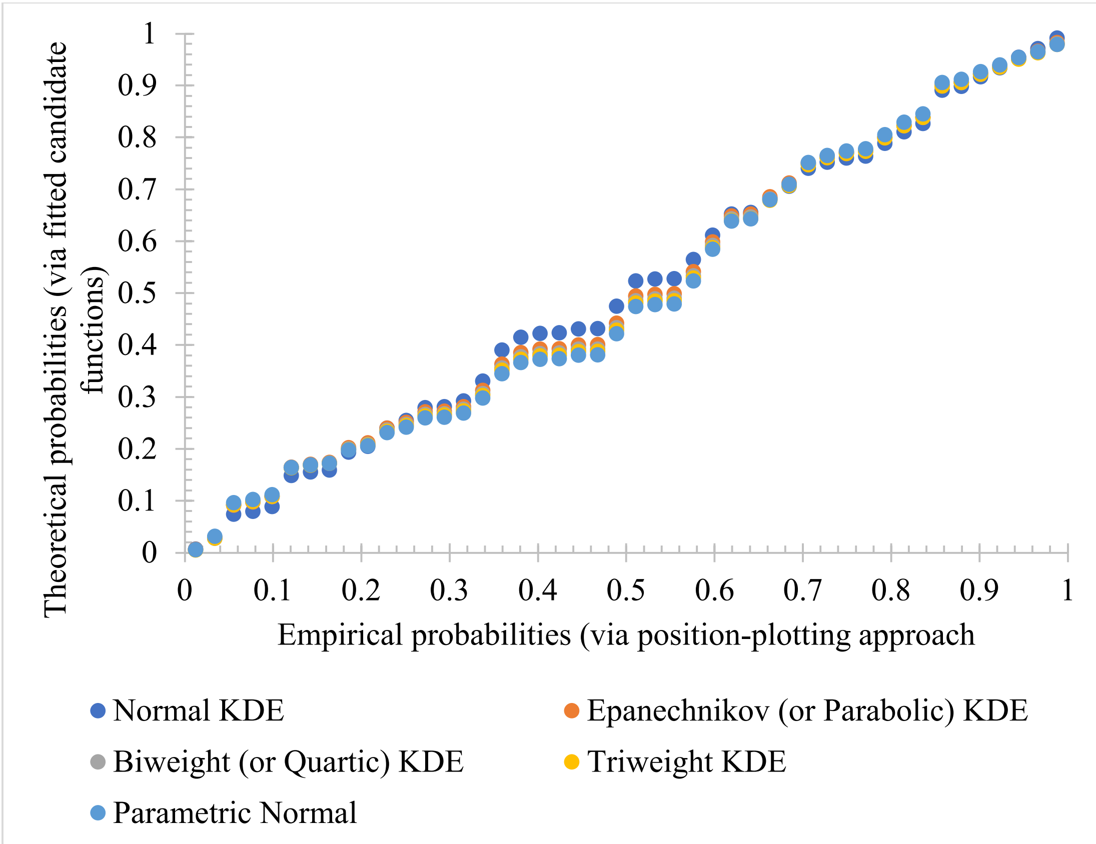

(c)

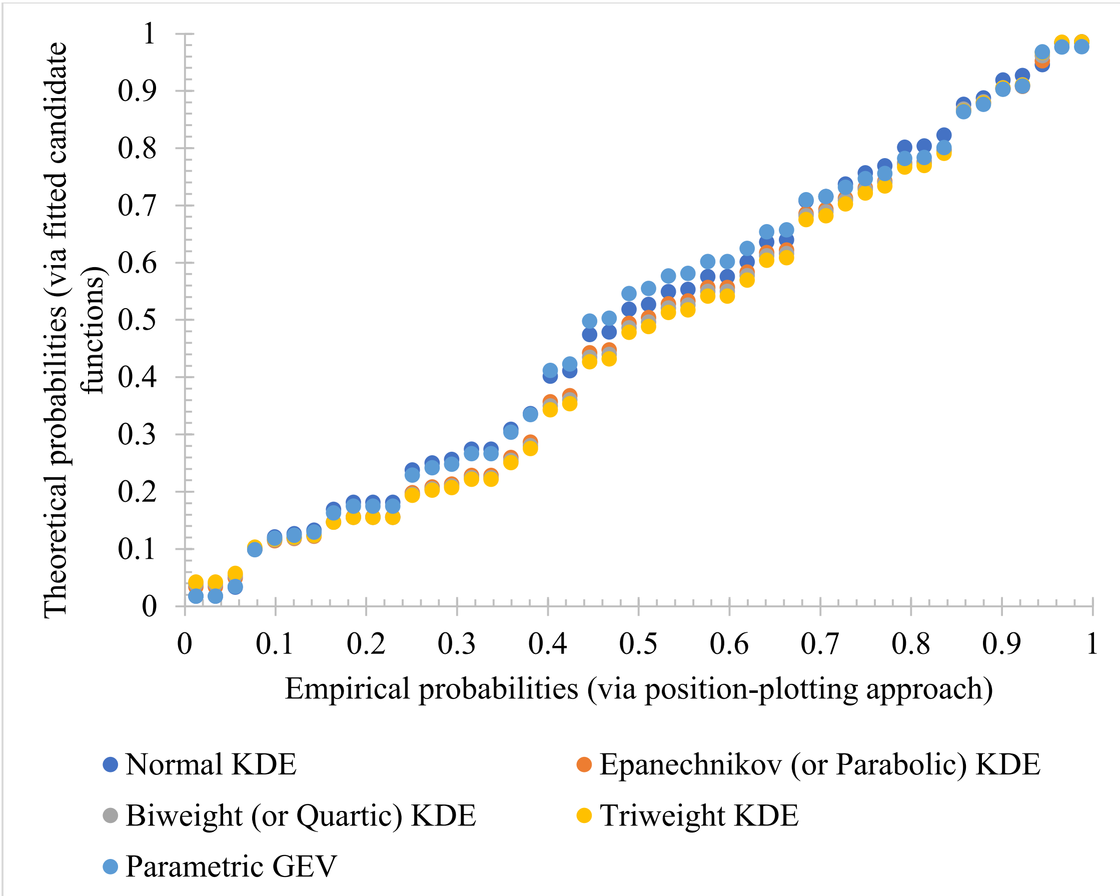
Figure S4: Qualitative based visual inspection of nonparametric model's performance fitted to (a) Annual maximum 24-hr Rainfall (mm) (b) Maximum Storm surge (Time interval = ± 4 days) (m) (c) Maximum River discharge (Time interval = ± 4 days) ($m^3 sec^{-1}$)



