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Does nonstationarity in rainfall require nonstationary intensity–duration–frequency curves?

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**Figure S1.** IPCC AR5 conceptual representation of changes in probability density functions of daily temperature (a – c) and precipitation. The previous and the new distributions are marked by the solid and the dashed lines respectively. The frequency (probability of occurrence) of extremes is denoted by the shaded areas (Source: IPCC AR5 Working Group I report, Figure 1.8, page no. 134).
SI 1. Infilling Missing AMP Record: Method and Results

Multiplicative Random Cascade (MRC) Models for Temporal Disaggregation of Rainfall

Multiplicative Random Cascades were first developed for studies of turbulence (Mandelbrot, 1999; Yaglom, 1966) with a motivation to have mathematical models, which produce time series that have statistically scale-invariant properties. In general, random cascade model for rainfall assumes a division of known rainfall total $R_L$ occurring over an interval of time among a number of smaller intervals of fixed size, which implies a successive fine graining process that starts from an original, large-scale resolution $R_L$ and continues till a target small-scale resolution is reached. The approach is based on scaling laws, which describe the scale-invariant properties or relationships that connect the statistical properties of rainfall for different timescales (Willems, 2012). The number of subintervals is defined by the branching number $b$, is set to 2, which is a redistribution of total rainfall in period $i$ at a resolution $r$, $R_{i,r}$, between the amount associated with the first and last half respectively.

Here we implement a micro-canonical (exact conservation of mass in each cascade branching) cascade-based temporal disaggregation model as proposed by (Olsson, 1998), in which daily rainfall is disaggregated using a uniformly distributed generator, dependent on rainfall intensity and position of the rain sequence. The technique was later successfully implemented by (Güntner et al., 2001; Jebari et al., 2012; Rana et al., 2013) for temporal disaggregation of point rainfall and the development of IDF-curves from short-duration rainfall extremes. In the disaggregation process, each time interval (box) at a given resolution (for example 1 day) is split into two half of the original length (1/2 day). The procedure is continued as a cascade until the desired time resolution is reached, i.e., to ¼ day, then to 1/8 of a day and so on. Each step is termed as a cascade step, with cascade step 0 as the longest time period with only one box (i.e., a day). The distribution of the volume between two sub-intervals (or smaller boxes) is computed by multiplication with the cascade weights ($W_{i,r}$), $0 \leq W_{i,r} \leq 1$ that assigns $W_{i,r} \cdot R_{i,r}$ to the first half of the period and $(1 - W_{i,r}) \cdot R_{i,r}$ to the next half. In each branching two possibilities exist: (1) $W_1 = 0$, $W_1 = 1$ (2) $0 < W_1 < 1$. The occurrence of (1) and (2) may be expressed in terms of probabilities, $P_{01} = P_{(0/1)}$ or $P_{01} = P(W_1 = 0 \text{ or } W_1 = 1)$ and $P_{xx} = P_{(x/x)} = P(0 < W_1 < 1) = 1 - P_{01}$.

Depending on the range of resolution involve, $P_{01}$ either be assumed as resolution independent or parameterized as a scaling law: $P_{01}(r) = c_1 r^{c_2}$ where $c_1$ and $c_2$ are constants. The distribution of $W_{i,r}$ is termed as cascade generator, assumed to follow 1-parameter beta distribution (Olsson, 2012). Following (Olsson, 1998), the probabilities $P$, the probability distribution of cascade generator are assumed to be related to (1) position in rainfall sequence, and (2) rainfall volume. The wet boxes, with a rainfall volume $V > 0$, can be characterized by their position in the rainfall series: (1) the starting box, box preceded by a dry box ($V = 0$) and succeeded by a wet box ($V > 0$); (2) the enclosed box, box preceded and succeeded by wet boxes; (3) the ending box, box preceded by a wet box and succeeded by a dry box, and (4) the isolated box, box preceded and succeeded by dry boxes. On the other hand, based on volume dependence, if the volume is large then it is more likely that both halves of the subintervals
contribute to nonzero volume than if the volume is small. Following (Olsson, 1998), a partition into three volume classes \((v_c = 1, 2, 3)\) was used, separated by percentiles 33rd and 67th of the values at the cascade step. Next, the variation of \(P_{(x/x)}\) with volume is parameterised as, \(P_{(x/x)} = a + b_m v_c\), where \(a\) is the intercept at \(v_c = 0\), \(b_m\) is the mean slope of linear regression obtained from all cascade steps and \(v_c\) is volume class. For details about theory and implementation issues of MRC-based disaggregation tool, interested readers are requested to refer (Olsson, 1998).

For calibration and application of the disaggregated model from an original resolution \(R_o\), two situations are considered: (1) when representative data at target resolution \(R_t\) is available; such as in this case, disaggregation from daily to hourly time steps, in which hourly data were available. Hence, parameters are calibrated over the actual resolution interval \(R_t < r < R_o\) using 5 cascade steps. This implies, 5 successive “halving” from one day to generate 45-minute (2700 seconds) data. (2) When no representative high-resolution data are available, then parameters are estimated by coarse graining from lower resolution \(R_t\) to a higher resolution \(R_o\) by successive disaggregation steps. In this study, it is the disaggregation from daily to minute scales (or sub-hourly time steps), in which no sub-hourly data were available for any of the representative sites. In such case, parameters are calibrated from daily rainfall data using 7 cascade steps. This implies disaggregating by halving from 1-day to 11-minute 15 seconds (675 seconds) data. After calibration, Monte Carlo simulation is performed to gradually fine-grain the data and generate realizations at desired resolution, \(R_o\). Since \(R_o\) in these cases are not directly achieved by exact resolution doubling from \(R_t\), the target resolutions are obtained by geometric interpolation of the disaggregated model output at the final time step. In the next sub-sections, we demonstrate the performance of the MRC-based disaggregation tool using two different sets of observations.

S 1.1 Performance Evaluation of MRC-based disaggregation Tools for McMaster Weather Station Data

McMaster weather station is situated on a rooftop of McMaster University campus \((43.26^\circ\) N latitude and 79.92° W longitude, 114 m above sea level). We obtain daily, hourly and sub-hourly (15-min) rainfall information from the year 2010 to 2013, archived at McMaster Weather Station (MUWS; http://geomedia.mcmaster.ca/muws/weatherstation.html) website. The time slice was chosen based on data completeness and quality of available records.

We investigate two cases: (1) First, we calibrate the model using 1-year (2012 – 2013) hourly data, estimated model parameters, and then assess the performance of disaggregated model output using 2010 – 2013 observed data (2) Next, the observed 15-min time series was first aggregated to an hourly time step and then calibrated the model using aggregated hourly data. Then we compare disaggregated versus observed data at a 15-min temporal resolution for validation. Since we do not have 15-min daily rainfall information available for any of the rain gauge locations, in both cases we calibrate the model using hourly data, which in turn gives us the opportunity to evaluate the performance of the disaggregation algorithm. In all cases, disaggregation was performed from daily time scales. Table S1 shows results of disaggregation experiments. We find a satisfactory performance between
observed and simulated model output, especially for the simulation of the percentage of zero values. However, we find a slight underestimation for simulated standard deviations of event volume and duration, whereas variance of mean inter-arrival time is overestimated.

**Table S1.** Comparison between observed and disaggregated 15-min and 1-hour time series for McMaster Weather Station Data

| Time scale (1-hr) | Metrics                                | Observed     | Simulated    |
|------------------|----------------------------------------|--------------|--------------|
|                  | Zero values (%)                        | 92           | 91.5         |
|                  | Individual Rainfall volume (mean ± SD) mm | 1.60 ± 2.95  | 1.45 ± 2.89  |
|                  | Event volume (mean ± SD) mm            | 4.52 ± 10.40 | 4.50 ± 8.82  |
|                  | Event duration (mean ± SD) hour        | 2.83 ± 3.51  | 3.09 ± 2.69  |
|                  | Mean inter-arrival time between event, hour | 36.82 ± 64.70 | 37.33 ± 65.10 |
|                  | Mean annual maxima (mean ± SD) mm      | 39.97 ± 21.42 | 32.97 ± 12.33 |
| Minute (15-min)  | Zero values (%)                        | 94.63        | 95.35        |
|                  | Individual Rainfall volume (mean ± SD) mm | 0.032 ± 1.20 | 0.031 ± 1.28 |
|                  | Event volume (mean ± SD) mm            | 1.87 ± 6.28  | 1.96 ± 4.64  |
|                  | Event duration (mean ± SD) hour        | 3.15 ± 5.77  | 2.94 ± 3.47  |
|                  | Mean inter-arrival time between event, hour | 59.54 ± 177.33 | 64.12 ± 182.01 |
|                  | Mean annual maxima (mean ± SD) mm      | 20.4 ± 10.22 | 23.4 ± 12.70 |

**S 1.2 Performance Evaluation of MRC-based disaggregation Tools for the Nine Locations in Southern Ontario**

Figures S2 – S8 display disaggregation fit of the MRC-based tools for Toronto International Airport. Figure S2 presents variations of probability with volume classes, which often show substantial differences between the classes. The figure shows a linear relationship between precipitation, \( P \) and volume class, \( v_c \) changes with cascade steps. The mean regression line \( a_p + b_m \times v_c \) (where \( a_p \) is the intercept and \( b_m \) is the slope) is shown as a dashed line with squares (Figure S2). Figures S3 and S4 show variations of intercepts with cascade steps. The probabilities \( P(x/x) \) and \( P(0/1) \) for daily to minute-scale disaggregation of four different type of boxes are shown in Tables S2 and S3. \( P(x/x) \) can be modelled assuming linear dependence on the cascade step, which is given as, \( P(x/x) = a_p + b_m \times v_c \) with \( a_p \) is estimated as, \( a_p = c_1 + c_2 \times C_s \), where \( c_1 \) and \( c_2 \) are the slopes and the intercept of the linear regression. Since \( P(0/1) \) [or \( P(1/0) \)] is relatively independent of cascade step, it can be modeled using \( a_p + b_m \times v_c \). Finally, \( P(0/1) \) [or \( P(1/0) \)] can be estimated as, \( P(0/1) = 1 - (P(x/x) + P(1/0)) \) [or \( P(1/0) = 1 - (P(x/x) + P(0/1)) \)]. The empirical histograms (the observed, shown in bars) and the fitted beta distributions (shown in lines) [Figures S5 and S6] show a good agreement in the overall fit. However, at higher cascade steps, i.e. finer time scales, the number of bins in the histogram is small, and the fits appear naturally uncertain.
Figure S7 shows time series of disaggregated versus observed annual maxima (the 15-min and 1-hour) for Toronto International Airport. The Quantile Mapping (QM) is employed to adjust occasional overestimation due to disaggregation. Except for a few extremes, we find a close agreement between the observed versus bias-corrected disaggregated annual maxima time series. For example, the algorithm overestimates the wettest event in Toronto (137.4 mm of rainfall) during Hurricane Hazel (1954) at hourly disaggregation time steps. However, due to lack of observation, we could not validate 15-min disaggregation model performance. Figure S8 shows 1-hour disaggregated model performance for the nine sites. Although we find evidence of occasional overestimations in disaggregated model output, the adjustment of extremes by QM could correct biases to some extent. However, the algorithm fails to correct extreme wet biases for London International Airport (during 1954), Trenton Airport (2000), Stratford WWTP (2002) and Fergus Shand Dam (2004 and 2006).
Table S2. Probabilities $P(x|x)$ as function of volume class, cascade step and type of box for daily to minute scale disaggregation

| Volume Class/Cascade Step | 1               | 2               | 3               | 4               | 5               | 6               | 7               | Mean |
|---------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------|
| 1                         | 0.001           | 0.030           | 0.051           | 0.048           | 0.073           | 0.082           | 0.031           | 0.045 |
| 2                         | 0.244           | 0.254           | 0.266           | 0.299           | 0.249           | 0.289           | 0.267           | 0.27  |
| 3                         | 0.509           | 0.505           | 0.510           | 0.513           | 0.512           | 0.470           | 0.420           | 0.49  |