Theoretical probabilities (via fitted candidate functions)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Empirical probabilities (via position-plotting approach)
Normal KDE
Epanechnikov (or Parabolic) KDE
Biweight (or Quartic) KDE
Triweight KDE
Parametric GEV


(a)


Theoretical probabilities (via fitted candidate functions)
Empirical probabilities (via position-plotting approach
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Normal KDE
Epanechnikov (or Parabolic) KDE
Biweight (or Quartic) KDE
Triweight KDE
Parametric Normal
(b)




(c)

Figure S5: Comparing Probability-Probability (P-P) plots of the nonparametric models fitted to (a) Annual maximum 24-hr Rainfall (mm) (b) Maximum Storm surge (Time interval = ± 4 days) (m) (c) Maximum River discharge (Time interval = ± 4 days) ($m^3 sec^{-1}$)

Table S3: Fitting 2-D parametric copulas in the second tree level (Tree 2) of vine structure constructed in parametric settings for (a) D-vine structure-1 (case-1) (b) D-vine structure-2 (case-2) (c) D-vine structure-3 (case-3)

| (a) | | | | Cramer von Mises functional statistics with parametric bootstrap procedure (N = 1000 (No. of bootstrap samples)) | |
|---|---|---|---|---|---|
| Copula family | Parameter estimates ($\theta_{12\|3}$) via MPL estimators | Standard Error estimates | MLL (Maximized Log-likelihood) | $S_n$ | p-value |
| Clayton | 0.4563 | 0.226 | 2.994 | 0.045034 | 0.1004 |

| | | | | | |
|---|---|---|---|---|---|
| Gumbel | 1.326 | 0.137 | 3.885 | 0.0259 | 0.4241 |
| **Frank*** | **2.925** | **0.886** | **4.651** | **0.018882** | **0.9096** |
| Joe | 1.387 | 0.189 | 2.751 | | |
| BB1 (Clayton-Gumbel) | θ = theta = 0.1784; δ = delta = 1.2295 | NA | 4.165 | 0.039161 | 0.3651 |
| BB6 (Joe-Gumbel) | θ = theta = 1; δ = delta = 1.326 | NA | 3.885 | 0.041983 | 0.3312 |
| BB7 (Joe-Clayton) | θ = theta = 1.2509; δ = delta = 0.3332 | NA | 3.956 | 0.047131 | 0.2882 |
| BB8 (Joe-Frank) | θ = theta = 6; δ = delta = 0.41 | NA | 4.65 | 0.025064 | 0.6938 |
| Survival clayton | 0.4985 | NA | 2.951 | 0.062309 | 0.1503 |
| Survival Joe | 1.361 | NA | 2.082 | 0.080925 | 0.08242 |
| Survival Gumbel | 1.301 | NA | 3.165 | 0.049017 | 0.2423 |
| Survival BB1 | θ = theta = 0.2346; δ = delta = 1.1872 | NA | 3.523 | 0.041955 | 0.3242 |
| Survival BB6 | $\theta = theta = 1; \delta = delta = 1.301$ | NA | 3.165 | 0.049017 | 0.2512 |
| Survival BB7 | $\theta = theta = 1.1831; \delta = delta = 0.3829$ | NA | 3.226 | 0.050101 | 0.2313 |
| Survival BB8 | $\theta = theta = 6; \delta = delta = 0.42$ | NA | 4.732 | 0.023331 | 0.7258 |