2. Starting Box ($b_m = 0.244$)

| Volume Class/Cascade Step | 1               | 2               | 3               | 4               | 5               | 6               | 7               | Mean |
|---------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------|
| 1                         | 0.054           | 0.122           | 0.081           | 0.064           | 0.101           | 0.130           | 0.095           | 0.092 |
| 2                         | 0.399           | 0.415           | 0.345           | 0.290           | 0.275           | 0.283           | 0.437           | 0.349 |
| 3                         | 0.635           | 0.612           | 0.610           | 0.527           | 0.487           | 0.570           | 0.628           | 0.581 |

3. Enclosed Box ($b_m = 0.263$)

| Volume Class/Cascade Step | 1               | 2               | 3               | 4               | 5               | 6               | 7               | Mean |
|---------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------|
| 1                         | 0.423           | 0.357           | 0.272           | 0.157           | 0.097           | 0.156           | 0.194           | 0.236 |
| 2                         | 0.862           | 0.817           | 0.703           | 0.510           | 0.335           | 0.345           | 0.463           | 0.576 |
| 3                         | 0.951           | 0.938           | 0.875           | 0.736           | 0.585           | 0.562           | 0.685           | 0.762 |

4. Ending Box ($b_m = 0.247$)

| Volume Class/Cascade Step | 1               | 2               | 3               | 4               | 5               | 6               | 7               | Mean |
|---------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------|
| 1                         | 0.063           | 0.033           | 0.064           | 0.087           | 0.084           | 0.109           | 0.114           | 0.079 |
| 2                         | 0.381           | 0.372           | 0.323           | 0.253           | 0.303           | 0.237           | 0.439           | 0.330 |
| 3                         | 0.651           | 0.639           | 0.591           | 0.564           | 0.474           | 0.496           | 0.593           | 0.572 |
**Table S3.** Probabilities $P(0/1)$ as function of volume class, cascade step and type of box for daily to minute scale disaggregation

| Volume Class/Cascade Step | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Mean |
|---------------------------|---|---|---|---|---|---|---|------|
| 1                         | 0.446 | 0.449 | 0.494 | 0.466 | 0.427 | 0.482 | 0.50 | 0.466 |
| 2                         | 0.369 | 0.388 | 0.370 | 0.330 | 0.400 | 0.369 | 0.30 | 0.361 |
| 3                         | 0.257 | 0.248 | 0.236 | 0.242 | 0.241 | 0.259 | 0.193 | 0.239 |

2. Starting Box ($b_m = -0.175$)

| Volume Class/Cascade Step | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Mean |
|---------------------------|---|---|---|---|---|---|---|------|
| 1                         | 0.747 | 0.713 | 0.771 | 0.711 | 0.681 | 0.565 | 0.526 | 0.673 |
| 2                         | 0.535 | 0.521 | 0.583 | 0.593 | 0.558 | 0.409 | 0.295 | 0.499 |
| 3                         | 0.320 | 0.333 | 0.347 | 0.408 | 0.394 | 0.274 | 0.195 | 0.324 |

3. Enclosed Box ($b_m = -0.113$)

| Volume Class/Cascade Step | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Mean |
|---------------------------|---|---|---|---|---|---|---|------|
| 1                         | 0.272 | 0.283 | 0.330 | 0.387 | 0.400 | 0.405 | 0.374 | 0.350 |
| 2                         | 0.078 | 0.103 | 0.159 | 0.220 | 0.350 | 0.348 | 0.253 | 0.216 |
| 3                         | 0.027 | 0.031 | 0.077 | 0.154 | 0.204 | 0.224 | 0.158 | 0.125 |

4. Ending Box ($b_m = -0.068$)

| Volume Class/Cascade Step | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Mean |
|---------------------------|---|---|---|---|---|---|---|------|
| 1                         | 0.215 | 0.211 | 0.167 | 0.202 | 0.210 | 0.330 | 0.298 | 0.233 |
| 2                         | 0.093 | 0.083 | 0.098 | 0.144 | 0.187 | 0.318 | 0.263 | 0.169 |
| 3                         | 0.040 | 0.054 | 0.068 | 0.072 | 0.120 | 0.174 | 0.159 | 0.098 |
Figure S2. Variation of probabilities with volume class, $v_c$ for Toronto International Airport at (a) daily to hourly-, and (b) daily to minute-time step disaggregation. X-axes show, $v_c$: 1 – small, 2 – medium, and 3 – large; Y-axes show, probabilities. $P$ – denotes position type, 1: Isolated, 2: Starting, 3: Enclosed, and 4: Ending, $D$ denotes division type (1: 0/1, 2: 1/0, 3: x/x), and $N$ denotes the total number of periods for associated position and division type. The solid lines marked with different colors indicate different cascade steps. The dashed line with squares represents the mean of all cascade levels.
Figure S3. Variations of intercept, $a_p$, with cascade steps for daily to hourly-time step disaggregation at Toronto International Airport. $P$-denotes position types, 1: Isolated, 2: Starting, 3: Enclosed and 4: Ending. $D$ denotes division type (1: 0/1, 2: 1/0, 3: x/x), and $b_m$ indicates the mean slope for corresponding position and division type, estimated from the fitted mean lines as in Figure S3. The third column indicates the fraction of 0/1-divisions of all “non-x/x-divisions” summed over volume classes.
Figure S4. Same as in Figure S3 but for daily to minute- time step disaggregation.
Figure S5. Variations of empirical $x/x$-distributions with cascade steps (bars) and fitted beta distributions (lines) for daily to hourly- time step disaggregation at Toronto International Airport. $P$-denotes position types, 1: Isolated, 2: Starting, 3: Enclosed and 4: Ending; $C_s$ denotes cascade steps, for example, step 1 shows cascading from 32 to 16 minute, step 2 indicates from 16 to minute and so on. $N$ indicates the total number of $x/x$-divisions for this position type and cascade level.
Figure S6. Same as in Figure S5 but for daily to minute-time step disaggregation.
**Figure S7.** Comparison of observed versus disaggregated (a) sub-hourly and (b) hourly Annual Maximum (AM) rainfall values (Observed – red, disaggregated – blue and disaggregated and bias corrected - black) for Toronto International Airport. (c) The bottom panel shows AM daily rainfall values. A multiplicative random cascade-based disaggregation tool is used to disaggregate daily rainfall time series into a sub-hourly and hourly time step.
Figure S8. Comparison of observed versus disaggregated time series for 1-hour AMP across nine locations (a-g)
SI 2 Trend and Change point, Autocorrelation: Methods and Results

SI 2.1 Detection of Monotonic trend: Mann-Kendall Test Statistics

The null hypothesis \( H_0 \) of the test assumes that no temporal trend exists in the data and the alternate hypothesis \( H_1 \) assumes that a significant temporal trend (upward or downward) exists. The test statistic \( Z_{MK} \) is computed as (Hirsch et al., 1982)

\[
Z_{MK} = \begin{cases} 
  \frac{S - 1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0; \\
  0 & \text{if } S = 0; \\
  \frac{S + 1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0
\end{cases}
\]  

(2.1)

where \( S \) is defined by,

\[
S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sgn}(x_j - x_k) 
\]

(2.2)

where \( x_j \) and \( x_k \) are the data points in time periods \( j \) and \( k \) \((j > k)\) respectively, and \( n \) is number of observed data points. For \( n \geq 10 \), the test statistic \( S \) is approximately normally distributed with the mean of \( E(S) = 0 \), and the variance of,

\[
\text{Var}(S) = \frac{1}{18} \left[ n(n-1)(2n+5) - \sum_{i=1}^{g} t_i(i-1)(2i+5) \right] 
\]  

(2.3)

where \( g \) is the number of tied groups and \( t_i \) is the number of data points in the \( i^{th} \) group.

SI 2.2 Detection of Abrupt or Step Change

SI 2.2.1 General Formulation of Sequential Change Point Test

When a sequence of random variables is divided into two segments represented by \( x_1, \ldots, x_n \) and \( x_{n+1}, x_{n+2}, \ldots, x_m \), if each segment has distribution functions, \( F_1(x) \) and \( F_2(x) \), where \( F_1(x) \neq F_2(x) \), then change point is identified at \( t_0 \). Thus the null hypothesis of the test is “no change”, \( H_0 : \tau = T \) against the alternative of “change” \( H_1 : 1 \leq \tau < T \). Suppose \( t \) points in the sequence of observations and we wish to test whether a change point has occurred at some point in the historical observation. For any fixed \( k < t \) the hypothesis that a change point occurs at the \( k^{th} \) observation can be written as (Ross et al., 2011)
\[ H_0 \forall i \quad X_i \sim F_0, \quad H_1 : X_i \sim \begin{cases} F_0 & \text{if } i < k \\ F_1 & \text{if } i \geq k \end{cases} \] (2.4)

Now a two-sample hypothesis test can be used to test for a change point at a location \( k \) using a test statistic \( N_{k,t} \).

The test statistic \( N_{k,t} \) can be evaluated for all values of \( 1 < k < t \), and then using the maximum value, \( i.e., \)

\[ N_{\text{max},t} = \max_k N_{k,t} \] (2.5)

Then, the hypothesis that no change has occurred before the \( t^\text{th} \) observation is rejected if \( N_{\text{max},t} > h_t \) at a threshold \( h_t \). The value \( \tau \) of the change point is then the value of \( k \) which maximizes \( N_{\text{max},t} \)

**Change Point in Location**

- **Pettitt Change Point Test**

The test is based on following statistic (Serinaldi and Kilsby, 2016; Xie et al., 2014)

\[ K_T = \max_{1 \leq s \leq T} |U_{s,T}| \] (2.6)

Where \( U_{s,T} \) the ranked sample as is defined in Eq. 2.2. The statistical significance of Pettitt test quantified by \( p \)-value is approximately evaluated as (Xie et al., 2014), \( p = 2 \exp \left( -\frac{6K_T^2}{T^2 + T^2} \right) \). Given a certain significance level \( \alpha \), if \( p < \alpha \), we reject the null hypothesis and conclude that \( \tau \) is a significant change point at level \( \alpha \).

- **Mann-Whitney Change Point Test**

Mann-Whitney (MW) test statistics detect shifts in location parameter in the time series. The test is based on the following observation: if there are \( n \) points spread over two samples \( S \) and \( T \), containing \( n_s \) and \( n_t \) points respectively, \( n = n_s + n_t \). The MW U statistic is then defined as (Ross, 2013)

\[ U' = r_s - \frac{n_s(n_s + 1)}{2} \] (2.7)

Where \( r_s \) is the sum of the ranks of the points in sample \( S \). Under the null hypothesis that \( S \) and \( T \) have equal location parameter, the distribution of of \( U \) is independent of the distribution of the observations in two samples and its first two moments are

\[ \mu_{U'} = n_s n_t / 2, \quad \sigma_{U'}^2 = n_s n_t (1 + n_s + n_t) / 12 \] (2.8)

The standardized MW statistic, \( U = \left| (U' - \mu_{U'}) / \sigma_{U'} \right| \)
A nonparametric change point for location shifts is then defined as by replacing \( N_{\text{max},t} \) with this \( U \) statistic.