Note: Frank copula (bold letter with asterisk) fitted best in the dependence modelling of conditional flood pair (minimum value of $S_n$ test statistics) in the second tree level (Tree 2) for D-vine structure-1 (case 1)

| (b) | | | | Cramer von Mises functional statistics with parametric bootstrap procedure (N = 1000 (No. of bootstrap samples)) | |
|---|---|---|---|---|---|
| Copula family | Parameter estimates ($\theta_{13\|2}$) via MPL estimators | Standard Error estimates | MLL (Maximized Log-likelihood) | $S_n$ | p-value |
| Rotated Joe 90 degrees | -1.033 | NA | 0.03724 | 0.019008 | 0.8646 |
| Rotated Gumbel 90 degrees | -1.023 | NA | 0.03734 | 0.019269 | 0.8586 |
| Frank | -0.3719 | 0.858 | 0.08094 | 0.021318 | 0.9206 |
| Gaussian (or Normal) | -0.04792 | 0.149 | 0.05882 | 0.02055 | 0.9306 |
| Rotated BB1 90 degrees | Theta = par = -3.438e-08 Delta = par2 = -1.023 | NA | 0.03732 | 0.019269 | 0.8576 |
| Rotated BB6 90 degrees | Theta = par = -1.02, par2 = delta = -1.01 | NA | -6.883e-15 | 0.019159 | 0.8606 |
| Rotated BB7 90 degrees | Theta = par = -1.033; delta = par2 = -6.135e-08 | NA | 0.03724 | 0.019008 | 0.8506 |
| Rotated BB8 90 degrees | Theta = par = -1.2042 Delta = par2 = -0.8715 | NA | 0.2371 | 0.022101 | 0.7797 |
| Rotated BB1 270 degrees | Theta = par = -0.08613 | NA | 0.2099 | 0.020603 | 0.8397 |

| | | | | | |
|---|---|---|---|---|---|
| | Delta = par2 = -1.00000 | | | | |
| **Rotated BB6 270 degrees*** | **Theta = par = -1 Delta = par2 = -1** | **NA** | **-2.442e-15** | **0.018538** | **0.8696** |
| Rotated BB7 270 degrees | Theta = par = -1.0000 Delta = par2 = -0.0861 | NA | 0.2099 | 0.020602 | 0.8117 |
| Rotated BB8 270 degrees | Theta = par =-6 Delta = par2 = -0.07 | NA | 5.218e-15 | 0.020593 | 0.8167 |
| Note: Rotated BB6 270 degrees copula (bold letter with an asterisk) fitted best in the joint modelling of conditional flood pair (minimum value of $S_n$ test statistics) in second tree level (Tree-2) of the D-vine structure-2 (case-2) | | | | | |

| (c) | | | | Cramer von Mises functional statistics with parametric bootstrap procedure (N = 1000 (No. of bootstrap samples)) | |
|---|---|---|---|---|---|
| Copula family | Parameter estimates ($\theta_{23\|1}$) via MPL estimators | Standard Error estimates | MLL (Maximized Log-likelihood) | $S_n$ | p-value |
| Clayton | 0.6626 | 0.263 | 4.831 | 0.054285 | 0.05844 |
| Gumbel | 1.301 | 0.119 | 3.387 | 0.027878 | 0.2892 |
| **Frank*** | **2.972** | **0.946** | **5.483** | **0.019514** | **0.8776** |
| Joe | 1.324 | 0.147 | 1.882 | 0.052833 | 0.04046 |
| BB1 (Clayton-Gumbel) | θ = theta = 0.5498; δ = delta = 1.0660 | NA | 4.901 | 0.053774 | 0.1863 |

| | | | | | |
|---|---|---|---|---|---|
| BB6 (Joe-Gumbel) | θ = theta = 1; δ = delta = 1.301 | NA | 3.387 | 0.060648 | 0.1643 |
| BB7 (Joe-Clayton) | θ = theta = 1.0000; δ = delta = 0.6626 | NA | 4.831 | 0.063413 | 0.1214 |
| BB8 (Joe-Frank) | θ = theta = 6; δ = delta = 0.41 | NA | 5.483 | 0.033341 | 0.492 |
| Survival clayton | 0.4335 | NA | 2.747 | 0.08952 | 0.05544 |
| Survival Joe | 1.531 | NA | 4.078 | 0.073942 | 0.09241 |
| Survival Gumbel | 1.374 | NA | 4.879 | 0.048689 | 0.2343 |
| Survival BB1 | θ = theta = 2.813e − 08 ; δ = delta = 1.374 | NA | 4.879 | 0.048689 | 0.2363 |
| Survival BB6 | $\theta = theta = 1; \delta = delta = 1.374$ | NA | 4.879 | 0.048689 | 0.2363 |
| Survival BB7 | $\theta = theta = 1.4184; \delta = delta = 0.2054$ | NA | 4.415 | 0.057852 | 0.1863 |
| Survival BB8 | $\theta = theta = 5.77; \delta = delta = 0.44$ | NA | 5.557 | 0.032239 | 0.499 |

Note: Frank copula (bold letter with an asterisk) fitted best in the joint modelling of conditional flood pair (minimum value of $S_n$ test statistics) in second tree level (Tree-2) of the D-vine structure-3 (case-3)