**Change Point in Scale: Mood Test**

The Mood Test uses a test statistic which measures the extent to which the rank of each point deviates from its expected value (Ross et al., 2011)

\[
M' = \sum_{x_i \in S} \left( r(x_i) - \frac{(n + 1)}{2} \right)^2
\]  

(2.10)

Where \( r(x_i) \) denotes the rank of \( x_i \) in the pooled sample. Similar to MW statistic, the distribution of Mood statistic is independent of the underlying random variables. The mean and variance of the Mood statistic is given as

\[
\mu_{M'} = n_s \left( n^2 - 1 \right) / 12, \quad \sigma^2_{M'} = n_s n_T \left( n + 1 \right) \left( n^2 - 4 \right) / 180
\]  

(2.11)

Then the standardized statistic is given as (Ross et al., 2011)

\[
M = \left| \frac{M' - \mu_{M'}}{\sigma_{M'}} \right|
\]  

(2.12)

Similar to MW statistic, a nonparametric change point for scale shifts is defined as by replacing \( N_{\text{max},t} \) with this \( M \) statistic. Both Mann-Whitney and Mood tests were performed using R statistical software with add-on package “cpm”.

**SI 2.3 Non-parametric Trend Free Pre-Whitening (TPFW) for Correction of Autocorrelation**

To correct the autocorrelation present in the data, we followed the non-parametric procedure of trend-free pre-whitening (TPFW) as suggested by the (Petrow and Merz, 2009):

- At first, the trend of annual maxima time series of a particular duration is estimated by the non-parametric trend slope estimator, \( \beta \) as suggested by (Sen, 1968), which is the median of all pair wise slopes \( (b_i) \) in the time series of length \( N \):

\[
\beta = \begin{cases} 
\frac{b_{(N+1)/2}}{2} & \text{if } N \text{ is odd} \\
\frac{1}{2} \left( b_{N/2} + b_{(N+1)/2} \right) & \text{if } N \text{ is even}
\end{cases}
\]  

(2.13)

Where, \( b_i = \frac{(x_j - x_k)}{j - k}, \quad i=1,2,\ldots,N \text{ and } j > k \), and \( x_j \) and \( x_k \) are the data points in time periods \( j \) and \( k \) (\( j > k \)) respectively. Hence, if there are \( n \) values of data in the time series, it results into as many as \( N = \binom{n}{2} \) number of \( b_i \) values.
• Secondly, the computed trend is removed from the original series:

\[ Y_t = X_t - \beta t \]  

(2.14)

Where, \( X_t \) is the original time series and \( t \) is the time.

• Next, the lag1- autocorrelation [\( \rho \), using MATLAB function `autocorr()`], is computed from \( Y_t \). If no statistically significant (significance is checked at 5 and 10% significance level) autocorrelation is found, the trend and change-point detection algorithms are directly applied to the original time series. Otherwise, the lag-1 autocorrelation is removed from the time series:

\[ Y'_t = Y_t - \rho Y_{t-1} \]  

(2.15)

• Finally, the removed trend in the first step is added back into the time series free from trend and autocorrelation.

\[ Y''_t = Y'_t + \beta t \]  

(2.16)

The resulting time series \( Y''_t \) includes the original trend but free from autocorrelation.
Table S4. Detection of trends and nonstationarity in Toronto Pearson International Airport

| Time Slice | Ljung-Box Test p-value | Test statistics | Augmented Dickey-Fuller Test p-value | Test statistics | KPSS Test p-value | Test statistics | Mann-Kendall Trend Test $\beta$ p-value | Test statistics | Priestley-Subbarao Test p-value | Test statistics | Pettitt Test p-value | Test statistics | Mann-Whitney Change Point Test Year | Test statistics | Threshold Year | Test statistics | Mood Change Point Test Year | Test statistics | Threshold Year |
|------------|------------------------|----------------|------------------------------------|----------------|------------------|----------------|---------------------------------------|----------------|-------------------------------|----------------|-----------------------------|---------------|---------------------------|----------------|---------------------|----------------|---------------------|----------------|---------------------|
| 15-min     | 0.014**                | -0.326         | 0.53**                             | 0.120          | 0.098           | 0.71           | -0.23                                 | 0.48            | 0.383                         | 0.141          | x                             | x             | x                        | x             | x                   | x              | x                   |
| 30-min     | 0.027**                | -0.177         | 0.58**                             | 0.123          | 0.092           | 0.52           | -0.25                                 | 0.61            | 0.283                         | 0.179          | x                             | x             | x                        | x             | x                   | x              | x                   |
| 1-hr       | 0.805                  | -0.077         | 0.62**                             | 0.138          | 0.064           | 0.39           | 0.22                                  | 0.69            | 0.409                         | 0.368          | x                             | x             | x                        | x             | x                   | x              | x                   |
| 2-hr       | 0.920                  | 0.043          | 0.66**                             | 0.129          | 0.081           | -0.07          | -0.05                                 | 0.94            | 0.143                         | 0.564          | x                             | x             | x                        | x             | x                   | x              | x                   |
| 6-hr       | 0.959                  | 0.051          | 0.67**                             | 0.060          | >0.10           | -0.61          | -0.48                                 | 0.54            | 0.025                         | 0.733          | x                             | x             | x                        | x             | x                   | x              | x                   |
| 12-hr      | 0.965                  | 0.106          | 0.67**                             | 0.065          | >0.10           | -0.55          | -0.49                                 | 0.58            | 2.0e-4**                      | 0.659          | x                             | x             | x                        | x             | x                   | x              | x                   |
| 24-hr      | 0.885                  | 0.106          | 0.69**                             | 0.046          | >0.10           | -0.06          | -0.06                                 | 0.95            | 0.046**                       | -†             | x                             | x             | x                        | x             | x                   | x              | x                   |

** and * indicate statistically significant at 5% and 10% significance levels, ‘x’ denotes no change point is detected using Mann-Whitney and Mood tests respectively. $\beta$ indicates slope per decade calculated using Theil-Sen method. $P$-values larger than 0.1 in KPSS test indicates test statistics are non-significant, whereas $p$-values smaller than 0.01 are considered to be highly significant. The standardized Mann-Kendall test statistic (MKZ) is positive (negative) with an increasing (decreasing) trend, and statistically significant at 5% and 10% significance levels when $|MKZ| > 1.96$ and $|MKZ| > 1.64$ respectively. Change point tests are performed at 10% significance level. †$p$-values are not reported due to analytical intractability.

Table S4.1 Detection of trends and nonstationarity after performing TFPW in Toronto Pearson International Airport

| Time Slice | Ljung-Box Test p-value | Test statistics | Augmented Dickey-Fuller Test p-value | Test statistics | KPSS Test p-value | Test statistics | Mann-Kendall Trend Test $\beta$ p-value | Test statistics | Priestley-Subbarao Test p-value | Test statistics | Pettitt Test p-value | Test statistics | Mann-Whitney Change Point Test Year | Test statistics | Threshold Year | Test statistics | Mood Change Point Test Year | Test statistics | Threshold Year |
|------------|------------------------|----------------|------------------------------------|----------------|------------------|----------------|---------------------------------------|----------------|-------------------------------|----------------|-----------------------------|---------------|---------------------------|----------------|---------------------|----------------|---------------------|----------------|---------------------|
| 15-min     | 0.258                  | -0.60**        | 0.43                               | 0.089          | >0.10            | -0.17          | -0.04                                 | 0.87            | 0.504                         | 0.531          | x                             | x             | x                        | x             | x                   | x              | x                   |
| 30-min     | 0.243                  | -0.35**        | 0.52                               | 0.098          | >0.10            | 0.07           | 0.05                                  | 0.94            | 0.498                         | 0.777          | x                             | x             | x                        | x             | x                   | x              | x                   |
| Time Slice | Ljung-Box Test | Augmented Dickey-Fuller Test | KPSS Test | Mann-Kendall Trend Test | Priestley-Subbarao Test | Pettitt Test | Mann-Whitney Change Point Test | Mood Change Point Test |
|------------|----------------|-------------------------------|-----------|-------------------------|-------------------------|-------------|-------------------------------|-------------------------|
|            | p-value | Test statistics | p-value | Test statistics | p-value | MKZ | β | p-value | Test statistics | Threshold Year | Test statistics | Year | Test statistics | Threshold |
| 15-min     | 0.173   | -0.454          | 0.48**   | 0.033       | >0.10   | -0.65 | -0.24 | 0.516 | 0.406       | 0.438       | x             | x             | x             | x             |
| 30-min     | 0.911   | -0.428          | 0.49**   | 0.047       | >0.10   | -1.186 | -0.45 | 0.236 | 2.56e^-5** | 0.402       | x             | x             | x             | x             |
| 1-hr       | 0.918   | -0.170          | 0.58**   | 0.082       | >0.10   | 0.244 | 0.28  | 0.807 | 0.002**    | 0.870       | x             | x             | x             | x             |
| 2-hr       | 0.735   | -0.176          | 0.58**   | 0.154       | 0.043   | 1.023 | 0.75  | 0.306 | 8.03e^-6** | 0.300       | x             | x             | x             | x             |
| 6-hr       | 0.099   | -0.138          | 0.60**   | 0.193       | 0.019   | -0.097 | -0.11 | 0.922 | 3.49e^-9** | 0.216       | x             | x             | x             | x             |
| 12-hr      | 0.150   | -0.055          | 0.63**   | 0.183       | 0.023   | -0.122 | -0.14 | 0.903 | 2.78e^-10** | 0.506       | x             | x             | x             | x             |
| 24-hr      | 0.059   | -0.035          | 0.63**   | 0.307       | 0.010   | 0.309 | 0.39  | 0.758 | 1.82e^-7** | 0.199       | x             | x             | x             | x             |
Table S6. Detection of trends and nonstationarity in Oshawa WPCP

| Time Slice | Ljung-Box Test | Augmented Dickey-Fuller Test | KPSS Test | Mann-Kendall Trend Test | Priestley-Subbarao Test | Pettitt Test | Mann-Whitney Change Point Test | Mood Change Point Test |
|------------|----------------|-----------------------------|-----------|-------------------------|-------------------------|-------------|-------------------------------|------------------------|
|            | p-value        | Test statistics             | p-value   | Test statistics         | p-value                 | p-value     | Year                          | Test statistics        | Threshold |
| 15-min     | 0.986          | -0.152                      | 0.59**    | 0.044                   | >0.10                   | 0.93        | 2.12                          | 0.35                   | x         | x         | x         |
| 30-min     | 0.620          | -0.251                      | 0.55**    | 0.045                   | >0.10                   | 0.73        | 1.02                          | 0.47                   | -         | x         | x         |
| 1-hr       | 0.994          | -0.065                      | 0.62**    | 0.081                   | >0.10                   | 1.29        | 1.5                           | 0.20                   | 0.57      | 0.562     | x         | x         | x         |
| 2-hr       | 0.938          | -0.116                      | 0.61**    | 0.08                    | >0.10                   | 1.68        | 0.82                          | 0.09**                 | 0.005**   | 0.259     | 2009      | 2.64*     | 2.58      |
| 6-hr       | 0.924          | -0.311                      | 0.53**    | 0.075                   | >0.10                   | 1.49        | 0.3                           | 0.14                   | 0.027**   | 0.248     | x         | x         | x         |
| 12-hr      | 0.998          | -0.928                      | 0.31**    | 0.048                   | >0.10                   | 1.73        | 0.13                          | 0.08**                 | 2.4e-4**  | 0.321     | 1975      | 2.59*     | 2.67      |
| 24-hr      | 0.990          | -1.716                      | 0.08*     | 0.040                   | >0.10                   | 2.20        | 0.14                          | 0.03**                 | 2.4e-3**  | 0.056*    | 1983      | 2.90*     | 2.58      |
| Time Slice | Ljung-Box Test p-value | Ljung-Box Test Test statistics | Augmented Dickey-Fuller Test p-value | Augmented Dickey-Fuller Test Test statistics | KPSS Test p-value | KPSS Test Test statistics | Mann-Kendall Trend Test p-value | Mann-Kendall Trend Test MKz | Priestley-Subbarao Test p-value | Priestley-Subbarao Test β | Pettitt Test p-value | Pettitt Test Test statistics | Mann-Whitney Change Point Test Year | Test statistics | Threshold | Year | Test statistics | Threshold |
|------------|-----------------------|-------------------------------|-------------------------------------|---------------------------------------------|-------------------|-----------------------------|-------------------------------|------------------|-------------------------------|------------------------|-----------------|------------------|-------------------------------|----------------|---------|-------|----------------|---------|
| 15-min     | 0.595                 | -0.237                        | 0.56**                            | 0.108                                       | >0.10             | -1.29                      | 0.198                         | 0.156                    | 0.141                         | x                      | x               | x                |                                |                |         |       | x              | x       |
| 30-min     | 0.749                 | -0.363                        | 0.51**                            | 0.074                                       | >0.10             | -1.59                      | 0.111                         | 0.845                    | 0.093*                        | x                      | x               | x                |                                |                |         |       | x              | x       |
| 1-hr       | 0.462                 | -0.366                        | 0.51**                            | 0.083                                       | >0.10             | -1.52                      | 0.129                         | 0.851                    | 0.103                         | x                      | x               | x                |                                |                |         |       | x              | x       |
| 2-hr       | 0.614                 | -0.222                        | 0.56**                            | 0.127                                       | 0.085*            | -0.82                      | 0.414                         | 0.529                    | 0.281                         | 2005                   | 2.99*                       | 2.63             |                                |                |         |       | x              | x       |
| 6-hr       | 0.504                 | -0.098                        | 0.61**                            | 0.128                                       | 0.084*            | -0.47                      | 0.656                         | 0.256                    | 0.300                         | 2005                   | 2.95*                       | 2.63             |                                |                |         |       | x              | x       |
| 12-hr      | 0.969                 | -0.238                        | 0.56**                            | 0.065                                       | >0.10             | -1.48                      | 0.138                         | 0.296                    | 0.141                         | x                      | x               | x                |                                |                |         |       | x              | x       |
| 24-hr      | 0.414                 | -0.177                        | 0.58**                            | 0.041                                       | >0.10             | -0.035                     | -0.01                         | 0.972                    | 0.976                         | x                      | x               | x                |                                |                |         |       | x              | x       |
Table S8. Detection of trends and nonstationarity in Kingston P. Station

| Time Slice | Ljung-Box Test | Augmented Dickey-Fuller Test | KPSS Test | Mann-Kendall Trend Test | Priestley-Subbarao Test | Pettitt Test | Mann-Whitney Change Point Test | Mood Change Point Test |
|------------|----------------|-----------------------------|-----------|-------------------------|-------------------------|-------------|-------------------------------|------------------------|
|            | p-value        | Test statistics            | p-value   | p-value                 | β                       | p-value     | p-value | Year Test statistics | Threshold | Year Test statistics | Threshold |
| 15-min     | 0.257          | -0.502                      | 0.46**    | 0.024                   | >0.10                   | 0.63        | 0.2     | 0.53               | 0.040      | -                     | x         | x | x | x | x | x | x | x |
| 30-min     | 0.094          | -0.485                      | 0.47**    | 0.027                   | >0.10                   | 0.18        | 0.12    | 0.85               | 0.322      | -                     | x         | x | x | x | x | x | x | x |
| 1-hr       | 0.371          | -0.316                      | 0.53**    | 0.039                   | >0.10                   | 0.16        | 0.12    | 0.88               | 0.094*     | -                     | x         | x | x | 1996 | 2.73* | 2.6 |
| 2-hr       | 0.124          | -0.306                      | 0.53**    | 0.084                   | >0.10                   | 0.05        | 0.03    | 0.96               | 0.333      | -                     | x         | x | x | x | x | x | x | x |
| 6-hr       | 0.273          | -0.330                      | 0.53**    | 0.168                   | 0.032**                 | -0.22       | -0.36   | 0.83               | 0.0009**   | 0.397                  | x         | x | x | x | x | x | x | x |
| 12-hr      | 0.886          | -0.298                      | 0.54**    | 0.102                   | >0.10                   | 0.56        | 0.39    | 0.58               | 5.53e-6**  | 0.347                  | x         | x | x | x | x | x | x | x |
| 24-hr      | 0.346          | -0.258                      | 0.55**    | 0.131                   | 0.078*                  | 0.68        | 0.75    | 0.50               | 1.06e-5**  | 0.514                  | 1965      | 2.62* | 2.60 | x | x | x | x | x | x | x |
Table S9. Detection of trends and nonstationarity in London International Airport

| Time Slice | Ljung-Box Test p-value | Augmented Dickey-Fuller Test p-value | KPSS Test p-value | Mann-Kendall Trend Test β | Priestley-Subbarao Test MK₂ | Pettitt Test Year | Mann-Whitney Change Point Test Year | Mood Change Point Test Year |
|------------|------------------------|-------------------------------------|------------------|----------------------------|-----------------------------|-------------------|-----------------------------------|---------------------------|
| 15-min     | 0.344                  | -0.662                              | 0.179            | 0.024**                    | -0.549                      | 0.845             | 0.092*                            | 0.253                     | 2006                       | 2.94**                     | 2.63                       | 2006                       | 3.09**                     | 2.66                       |
| 30-min     | 0.288                  | -0.598                              | 0.106            | >0.10                      | -1.422                      | 0.344              | 0.019**                           | 0.240                     | 2005                       | 2.87**                     | 2.63                       | x                          | x                          | 2011                       | 2.96**                     | 2.66                       |
| 1-hr       | 0.783                  | -0.487                              | 0.117            | >0.10                      | -1.173                      | 0.638              | 0.031**                           | 0.359                     | 2011                       | 3.06**                     | 2.63                       | 2011                       | 3.15**                     | 2.66                       |
| 2-hr       | 0.845                  | -0.552                              | 0.135            | 0.070**                    | -1.566                      | 0.492              | 0.024**                           | 0.216                     | 2011                       | 3.14**                     | 2.63                       | 2011                       | 3.15**                     | 2.66                       |
| 6-hr       | 0.700                  | -0.418                              | 0.071            | >0.10                      | -1.893                      | 0.058*             | 0.199                             | 0.161                     | 2011                       | 3.01**                     | 2.63                       | 2011                       | 2.80**                     | 2.66                       |
| 12-hr      | 0.587                  | -0.347                              | 0.090            | >0.10                      | -2.142                      | 0.032**             | 0.755                             | 0.093**                    | 2011                       | 2.98**                     | 2.63                       | x                          | x                          | 2011                       | 2.96**                     | 2.66                       |
| 24-hr      | 0.733                  | -0.414                              | 0.223            | 0.010**                    | -2.297                      | 0.022**             | 0.909                             | 0.024**                    | 2005                       | 3.46**                     | 2.63                       | x                          | x                          | x                          | 3.16**                     | 2.66                       |

Table S10. Detection of trends and nonstationarity in Trenton Airport

| Time Slice | Ljung-Box Test p-value | Augmented Dickey-Fuller Test p-value | KPSS Test p-value | Mann-Kendall Trend Test β | Priestley-Subbarao Test MK₂ | Pettitt Test Year | Mann-Whitney Change Point Test Year | Mood Change Point Test Year |
|------------|------------------------|-------------------------------------|------------------|----------------------------|-----------------------------|-------------------|-----------------------------------|---------------------------|
| 15-min     | 0.263                  | -0.398                              | 0.051            | >0.10                      | 0.708                       | 0.16               | 0.479                             | 0.893                     | x                          | x                          | x                          | 1979                       | 3.66**                     | 2.66                       |
| 30-min     | 0.161                  | -0.325                              | 0.034            | >0.10                      | 1.732                       | 0.68               | 0.083*                            | 0.0033**                  | 0.264                     | x                          | x                          | x                          | 1978                       | 3.16**                     | 2.66                       |
| 1-hr       | 0.373                  | -0.328                              | 0.061            | >0.10                      | 1.776                       | 0.87               | 0.076*                            | 0.0013**                  | 0.098*                    | x                          | x                          | x                          | x                          | x                          | 1979                       | 3.66**                     | 2.66                       |
| 2-hr       | 0.423                  | -0.341                              | 0.063            | >0.10                      | 2.313                       | 1.27               | 0.021**                           | 5.1e**                    | 0.053*                    | 1994                       | 2.81**                     | 2.63                       | x                          | x                          | x                          | 1994                       | 2.66**                     | 2.63                       |
| 6-hr       | 0.638                  | -0.244                              | 0.078            | >0.10                      | 2.031                       | 1.12               | 0.042**                           | 0.005**                   | 0.092*                    | 1994                       | 2.66**                     | 2.63                       | x                          | x                          | x                          | 1994                       | 2.66**                     | 2.63                       |
| 12-hr      | 0.295                  | -0.105                              | 0.204            | 0.014**                    | 2.009                       | 1.64               | 0.045**                           | 0.044**                   | 0.022**                   | 1996                       | 3.25**                     | 2.63                       | x                          | x                          | x                          | 1996                       | 3.37**                     | 2.63                       |
| 24-hr      | 0.321                  | -0.131                              | 0.238            | 0.010**                    | 2.031                       | 1.82               | 0.042**                           | 0.39                      | 0.014**                   | 1994                       | 3.37**                     | 2.63                       | x                          | x                          | x                          | 1994                       | 3.37**                     | 2.63                       |
Table S11. Detection of trends and nonstationarity in Stratford WWTP