Table S4: Fitting 2-D parametric copulas in the second tree level (Tree 2) of vine structure constructed in semiparametric settings (parametric copula with nonparametric marginal pdfs) for (a) D-vine structure-1 (case-1) (b) D-vine structure-2 (case-2) (c) D-vine structure-3 (case-3)

| (a) | | | | Cramer von Mises functional statistics with parametric bootstrap procedure (N = 1000 (No. of bootstrap samples)) | |
|---|---|---|---|---|---|
| Copula family | Parameter estimates ($\theta_{12\|3}$) via MPL estimators | Standard Error estimates | MLL (Maximized Log-likelihood) | $S_n$ | p-value |
| Clayton | 0.4604 | 0.239 | 3.03 | 0.036116 | 0.1983 |
| Gumbel | 1.341 | 0.166 | 4.417 | 0.019725 | 0.7637 |
| **Frank*** | **2.898** | **0.889** | **4.743** | **0.015242** | **0.9865** |
| Joe | 1.425 | 0.239 | 3.375 | 0.039103 | 0.1404 |
| BB1 (Clayton-Gumbel) | $\theta$ = theta = 0.1479; $\delta$ = delta = 1.2585 | NA | 4.595 | 0.029008 | 0.5659 |
| BB6 (Joe-Gumbel) | $\theta$ = theta = 1; $\delta$ = delta = 1.341 | NA | 4.417 | 0.031311 | 0.538 |
| BB7 (Joe-Clayton) | $\theta$ = theta = 1.2868; $\delta$ = delta = 0.3207 | NA | 4.415 | 0.035376 | 0.4481 |
| BB8 (Joe-Frank) | $\theta$ = theta = 6; $\delta$ = delta = 0.41 | NA | 4.743 | 0.019621 | 0.8317 |

| | | | | | |
|---|---|---|---|---|---|
| Survival clayton | 0.5437 | NA | 3.515 | 0.047034 | 0.2443 |
| Survival Joe | 1.351 | NA | 2.049 | 0.070968 | 0.1164 |
| Survival Gumbel | 1.301 | NA | 3.255 | 0.039981 | 0.4011 |
| Survival BB1 | $\theta$ = theta = 0.3195; $\delta$ = delta = 1.1509 | NA | 3.904 | 0.032153 | 0.504 |
| Survival BB6 | $\theta = theta = 1$; $\delta = delta = 1.301$ | NA | 3.255 | 0.039981 | 0.3711 |
| Survival BB7 | $\theta = theta = 1.1397$; $\delta = delta = 0.4565$ | NA | 3.681 | 0.038429 | 0.3721 |
| Survival BB8 | $\theta = theta = 6$; $\delta = delta = 0.41$ | NA | 4.773 | 0.019717 | 0.8367 |
| Note: Frank copula (bold letter with an asterisk) exhibited minimum value Cramer-Von Mises functional $S_n$ statistics with p-value is greater than 0.05, thus recognized as the most parsimonious bivariate copula in defining bivariate joint dependence structure in Tree 2 for D-vine structure (case-1) | | | | | |

| (b) | | | | Cramer von Mises functional statistics with parametric bootstrap procedure (N = 1000 (No. of bootstrap samples)) | |
|---|---|---|---|---|---|
| Copula family | Parameter estimates ($\theta_{13\|2}$) via MPL estimators | Standard Error estimates | MLL (Maximized Log-likelihood) | $S_n$ | p-value |
| Rotated Joe 90 degrees | -1.03 | NA | 0.03642 | 0.018955 | 0.8736 |