| Time Slice | Ljung-Box Test p-value | Test statistics | Augmented Dickey-Fuller Test p-value | Test statistics | KPSS Test p-value | Test statistics | Mann-Kendall Trend Test MKz | β | p-value | Test statistics | Priestley-Subbarao Test p-value | Test statistics | Pettitt Test p-value | Test statistics | Mann-Whitney Change Point Test Year | Test statistics | Threshold | Test statistics | Mood Change Point Test Year | Test statistics | Threshold |
|------------|------------------------|-----------------|--------------------------------------|-----------------|-------------------|-----------------|--------------------------|----|-----------|-----------------|-------------------------------|----------------|-------------------|----------------|--------------------------------|----------------|-----------|----------------|-------------------------------|----------------|-----------|
| 15-min     | 0.070                  | -0.321          | 0.53**                               | 0.068           | >0.10             | -0.233          | -0.07                    | 0.816          | 0.143 | -        | 1994            | 3.37*                        | 2.63           | x                  | x             | x                           | x                  |
| 30-min     | 0.473                  | -0.375          | 0.51**                               | 0.039           | >0.10             | -0.297          | -0.13                    | 0.767          | 0.004** | -       | 2011            | 3.23*                        | 2.63           | x                  | x             | x                           | x                  |
| 1-hr       | 0.857                  | -0.230          | 0.56**                               | 0.077           | >0.10             | 0.417           | 0.26                     | 0.677          | 0.013** | -       | 1967            | 2.73*                        | 2.63           | x                  | x             | x                           | x                  |
| 2-hr       | 0.149                  | -0.263          | 0.55**                               | 0.055           | >0.10             | 0.389           | 0.3                      | 0.697          | 0.016** | -       | x               | x                            | x              | x                  | x             | 1967                          | x                  |
| 6-hr       | 0.375                  | -0.134          | 0.60**                               | 0.062           | >0.10             | -0.459          | -0.51                    | 0.646          | 3.9e-4** | 0.802       | x               | x                            | x              | x                  | x             | x                           | x                  |
| 12-hr      | 0.336                  | -0.186          | 0.58**                               | 0.058           | >0.10             | 0.82            | -0.67                    | 0.412          | 8.9e-5** | 0.254       | x               | x                            | x              | x                  | x             | x                           | x                  |
| 24-hr      | 0.789                  | -0.208          | 0.57**                               | 0.056           | >0.10             | -1.442          | -1.43                    | 0.149          | 8.7e-4** | 0.360       | x               | x                            | x              | x                  | x             | x                           | x                  |
Table S12. Detection of trends and nonstationarity in Fergus Shand Dam

| Time Slice | Ljung-Box Test | Augmented Dickey-Fuller Test | KPSS Test | Mann-Kendall Trend Test | Priestley-Subbarao Test | Pettitt Test | Mann-Whitney Change Point Test | Mood Change Point Test |
|------------|----------------|-------------------------------|-----------|-------------------------|-------------------------|-------------|-------------------------------|----------------------|
|            | p-value | Test statistics | p-value | Test statistics | p-value | Test statistics | p-value | Test statistics | Year | Test statistics | Threshold | Year | Test statistics | Threshold |
| 15-min     | 0.955   | -0.267           | 0.55**  | 0.184                | 0.022**  | 0.049**        | 0.25     | x                     | x     | x                     | x         | x     | x                     | x         |
| 30-min     | 0.935   | -0.204           | 0.57**  | 0.172                | 0.028**  | 0.015**        | 0.33     | x                     | x     | x                     | x         | x     | x                     | x         |
| 1-hr       | 0.879   | -0.494           | 0.47**  | 0.068                | >0.10    | -1.00          | 0.317    | 0.004**              | 0.57   | x                     | x         | x     | x                     | x         |
| 2-hr       | 0.849   | -0.540           | 0.45**  | 0.055                | >0.10    | -0.92          | -0.69    | 0.358               | 0.002** | 0.67                  | x         | x     | x                     | x         |
| 6-hr       | 0.967   | -0.318           | 0.53**  | 0.104                | >0.10    | -0.26          | -0.29    | 0.795               | 0.053** | 0.77                  | x         | x     | x                     | x         |
| 12-hr      | 0.018** (0.033**) | -0.116             | 0.61**  | 0.035                | >0.10    | -0.45          | -0.28    | 0.652               | 0.255  | -                     | x         | x     | x                     | x         |
| 24-hr      | 1.5e-4** (0.011**) | -0.218             | 0.57**  | 0.035                | >0.10    | -1.34          | -1.2     | 0.180               | 0.216  | 0.53                  | x         | x     | x                     | x         |

1Values within first Brackets indicate p-values of Ljung-Box Test after performing two-successive TFPWs.
SI 3 GEV Fitting: Methods and Results

SI 3.1 Estimation of GEV Parameters

GEV parameters are estimated using Bayesian Inference. For this, a Bayesian analysis is performed by imposing a prior distribution on the parameters. We estimated parameters using Bayesian Inference (BI) coupled with Differential Evaluation Markov Chain (DE-MC) simulation as in (Cheng and AghaKouchak, 2014; Cheng et al., 2014). This approach combines knowledge from a prior distribution and the observation vector \( y = \{ y_t \}_{t=1}^N \) (i.e., annual maxima rainfall, where \( N \) denotes the number of annual maxima in the observation vector \( Y \)) into the posterior distribution of parameters \( \omega = \{ \mu, \sigma, \zeta \} \) and \( \lambda = \{ \mu_1, \mu_0, \sigma_1, \sigma_0, \zeta \} \) assuming stationary and nonstationary conditions respectively. The priors for the location and scale parameters are non-informative normal distributions, whereas prior for the shape parameter is a normal distribution with a standard deviation of 0.3 (Renard et al., 2013) as used in the default option in the NEVA package. The Bayes theorem for estimation of GEV parameters under stationarity assumption can be expressed as (Cheng et al., 2014; Renard et al., 2013)

\[
p(\omega|y) \propto p(y|\omega)p(\omega) = \prod_{t=1}^N p(y_t|\omega)p(\omega) \quad (3.1)
\]

Under the assumption of nonstationarity, the equation (3.1) is given as (Cheng et al., 2014; Renard et al., 2013),

\[
p(\lambda|y,x) \propto p(y|\lambda,x)p(\lambda|x) \quad (3.2)
\]

\[
p(y|\lambda,x) = \prod_{t=1}^N p(y_t|\lambda,x(t)) = \prod_{t=1}^N p(y_t|\mu(t),\sigma(t),\zeta) \quad (3.3)
\]

Where, \( x(t) \) denote covariates under nonstationarity. The \( p(\omega|y) \) and \( p(\lambda|y,x) \) in Eqns. 3.1 and 3.2 indicate resulting posterior distributions whereas \( p(y|\omega) \) and \( p(y_t|\lambda,x(t)) \) denote likelihood functions.

Since the posterior distributions of model parameters are, in general, analytically intractable, the DE-MC is integrated with BI to generate a large number of realizations (Cheng et al., 2014). DE-MC is an adaptive Monte Carlo Markov Chain (MCMC) algorithm (Ter Braak and Vrugt, 2008; Ter Braak, 2006), in which multiple chains (here, we fix chain length \('n'\) as 5) are run in parallel. The resulting MC simulations are then run to an equilibrium. It is a standard practice to discard the initial iterations (often referred to as the \textit{burn-in} period) of simulated samples since they are strongly influenced by starting values and do not provide usable information of the target distribution. Here we run DE-MC simulations for 3000 iterations and kept the 2001-3000\textsuperscript{th} iterations of each chain. The convergence of MC simulation is checked by the “potential scale reduction
factor \( \hat{R} \) as in (Gelman et al., 2011), which suggests the value of \( \hat{R} \) should remain below the threshold value of 1.1. The post burn-in random draws from posterior distribution are then used to construct predictive distributions. For annual maxima time series of each duration, the mean and associated 95% credibility interval of parameters \((\mu(t), \sigma(t))\) are derived by computing 50th (the median), 2.5th and 97.5th (bounds) percentiles of post burn-in random draw (for example, 50th percentile of \(\mu(t_1), \ldots, \mu(t_{100})\)). The derived model parameters are then used to compute corresponding design rainfall quantiles at \(T\)-year return period. For more details of BI and parameter estimation by DE-MC simulation, interested readers are requested to refer (Gelman et al., 2014; Renard et al., 2013).

SI 3.2 Model Selection

SI 3.2.1 Bayes Factor

To evaluate the fit of the stationary model (null model, \(M_1\)) relative to the nonstationary model (alternative model, \(M_2\)) Bayes factor is computed based on the posterior distributions of sampled parameters, which is given as (Cheng et al., 2014)

\[
\gamma = \frac{\Pr(\mathbf{X} | M_1)}{\Pr(\mathbf{X} | M_2)} = \frac{\int \Pr(\mathbf{X} | M_1) \Pr(\omega | M_1) d\omega}{\int \Pr(\mathbf{X} | M_2) \Pr(\lambda | M_2) d\lambda}
\]

(3.4)

Where \(\mathbf{X}\) denotes input data, \(\omega\) and \(\lambda\) denote model parameters as described in the previous section. The term \(\Pr(\mathbf{X} | M)\) can be expressed using Monte Carlo integration estimation as described in (Kass and Raftery, 1995). A value of \(\gamma < 1\) indicates nonstationary model, the nonstationary model, \(M_2\) fits the data better than the stationary model, \(M_1\).

SI 3.2.2 Akaike Information Criterion (AIC) for Small Samples

The AIC (Anderson et al., 1994; Bozdogan, 2000) is defined as follows:

\[
AIC(m) = n \log(MSE) + 2m
\]

(3.5)

Where \(n\) is the number of observations, \(m\) denotes the number of fitted model parameters. \(MSE\) is the Mean Square Error of the fitted distribution against empirical distribution, which is expressed as (Dawson et al., 2007; Hu, 2007; Karmakar and Simonovic, 2007, 2007),

\[
MSE = \frac{1}{n-m} \sum_{i=1}^{n} (O_i - F_i)^2
\]

(3.6)
Where $O_i$ and $F_i$ are empirical (observed) and estimated distributions. The observed distribution ($O_X$) is computed using rank-based Gringorten’s plotting position formula (Yue, 2001)

$$O_X(X \leq x_i) = \frac{i - 0.44}{n + 0.12} \quad \forall i = 1, 2, \ldots, n \quad (3.7)$$

Where, $i$ is the rank in ascending order and $x_i$ is the $i^{th}$ largest variate in a data series of size $n$.

The AIC for small sample sizes ($n/m < 40$) is given by (Hurvich and Tsai, 1995),

$$AIC_c(m) = AIC + \frac{2m(m+1)}{n-m-1} \quad (3.8)$$

As sample size increases, the last term of the second-order AIC statistics ($AIC_c$) approaches zero, and the AICc tends to give the same conclusion as the traditional AIC (Burnham and Anderson, 2003). Since in the present study, length of data series varies from 46 to 66 years, we used AICc instead of traditional AIC, which is also a widely used method for model selection in hydrology (Caroni and Panagoulia, 2016; Gu et al., 2017; Panagoulia et al., 2014).
Table S13. Performance of stationary and nonstationary models for Oshawa WPCP

| Time Slice | Model  | Location parameter | Scale parameter | Shape parameter | AICc | Bayes-factor | LB (100yr) | UB (100yr) | UB/LB |
|------------|--------|--------------------|-----------------|----------------|------|--------------|------------|------------|-------|
| 15-min     | GEV_t0 | 48.33              | 15.71           | -0.075         | -332.55 | -            | 81.65      | 156.01     | 1.91  |
|            | GEV_t1 | 47.22+0.095t       | 17.95           | -0.202         | -304.31 | -3773.89     | 86.91      | 134.98     | 1.55  |
|            | GEV_t2 | 51.03-0.074t       | exp(3.06-0.007t)| -0.108         | -290.55 | 5.44         | 91.48      | 156.69     | 1.71  |
| 30-min     | GEV_t0 | 31.67              | 11.21           | -0.21          | -306.10 | -            | 47.64      | 107.8      | 2.26  |
|            | GEV_t1 | 27.66+0.135t       | 10.73           | -0.098         | -287.17 | 0.15         | 51.74      | 74.03      | 1.43  |
|            | GEV_t2 | 28.55+0.104t       | exp(2.47-0.005t)| -0.155         | -279.13 | 2.13         | 51.03      | 94.42      | 1.85  |
| 1-hr       | GEV_t0 | 18.10              | 7.33            | -0.03          | -317.73 | -            | 31.82      | 104.55     | 3.28  |
|            | GEV_t1 | 16.62+0.082t       | 7.28            | -0.05          | -320.87 | 0.47         | 39.59      | 59.46      | 1.50  |
|            | GEV_t2 | 16.44+0.07t        | exp(1.97-0.002t)| -0.002         | -319.36 | 0.42         | 38.23      | 77.35      | 2.02  |
| 2-hr       | GEV_t0 | 11.09              | 3.81            | 0.13           | -333.15 | -            | 21.21      | 73.71      | 3.47  |
|            | GEV_t1 | 10.04+0.05t        | 3.72            | 0.095          | -316.87 | 0.16         | 23.03      | 48.89      | 2.12  |
|            | GEV_t2 | 9.61+0.07t         | exp(1.41-0.0034t)| 0.007         | -304.53 | 0.54         | 24.97      | 47.67      | 1.91  |
| 6-hr       | GEV_t0 | 5.02               | 1.42            | 0.094          | -315.85 | -            | 9.49       | 22.66      | 2.39  |
|            | GEV_t1 | 4.5+0.02t          | 1.44            | 0.062          | -302.12 | 0.51         | 10.8       | 15.46      | 1.43  |
|            | GEV_t2 | 4.6+0.02t          | exp(0.52-0.004t)| 0.032          | -291.60 | 0.67         | 10.34      | 15.94      | 1.54  |
| 12-hr      | GEV_t0 | 2.83               | 0.78            | 0.28           | -310.34 | -            | 6.36       | 20.48      | 3.22  |
|            | GEV_t1 | 2.65+0.0073t       | 0.78            | 0.36           | -319.6  | 0.46         | 9.3        | 15.85      | 1.70  |
|            | GEV_t2 | 2.68+0.0092t       | exp(-0.24+0.0017t)| 0.29         | -304.38 | 3.83         | 8.2        | 14.16      | 1.72  |
| 24-hr      | GEV_t0 | 1.65               | 0.51            | 0.17           | -318.65 | -            | 3.3        | 10.1       | 3.06  |
|            | GEV_t1 | 1.51+0.0056t       | 0.50            | 0.17           | -316.24 | 0.46         | 3.8        | 7.63       | 2.00  |
|            | GEV_t2 | 1.51+0.0072t       | exp(-0.68+0.00135t)| 0.14         | -305.97 | 1.98         | 3.94       | 7.18       | 1.82  |

*GEV_t0 is stationary model whereas GEV_t1 and GEV_t2 are nonstationary models with time-variant mean, and both time-variant mean and standard deviation respectively. The selected best fitted nonstationary model is marked in bold letters. Bayes factor, $\gamma < 1$ indicates that the nonstationary model fits better than the stationary model. However, in cases $\gamma > 1$, to compare with stationary model, the nonstationary model is selected following minimum AICc criteria. LB and UB indicate lower and upper bounds of DSI at 100-year return period.
| Time Slice | Model      | Location parameter | Scale parameter | Shape parameter | AICc       | Bayes-factor | LB (100yr) | UB (100yr) | UB/LB |
|------------|------------|--------------------|-----------------|-----------------|------------|--------------|------------|------------|-------|
| 15-min     | GEV_t-0    | 44.59              | 12.70           | -0.04           | -315.08    | -            | 76         | 140.88     | 1.85  |
|            | GEV_t-I    | 41.36+0.13t        | 12.83           | -0.04           | -311.53    | 1.93         | 85.2       | 118.76     | 1.40  |
|            | GEV_t-II   | 40.83+0.19t        | exp(2.92-0.013t) | -0.07           | **-317.65** | 5.19         | 78.8       | 142.36     | 1.81  |
| 30-min     | GEV_t-0    | 28.40              | 9.04            | -0.05           | -345.71    | -            | 48.1       | 97.36      | 2.02  |
|            | GEV_t-I    | 27.61+0.042t       | 9.01            | -0.04           | **-348.92** | 0.91         | 53.41      | 98.27      | 1.84  |
|            | GEV_t-II   | 27.57+0.035t       | exp(2.11+0.0026t) | -0.07           | -331.17    | 37.31        | 53.12      | 73.41      | 1.38  |
| 1-hr       | GEV_t-0    | 18.35              | 5.87            | -0.11           | -318.56    | -            | 29.45      | 56.19      | 1.91  |
|            | GEV_t-I    | 18.4+0.008t        | 6.02            | -0.12           | **-326.50** | 3.76         | 31.21      | 61.45      | 1.97  |
|            | GEV_t-II   | 16.77+0.046t       | exp(1.84-0.0059t) | 0.02           | -291.35    | 1.84         | 37.8       | 52.93      | 1.40  |
| 2-hr       | GEV_t-0    | 11.32              | 3.16            | 0.06            | -300.11    | -            | 19.36      | 49.78      | 2.57  |
|            | GEV_t-I    | 11.09+0.009t       | 3.19            | 0.05            | -321.46    | 1.27         | 23.74      | 33.6       | 1.41  |
|            | GEV_t-II   | 11.12+0.0055t      | exp(1.10+0.0004t) | 0.15           | **-325.34** | 4.47         | 22.89      | 46.26      | 2.02  |
| 6-hr       | GEV_t-0    | 5.21               | 1.44            | 0.10            | -327.18    | -            | 10.1       | 23.64      | 2.34  |
|            | GEV_t-I    | 5.07+0.0073t       | 1.41            | 0.13            | **-329.47** | 0.23         | 11.17      | 17.79      | 1.59  |
|            | GEV_t-II   | 4.88+0.0093t       | exp(0.38-0.00335t) | 0.21           | -326.79    | 0.77         | 12.91      | 19.57      | 1.51  |
| 12-hr      | GEV_t-0    | 3.13               | 0.83            | 0.11            | -312.19    | -            | 6.09       | 13.04      | 2.14  |
|            | GEV_t-I    | 2.85+0.009t        | 0.78            | 0.14            | **-321.61** | 0.57         | 6.36       | 10.59      | 1.66  |
|            | GEV_t-II   | 2.84+0.009t        | exp(-0.126-0.006t) | 0.14           | -317.09    | 0.16         | 6.78       | 9.5        | 1.40  |
| 24-hr      | GEV_t-0    | 1.77               | 0.46            | 0.07            | -297.12    | -            | 3.18       | 6.43       | 2.02  |
|            | GEV_t-I    | 1.59+0.0071t       | 0.44            | 0.08            | **-299.78** | 0.54         | 6.36       | 10.59      | 1.66  |
|            | GEV_t-II   | 1.64+0.005t        | exp(-0.81-0.0006t) | 0.07           | -296.75    | 0.97         | 3.42       | 5.57       | 1.63  |
Table S15. Performance of stationary and nonstationary models for Trenton Airport

| Time Slice | Model       | Location parameter | Scale parameter | Shape parameter | AICc  | Bayes-factor | LB (100yr) | UB (100yr) | UB/LB |
|------------|-------------|--------------------|-----------------|----------------|-------|--------------|-------------|-------------|-------|
| 15-min     | GEVt-0      | 43.08              | 12.41           | 0.24           | -485.30 | -            | 95.12       | 250.55      | 2.63  |
|            | GEVt-I      | 43.96-0.05t        | 11.87           | 0.19           | -474.35 | 4.18         | 98.79       | 173.25      | 1.75  |
|            | GEVt-II     | 40.37+0.16t        | exp(1.65+0.04t) | -0.20          | -472.29 | 7075420      | 86.12       | 120.33      | 1.40  |
| 30-min     | GEVt-0      | 26.94              | 8.50            | 0.13           | -495.06 | -            | 55.05       | 133.25      | 2.42  |
|            | GEVt-I      | 26.71+0.014t       | 8.28            | 0.09           | -477.87 | 13.50        | 55.16       | 111.31      | 2.02  |
|            | GEVt-II     | 22.39+0.16t        | exp(2.34+0.0024)| -0.07          | -418.98 | 77.76        | 56.23       | 96.9        | 1.72  |
| 1-hr       | GEVt-0      | 16.25              | 5.022           | 0.15           | -448.76 | -            | 34.7        | 88.1        | 2.54  |
|            | GEVt-I      | 15.40 + 0.032t     | 5.44            | 0.17           | -476.72 | 0.73         | 39.3        | 73.74       | 1.88  |
|            | GEVt-II     | 14.62+0.057t       | exp(1.31+0.010) | 0.13           | -463.04 | 0.06         | 37.0        | 81.02       | 2.19  |
| 2-hr       | GEVt-0      | 10.13              | 3.32            | 0.17           | -524.45 | -            | 21.72       | 59.53       | 2.74  |
|            | GEVt-I      | 9.03 + 0.03t       | 3.38            | 0.09           | -481.72 | 0.99         | 20.46       | 51.05       | 2.49  |
|            | GEVt-II     | 8.63 + 0.05t       | exp(1.02 + 0.007t) | 0.09           | -493.82 | 0.16         | 24.76       | 36.64       | 1.48  |
| 6-hr       | GEVt-0      | 5.100              | 1.31            | 0.14           | -419.26 | -            | 10.24       | 22.05       | 2.15  |
|            | GEVt-I      | 4.72 + 0.0124t     | 1.37            | 0.16           | -429.78 | 1.83         | 12.56       | 17.14       | 1.36  |
|            | GEVt-II     | 4.75 + 0.014t      | exp(0.33+0.0012t) | 0.15           | -415.55 | 1.11         | 12.65       | 17.03       | 1.35  |
| 12-hr      | GEVt-0      | 3.19               | 0.94            | 0.14           | -480.19 | -            | 6.09        | 14.86       | 2.44  |
|            | GEVt-I      | 2.85 + 0.0114t     | 0.87            | 0.09           | -491.15 | 0.93         | 6.74        | 10.26       | 1.52  |
|            | GEVt-II     | 2.84 + 0.0113t     | exp(-0.16+0.0014t) | 0.15           | -488.52 | 0.15         | 7.95        | 10.58       | 1.33  |
| 24-hr      | GEVt-0      | 1.90               | 0.52            | -0.04          | -499.41 | -            | 3.38        | 4.99        | 1.48  |
|            | GEVt-I      | 1.51 + 0.011t      | 0.50            | 0.02           | -467.34 | 0.26         | 3.19        | 5.84        | 1.83  |
|            | GEVt-II     | 1.57 + 0.0096t     | exp(-0.80 + 0.0033t) | -0.02          | -475.74 | 0.14         | 3.38        | 4.99        | 1.48  |
Table S16. Performance of stationary and nonstationary models for Stratford WWTP