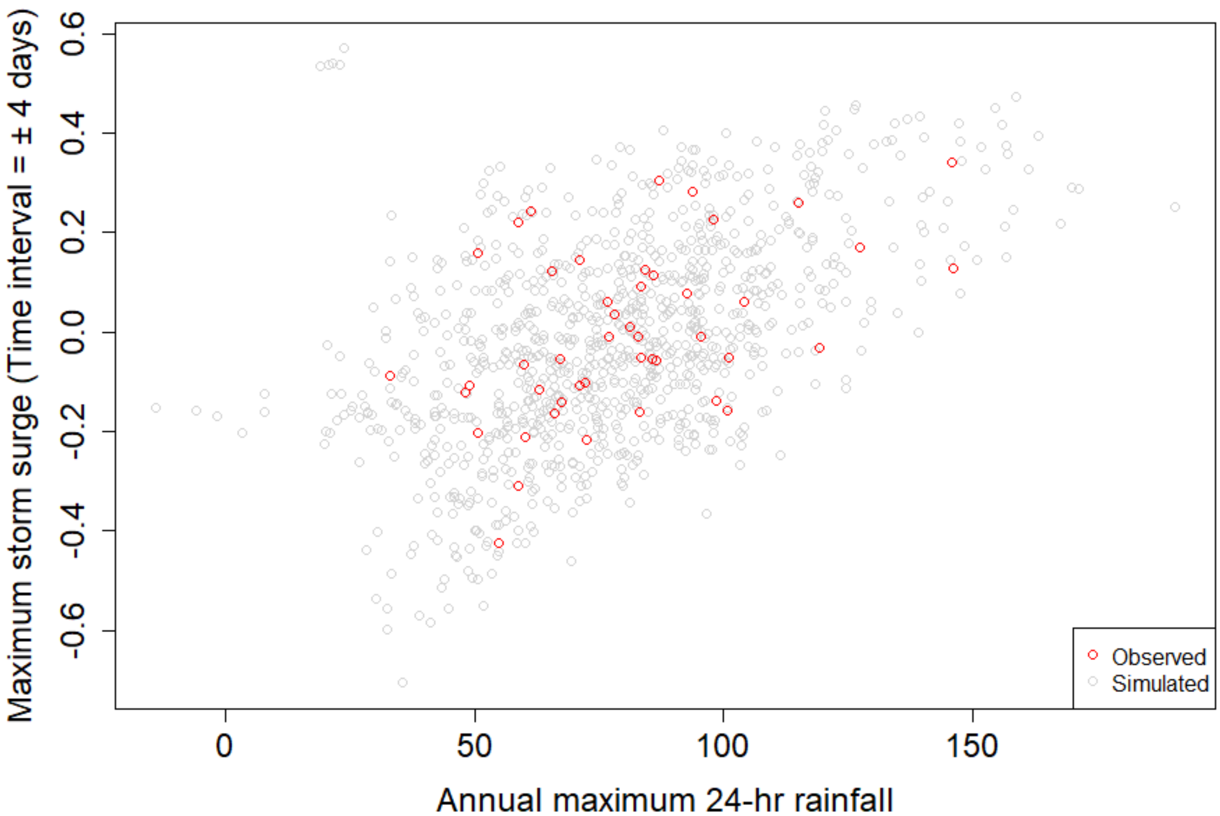
| | | | | | |
|---|---|---|---|---|---|
| Rotated Gumbel 90 degrees | -1.019 | NA | 0.03016 | 0.019115 | 0.8746 |
| Frank | -0.2357 | 0.859 | 0.03313 | 0.021389 | 0.9066 |
| Gaussian (or Normal) | -0.0437 | 0.15 | 0.04946 | 0.022396 | 0.8696 |
| Rotated BB1 90 degrees | Theta = par = -5.383e-08 Delta = par2 = -1.019e+00 | NA | 0.03016 | 0.019115 | 0.8546 |
| Rotated BB6 90 degrees | Theta = par = -1.03, par2 = delta = -1 | NA | -4.441e-15 | 0.018955 | 0.8606 |
| Rotated BB7 90 degrees | Theta = par = -1.030e+00; delta = par2 = -4.136e-09 | NA | 0.03641 | 0.018955 | 0.8516 |
| Rotated BB8 90 degrees | Theta = par = -1.1328 Delta = par2 = -0.8967 | NA | 0.1476 | 0.021387 | 0.7817 |
| Rotated BB1 270 degrees | Theta = par = --0.081 Delta = par2 = -1.00000 | NA | 0.195 | 0.021287 | 0.7847 |
| **Rotated BB6 270 degrees*** | **Theta = par = -1 Delta = par2 = -1** | **NA** | **-6.661e-16** | **0.017848** | **0.8866** |
| Rotated BB7 270 degrees | Theta = par = -1.0000 Delta = par2 = -0.08104 | NA | 0.195 | 0.021289 | 0.7977 |

| | | | | | |
|---|---|---|---|---|---|
| Rotated BB8 270 degrees | Theta = par =-6 Delta = par2 = -0.04 | NA | 8.993e-15 | 0.01939 | 0.8467 |
| Note: Rotated BB6 270 degrees (or r270BB6 Copula) (bold letter with asterisk) exhibited minimum value Cramer-Von Mises functional $S_n$ statistics with p-value is greater than 0.05, thus recognized as the most parsimonious bivariate copula in defining bivariate joint dependence structure in Tree 2 for D-vine structure-2 (case 2). | | | | | |

| (c) | | | | Cramer von Mises functional statistics with parametric bootstrap procedure (N = 1000 (No. of bootstrap samples)) | |
|---|---|---|---|---|---|
| Copula family | Parameter estimates ($\theta_{23\|1}$) via MPL estimators | Standard Error estimates | MLL (Maximized Log-likelihood) | $S_n$ | p-value |
| Clayton | 0.6005 | 0.258 | 4.211 | 0.04817 | 0.07842 |
| Gumbel | 1.264 | 0.135 | 2.824 | 0.028095 | 0.3262 |
| **Frank*** | **2.754** | **0.985** | **4.903** | **0.020058** | **0.8616** |
| Joe | 1.278 | 0.174 | 1.475 | 0.052335 | 0.03646 |
| BB1 (Clayton-Gumbel) | θ = theta = 0.5261; δ = delta = 1.0435 | NA | 4.244 | 0.053884 | 0.2003 |
| BB6 (Joe-Gumbel) | θ = theta = 1; δ = delta = 1.264 | NA | 2.824 | 0.059203 | 0.2023 |
| BB7 (Joe-Clayton) | θ = theta = 1.0000; δ = delta = 0.6006 | NA | 4.211 | 0.060295 | 0.1643 |
| BB8 (Joe-Frank) | θ = theta = 6; δ = delta = 0.39 | NA | 4.902 | 0.031829 | 0.498 |