| Time Slice | Model   | Location parameter | Scale parameter | Shape parameter | AICc  | Bayes-factor | LB (100yr) | UB (100yr) | UB/LB |
|------------|---------|--------------------|-----------------|-----------------|-------|-------------|------------|------------|-------|
| 15-min     | GEVt-0  | 56.30              | 15.70           | 0.04            | -423.32 | -           | 100.59     | 216.41     | 2.15  |
|            | GEVt-I  | 57.31-0.05t        | 15.06           | 0.18            | -414.85 | 5.26        | 105.08     | 144.59     | 1.38  |
|            | GEVt-II | 60.72-0.13t        | exp(3.04-0.009t) | 0.12            | -384.65 | 54.70       | 134.37     | 184.4      | 1.37  |
| 30-min     | GEVt-0  | 33.83              | 10.81           | 0.17            | -413.45 | -           | 73.35      | 205.5      | 2.80  |
|            | GEVt-I  | 34.76-0.023t       | 11.16           | 0.28            | -419.35 | 6.24        | 110.13     | 177.76     | 1.61  |
|            | GEVt-II | 38.75-0.164t       | exp(2.97-0.015t) | 0.45            | -314.14 | 68.72       | 311.05     | 163.32     | 1.90  |
| 1-hr       | GEVt-0  | 19.03              | 6.31            | 0.21            | -388.39 | -           | 44.6       | 149.69     | 3.36  |
|            | GEVt-I  | 18.62-0.0045t      | 6.42            | 0.36            | -398.93 | 3.93        | 74.66      | 125.4      | 1.68  |
|            | GEVt-II | 17.43+0.0552t      | exp(1.5+0.0125t)| 0.17            | -372.02 | 2.79        | 49.84      | 84.84      | 1.70  |
| 2-hr       | GEVt-0  | 11.71              | 4.37            | 0.26            | -390.44 | -           | 28.84      | 118.37     | 4.10  |
|            | GEVt-I  | 11.49-0.023t       | 4.99            | 0.34            | -371.43 | 3.77        | 33.97      | 158.15     | 4.65  |
|            | GEVt-II | 11.82-0.027t       | exp(1.70-0.008t)| 0.53            | -342.82 | 3.35        | 70.43      | 147.35     | 2.09  |
| 6-hr       | GEVt-0  | 5.32               | 1.80            | 0.24            | -400.01 | -           | 13.34      | 38.24      | 2.87  |
|            | GEVt-I  | 5.76-0.012t        | 1.78            | 0.21            | -392.41 | 3.97        | 13.2       | 31.6       | 2.40  |
|            | GEVt-II | 5.52-0.007t        | exp(0.59+0.0002t)| 0.28            | -400.2 | 29.5        | 18.2       | 28.63      | 1.57  |
| 12-hr      | GEVt-0  | 3.11               | 0.89            | 0.26            | -365.66 | -           | 7.45       | 19.5       | 2.62  |
|            | GEVt-I  | 3.38-0.01t         | 0.89            | 0.34            | -377.72 | 0.96        | 9.75       | 17.42      | 1.79  |
|            | GEVt-II | 3.44-0.0097t       | exp(-0.11-6e^5t)| 0.29            | -367.39 | 0.25        | 9.88       | 14.77      | 1.50  |
| 24-hr      | GEVt-0  | 1.68               | 0.45            | 0.26            | -376.96 | -           | 3.75       | 9.93       | 2.65  |
|            | GEVt-I  | 1.77-0.004t        | 0.45            | 0.29            | -377.32 | 0.71        | 9.75       | 17.42      | 1.79  |
|            | GEVt-II | 1.82-0.005t        | exp(-0.80-0.0008t)| 0.30            | -378.44 | 0.41        | 4.56       | 8.69       | 1.90  |
| Time Slice | Model | Location parameter | Scale parameter | Shape parameter | AICc | Bayes-factor | LB (100yr) | UB (100yr) | UB/LB |
|------------|-------|--------------------|-----------------|----------------|------|--------------|------------|------------|-------|
| 15-min     | GEV_t-0 | 54.92              | 15.4            | 0.13           | -538.02 | -            | 116.76     | 224.08     | 1.92  |
|            | GEV_t-I | 61.55-0.09t        | 20.77           | 0.047          | -516.45 | 3.40         | 119.9      | 255.47     | 2.13  |
|            | GEV_t-II| 65.49-0.19t        | exp(2.99-0.00064t) | 0.03          | -529.81 | 1.22         | 117.27     | 230.15     | 1.96  |
| 30-min     | GEV_t-0 | 37.63              | 13.2            | 0.11           | -469.76 | -            | 86.68      | 185.36     | 2.14  |
|            | GEV_t-I | 38.27-0.024t       | 13.6            | 0.11           | -462.14 | 2.98         | 85.51      | 200.77     | 2.35  |
|            | GEV_t-II| 34.08+0.074t       | exp(2.12+0.0115t) | 0.14          | -444.82 | 105.23       | 93.66      | 150.24     | 1.60  |
| 1-hr       | GEV_t-0 | 22.10              | 8.57            | 0.16           | -532.24 | -            | 52.91      | 137.9      | 2.61  |
|            | GEV_t-I | 25.35-0.096t       | 8.58            | 0.17           | -526.26 | 0.12         | 60.42      | 115.43     | 1.91  |
|            | GEV_t-II| 19.54+0.04t        | exp(1.59+0.013t) | 0.28          | -476.74 | 11.4         | 74.7       | 112.48     | 1.50  |
| 2-hr       | GEV_t-0 | 12.54              | 5.26            | 0.12           | -542.06 | -            | 30.02      | 76.43      | 2.55  |
|            | GEV_t-I | 13.75-0.049t       | 5.02            | 0.23           | -487.49 | 1.17         | 41.93      | 69.76      | 1.66  |
|            | GEV_t-II| 12.89-0.026t       | exp(1.64-0.00013t) | 0.32        | -462.93 | 1.95         | 49.89      | 89.83      | 1.80  |
| 6-hr       | GEV_t-0 | 5.34               | 2.31            | 0.055          | -558.5  | -            | 12.11      | 28.94      | 2.39  |
|            | GEV_t-I | 5.30-0.0026t       | 2.35            | 0.064          | -537.24 | 1.35         | 14.66      | 21.69      | 1.48  |
|            | GEV_t-II| 5.15+0.0011t       | exp(0.88-0.00035t) | 0.046       | -524.53 | 1.25         | 14.86      | 20.51      | 1.38  |
Figure S9. The performance of stationary (Blue) versus nonstationary (Orange - nonstationary with time variant mean; red - nonstationary with time variant mean and standard deviation) GEV models with durations ranging between 15-minute and 24-hour (a-g) in nine urbanized sites. Sites with double circles indicate either better or comparable performance of stationary model relative to the nonstationary model. The shades denote the type of distribution.
Figure S10. PP plots of nonstationary versus stationary GEV distributions for 30-min storm duration in nine sites (a - i)
Figure S11. *PP* plots of nonstationary versus stationary GEV distributions for 1-hour storm duration in nine sites (a - i).
Figure S12. PP plots of nonstationary versus stationary GEV distributions for 6-hour duration in nine sites (a - i)
4 Estimation of Design Storm Intensity (DSI)

The DSI $q_p$, often referred as return level in the literature is the value which is expected to be exceeded on an average once in every $\frac{1}{p}$ periods, where $1 - p$ is the specific probability associated with the quantile (Gilleland and Katz, 2014). We obtain the $1 - p$ (i.e., non-exceedance probability of occurrence) quantile of the annual maximum rainfall fitted with stationary GEV distribution using following expression (Coles and Tawn, 1996):

$$q_p = \mu + \frac{\sigma}{\xi} \left( -\ln (1 - p) \right)^{-\frac{1}{\xi}} - 1 \quad \forall \xi \neq 0 \tag{4.1}$$

Where, $q_p$ is the DSI, associated with a $T = \frac{1}{1 - p}$ - year return period. The nonstationary design intensity is analogous to the standard stationary precipitation intensity with the exception of inclusion of time variant parameters (Cheng et al., 2014)

$$q_p = \bar{\mu} + \frac{\bar{\sigma}}{\xi} \left( -\ln (1 - p) \right)^{-\frac{1}{\xi}} - 1 \quad \forall \xi \neq 0 \tag{4.2}$$

Where time-variant parameters, $\bar{\mu}$ and $\bar{\sigma}$ are derived by computing 0.50, 0.025 and 0.975 quantiles of DE-MC sampled $\mu(t)$ and $\sigma(t)$ $\{\mu(t_1), ..., \mu(t_n)\}$ and $\{\sigma(t_1), ..., \sigma(t_n)\}$ respectively. In Eq. 4.1, when $\xi \rightarrow 0$, the GEV distribution reduces to Gumbel distribution (or Extreme Value Type I). It should be noted that Gumbel Extreme value distribution has been commonly used to estimate design storm by Environment Canada (CSA, 2010). The Gumbel probability distribution has following form (Wang et al., 2015)

$$q_p = \mu + K_p \sigma \tag{4.3}$$

Where $K_p$ denotes frequency factor depending on the return period $T$, which is obtained using following relationship (Wang et al., 2015)

$$K_p = \frac{-\sqrt{6}}{\pi} \left[ 0.5772 + \ln \left( \ln \left( \frac{T}{T-1} \right) \right) \right] \tag{4.4}$$

Environment Canada uses this method to estimate rainfall frequency at a given duration and obtain nationwide IDF curves.
Figure S13. Uncertainty in DSI for 10-year return periods for stationary (blue) versus nonstationary (red) models. The boxplots indicate 95% credibility interval in DSI estimate.
Figure S14. Same as Figure S13 but for 5-year return period.
More than 10% increase is marked in bold italics. Results within brackets indicate percentage changes between updated versus EC-generated DSI. More than 1% increase in DSI is shown in bold, whereas 10% or more is marked with bold italic letters.

### Table S18.1 Ratio and percentage changes between updated nonstationary versus EC-generated DSI for Toronto International Airport for different durations

| Duration | 2-year | 5-year | 10-year | 25-year | 50-year | 100-year |
|----------|--------|--------|---------|---------|--------|---------|
| 15-min   | 0.72   | 0.84   | 0.91    | 0.99    | 1.05   | 1.12    |
|          | [-38.6%] | [-19.1%] | [-10.0%] | [-0.8%] | [5.1%] | [10.4%] |
| 30-min   | 0.75   | 0.80   | 0.81    | 0.82    | 0.82   | 0.82    |
|          | [-33.2%] | [-25.1%] | [-22.9%] | [-21.7%] | [-21.6%] | [-21.8%] |
| 1-hour   | 0.94   | 0.93   | 0.92    | 0.90    | 0.88   | 0.86    |
|          | [-6.7%] | [-7.3%] | [-8.9%] | [-11.7%] | [-14.1%] | [-16.7%] |
| 2-hour   | 0.97   | 0.93   | 0.91    | 0.90    | 0.89   | 0.88    |
|          | [-3.3%] | [-7.5%] | [-9.4%] | [-11.3%] | [-12.6%] | [-13.7%] |
| 6-hour   | 0.96   | 0.92   | 0.94    | 0.99    | 1.05   | 1.13    |
|          | [-4.4%] | [-9.17%] | [-6.8%] | [-0.7%] | [5.2%] | [11.7%] |
| 12-hour  | 0.94   | 0.94   | 1.03    | 1.23    | 1.47   | 1.80    |
|          | [-6.4%] | [-6.7%] | [2.5%] | [18.9%] | [32.2%] | [44.5%] |
| 24-hour  | 0.94   | 0.89   | 0.90    | 0.96    | 1.03   | 1.11    |
|          | [-5.9%] | [-12.1%] | [-10.7%] | [-4.18%] | [2.8%] | [10.1%] |

*Results within brackets indicate percentage changes between updated versus EC-generated DSI. More than 1% increase in DSI is shown in bold, whereas 10% or more is marked with bold italic letters.