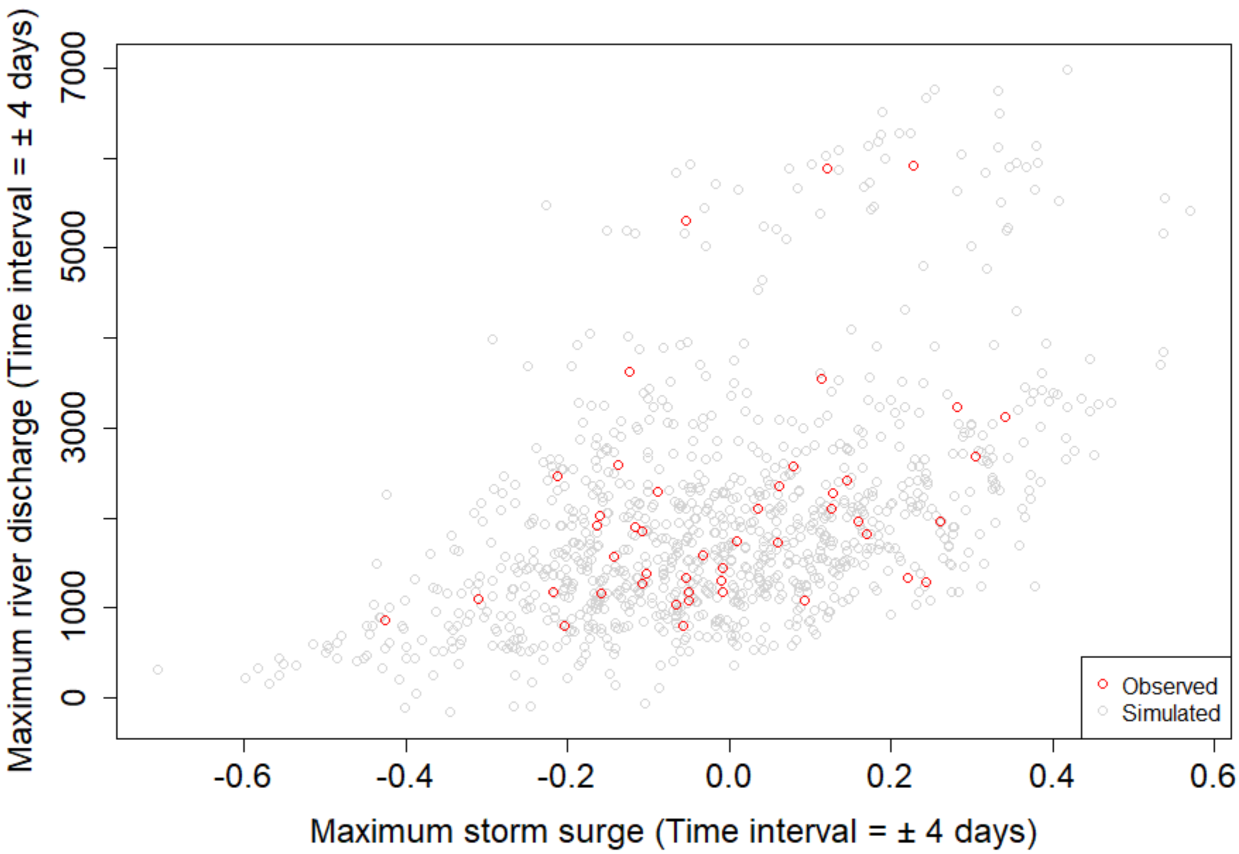
| | | | | | |
|---|---|---|---|---|---|
| Survival clayton | 0.3986 | NA | 2.628 | 0.080974 | 0.07642 |
| Survival Joe | 1.462 | NA | 3.455 | 0.072261 | 0.09141 |
| Survival Gumbel | 1.336 | NA | 4.312 | 0.047635 | 0.2692 |
| Survival BB1 | θ = theta = 0.03614 ; δ = delta = 1.31411 | NA | 4.323 | 0.04636 | 0.2712 |
| Survival BB6 | $\theta = theta = 1$; $\delta = delta = 1.336$ | NA | 4.312 | 0.047635 | 0.2702 |
| Survival BB7 | $\theta = theta = 1.3412$; $\delta = delta = 0.2268$ | NA | 3.978 | 0.053815 | 0.2273 |
| Survival BB8 | $\theta = theta = 6$; $\delta = delta = 0.4$ | NA | 4.918 | 0.032336 | 0.483 |

**Note:** Frank copula (bold letter with asterisk) exhibited minimum value Cramer-Von Mises functional $S_n$ statistics with p-value is greater than 0.05, thus recognized as the most parsimonious bivariate copula in defining bivariate joint dependence structure in Tree 2 for D-vine structure-2 (case 2).

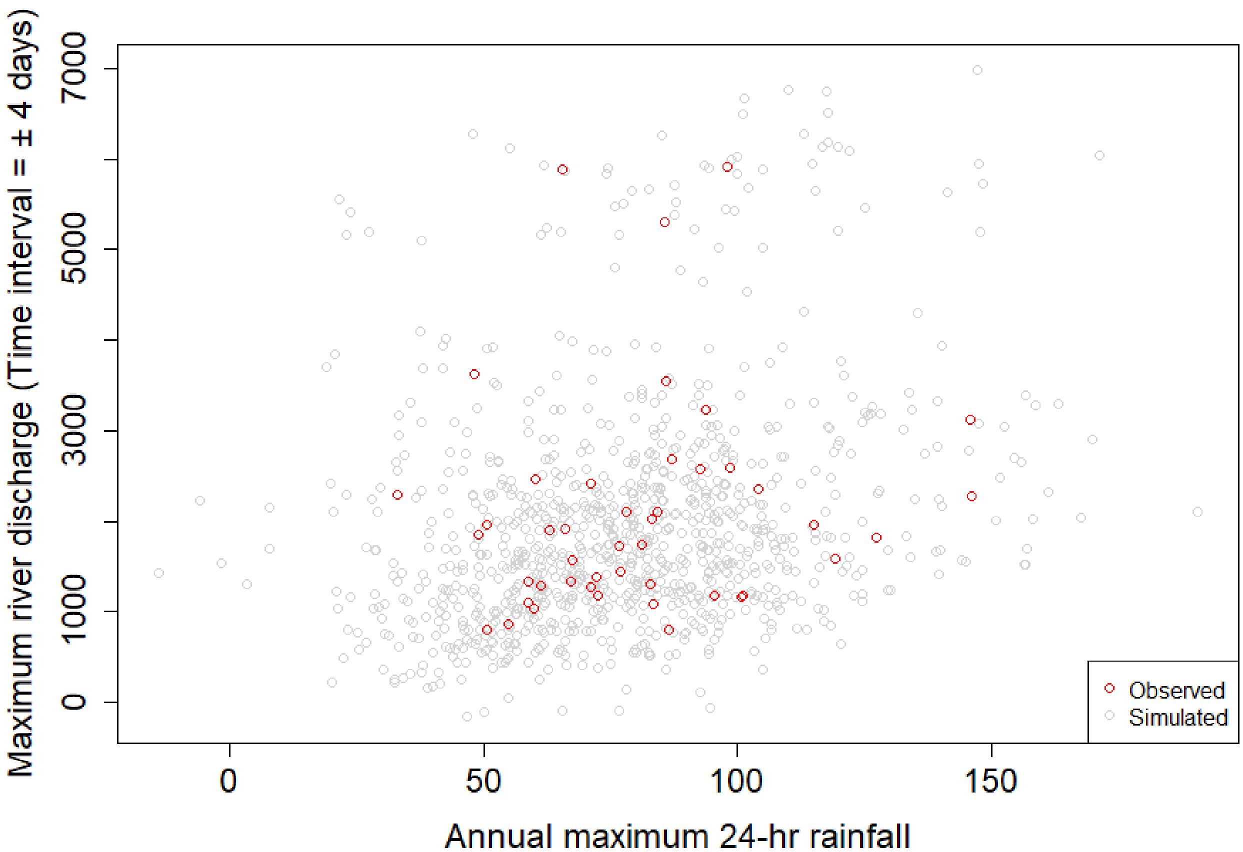


Maximum storm surge (Time interval = ± 4 days)
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
0
50
100
150
Annual maximum 24-hr rainfall
Observed
Simulated


(a)


Maximum river discharge (Time interval = ± 4 days)
7000
5000
3000
1000
0
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
Maximum storm surge (Time interval = ± 4 days)
Observed
Simulated

(b)




(c)

Figure S6: Overlapped 2-D scatterplot between simulated flood events (of sample size, N=1000, using D-vine structure in the nonparametric setting) and historical flood events for (a) rainfall and storm surge (b) storm surge and river discharge (c) rainfall and river discharge pair

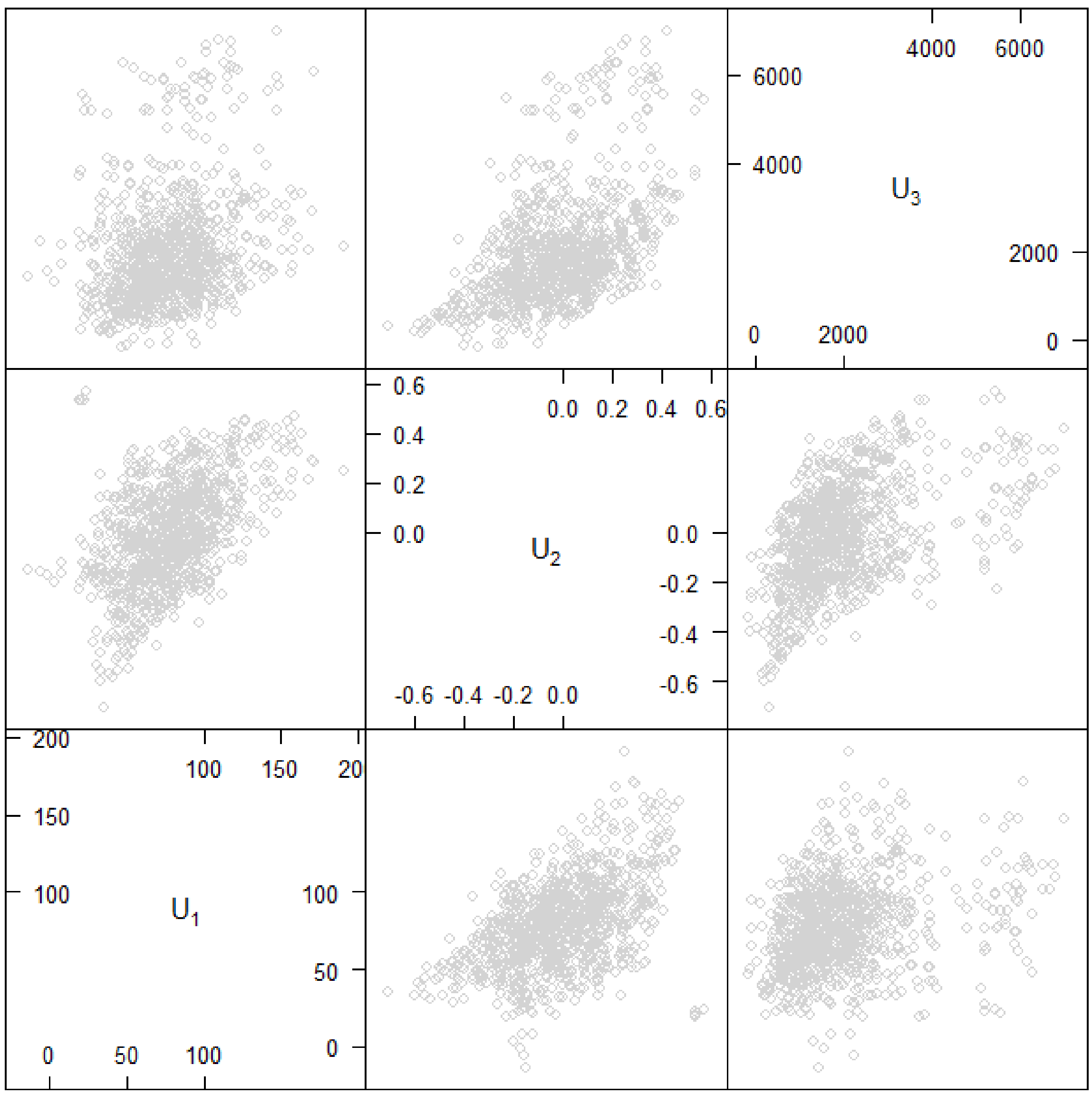



Figure S7: 3-D scatterplot of flood samples generated from best-fitted D-vine structure in the nonparametric settings

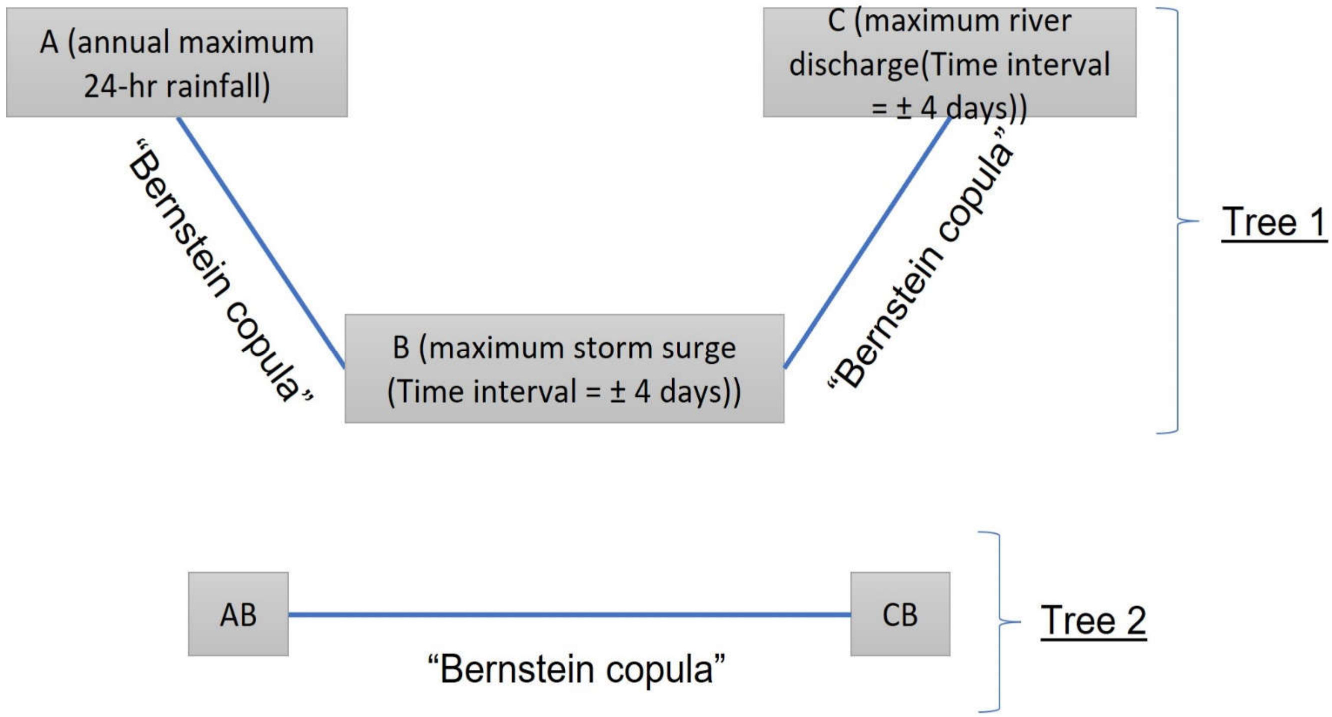



Figure S8: Vine tree plot of the fitted D-vine structure (case-2) in the nonparametric distribution setting