### Table S18.2 Ratio and percentage changes between updated stationary versus EC-generated DSI for Toronto International Airport for different durations

| Duration | 2-year | 5-year | 10-year | 25-year | 50-year | 100-year |
|----------|--------|--------|---------|---------|--------|---------|
| 15-min   | 0.73   | 0.80   | 0.82    | 0.83    | 0.83   | 0.83    |
|          | [-37.7%] | [-25.3%] | [-22.1%] | [-20.6%] | [-20.5%] | [-25.6%] |
| 30-min   | 0.76   | 0.83   | 0.86    | 0.89    | 0.91   | 0.93    |
|          | [-32.3%] | [-21.0%] | [-16.5%] | [-12.4%] | [-10.0%] | [-8.08%] |
| 1-hour   | 0.97   | 0.97   | 0.98    | 1.01    | 1.03   | 1.05    |
|          | [-2.9%] | [-2.9%] | [-1.7%] | [0.6%] | [2.5%] | [4.6%] |
| 2-hour   | 0.98   | 0.96   | 0.97    | 0.99    | 1.02   | 1.05    |
|          | [-1.6%] | [-4.35%] | [-3.4%] | [-0.7%] | [1.9%] | [4.9%] |
| 6-hour   | 0.93   | 0.89   | 0.91    | 0.98    | 1.05   | 1.13    |
|          | [-7.7%] | [-12.6%] | [-9.7%] | [-2.4%] | [4.4%] | [11.8%] |
| 12-hour  | 0.93   | 0.88   | 0.91    | 1.0     | 1.1    | 1.25    |
|          | [-8.0%] | [-13.5%] | [-9.8%] | [0.3%] | [9.8%] | [19.9%] |
| 24-hour  | 0.94   | 0.90   | 0.91    | 0.98    | 1.06   | 1.15    |
|          | [-5.9%] | [-11.6%] | [-9.6%] | [-2.3%] | [5.3%] | [13.2%] |

*More than 10% increase is marked in bold italics.
Table S19.1 Ratio and percentage changes between updated nonstationary versus EC-generated DSI for Hamilton Airport for different durations

| Duration | 2-year | 5-year | 10-year | 25-year | 50-year | 100-year |
|----------|--------|--------|---------|---------|---------|----------|
| 15-min   | 0.96   | 0.93   | 0.94    | 0.97    | 1.0     | 1.03     |
|          | [-4.7%]| [-7.1%]| [-6.1%]| [-3.2%]| [-0.3%]| [3.1%]   |
| 30-min   | 0.71   | 0.72   | 0.75    | 0.80    | 0.86    | 0.94     |
|          | [-40.1%]| [-39.5%]| [-34.2%]| [-24.3%]| [-15.7%]| [-6.7%] |
| 1-hour   | 0.98   | 0.93   | 0.91    | 0.90    | 0.90    | 0.90     |
|          | [-2.1%]| [-7.8%]| [-9.7%]| [-10.9%]| [-11.2%]| [-11.2%]|
| 2-hour   | 0.94   | 0.89   | 0.90    | 0.93    | 0.97    | 1.02     |
|          | [-6.1%]| [-12.3%]| [-11.7%]| [-7.8%]| [-3.5%]| [1.5%]   |
| 6-hour   | 0.90   | 0.85   | 0.87    | 0.93    | 1.0     | 1.09     |
|          | [-11.6%]| [-17.7%]| [-15.2%]| [-7.8%]| [-0.3%]| [7.9%]   |
| 12-hour  | 0.91   | 0.88   | 0.89    | 0.94    | 0.99    | 1.06     |
|          | [-9.2%]| [-13.8%]| [-6.5%]| [-0.76%]| [-12.07%]| [5.59%] |
| 24-hour  | 0.75   | 0.80   | 0.84    | 0.92    | 0.99    | 1.07     |
|          | [-32.9%]| [-25.8%]| [-19.0%]| [-8.9%]| [-1.1%]| [6.5%]   |

Table S19.2 Ratio and percentage changes between updated stationary versus EC-generated DSI for Hamilton Airport for different durations

| Duration | 2-year | 5-year | 10-year | 25-year | 50-year | 100-year |
|----------|--------|--------|---------|---------|---------|----------|
| 15-min   | 0.98   | 0.97   | 0.99    | 1.02    | 1.05    | 1.08     |
|          | [-1.7%]| [-2.8%]| [-1.5%]| [1.6%]| [4.5%]| [7.7%]   |
| 30-min   | 0.72   | 0.72   | 0.75    | 0.79    | 0.83    | 0.61     |
|          | [-38.5%]| [-38.3%]| [-34.2%]| [-26.5%]| [-19.8%]| [-63.9%]|
| 1-hour   | 0.96   | 0.92   | 0.91    | 0.93    | 0.95    | 0.98     |
|          | [-3.7%]| [-9.2%]| [-9.5%]| [-7.6%]| [-5.2%]| [-2.1%] |
| 2-hour   | 0.94   | 0.87   | 0.85    | 0.85    | 0.86    | 0.87     |
|          | [-6.4%]| [-15.4%]| [-17.5%]| [-17.5%]| [-16.3%]| [-14.4%]|
| 6-hour   | 0.91   | 0.86   | 0.86    | 0.91    | 0.96    | 1.02     |
|          | [-10.1%]| [-16.8%]| [-15.6%]| [-10.4%]| [-4.7%]| [1.7%]   |
| 12-hour  | 0.92   | 0.87   | 0.87    | 0.90    | 0.94    | 0.99     |
|          | [-8.5%]| [-14.5%]| [-14.2%]| [-10.4%]| [-6.3%]| [-1.3%] |
| 24-hour  | 0.76   | 0.79   | 0.83    | 0.88    | 0.93    | 0.99     |
|          | [-31.3%]| [-26.3%]| [-21.1%]| [-13.3%]| [-7.2%]| [-1.2%] |
### Table S20.1 Ratio and percentage changes between updated nonstationary versus EC-generated DSI for Oshawa WPCP for different durations

| Duration  | 2-year | 5-year | 10-year | 25-year | 50-year | 100-year |
|-----------|--------|--------|---------|---------|---------|----------|
| 15-min    | 1.09   | 1.08   | 1.06    | 1.01    | 0.97    | 0.94     |
|           | [7.8%] | [7.6%] | [5.3%]  | [1.06%] | [-2.7%] | [-6.8%]  |
| 30-min    | 1.09   | 1.05   | 1.0     | 0.93    | 0.88    | 0.83     |
|           | [8.7%] | [4.83%]| [0.1%]  | [-7.4%] | [-13.6%]| [-20.3%]|
| 1-hour    | 1.05   | 1.07   | 1.07    | 1.06    | 1.05    | 1.04     |
|           | [4.3%] | [6.4%] | [6.5%]  | [5.9%]  | [5.1%]  | [4.2%]   |
| 2-hour    | 1.0    | 1.02   | 1.04    | 1.07    | 1.10    | 1.14     |
|           | [0.24%]| [1.81%]| [3.7%]  | [6.9%]  | [9.4%]  | [12.0%]  |
| 6-hour    | 1.0    | 0.99   | 1.0     | 1.01    | 1.03    | 1.04     |
|           | [0%]   | [-0.55%]| [-0.11%]| [1.3%]  | [2.5%]  | [4.0%]   |
| 12-hour   | 0.96   | 0.90   | 0.93    | 1.03    | 1.15    | 1.30     |
|           | [-4.2%]| [-11.6%]| [-7.56%]| [3.04%] | [12.8%] | [23.0%]  |
| 24-hour   | 0.99   | 0.95   | 0.96    | 0.99    | 1.03    | 1.08     |
|           | [-1.1%]| [-5.6%]| [-4.6%] | [-1.05%]| [2.9%]  | [7.3%]   |

### Table S20.2 Ratio and percentage changes between updated stationary versus EC-generated DSI for Oshawa WPCP for different durations

| Duration  | 2-year | 5-year | 10-year | 25-year | 50-year | 100-year |
|-----------|--------|--------|---------|---------|---------|----------|
| 15-min    | 1.05   | 1.05   | 1.04    | 1.03    | 1.01    | 0.99     |
|           | [4.9%] | [4.9%] | [4.1%]  | [2.5%]  | [1.0%]  | [-0.6%]  |
| 30-min    | 1.07   | 1.06   | 1.03    | 0.99    | 0.95    | 0.91     |
|           | [6.3%] | [5.6%] | [3.0%]  | [-1.5%] | [-5.5%] | [-9.9%]  |
| 1-hour    | 1.03   | 1.06   | 1.07    | 1.08    | 1.08    | 1.08     |
|           | [2.6%] | [5.9%] | [6.9%]  | [7.4%]  | [7.5%]  | [7.3%]   |
| 2-hour    | 1.0    | 1.04   | 1.07    | 1.13    | 1.18    | 1.23     |
|           | [0.4%] | [3.5%] | [6.7%]  | [11.4%]| [15.1%]| [18.9%]  |
| 6-hour    | 1.01   | 1.01   | 1.02    | 1.04    | 1.06    | 1.09     |
|           | [0.9%] | [0.5%] | [1.5%]  | [3.7%]  | [5.9%]  | [8.1%]   |
| 12-hour   | 0.96   | 0.88   | 0.88    | 0.93    | 1.0     | 1.08     |
|           | [-3.8%]| [-14.2%]| [-13.3%]| [-7.0%] | [0%]    | [7.8%]   |
| 24-hour   | 0.98   | 0.95   | 0.96    | 0.99    | 1.03    | 1.07     |
|           | [-1.6%]| [-5.5%]| [-4.6%] | [-1.0%] | [2.7%]  | [6.9%]   |
Table S21.1 Ratio and percentage changes between updated nonstationary versus EC-generated DSI for Windsor Airport for different durations

| Duration     | 2-year | 5-year | 10-year | 25-year | 50-year | 100-year |
|--------------|--------|--------|---------|---------|---------|----------|
| 15-min       | 0.94   | 0.97   | 1.02    | 1.11    | 1.20    | 1.31     |
|              | [-6.1%]| [-3.3%]| [1.6%]  | [9.8%]  | [16.5%] | [23.4%]  |
| 30-min       | 0.99   | 1.00   | 1.03    | 1.07    | 1.11    | 1.15     |
|              | [-1.5%]| [0.5%] | [2.9%]  | [6.8%]  | [9.9%]  | [13.2%]  |
| 1-hour       | 0.98   | 0.98   | 1.00    | 1.04    | 1.08    | 1.12     |
|              | [-1.7%]| [-1.7%]| [0.21%] | [3.9%]  | [7.4%]  | [10.9%]  |
| 2-hour       | 1.06   | 1.06   | 1.04    | 1.00    | 0.98    | 0.95     |
|              | [5.8%]| [5.3%] | [3.5%]  | [0.27%] | [-2.5%] | [-5.5%]  |
| 6-hour       | 1.04   | 1.06   | 1.08    | 1.10    | 1.11    | 1.13     |
|              | [3.7%]| [5.9%] | [7.2%]  | [8.9%]  | [10.3%]| [11.6%]  |
| 12-hour      | 1.01   | 1.01   | 1.03    | 1.05    | 1.08    | 1.11     |
|              | [0.5%]| [1.2%] | [2.7%]  | [5.2%]  | [7.4%]  | [9.8%]   |
| 24-hour      | 1.00   | 1.00   | 1.01    | 1.02    | 1.03    | 1.03     |
|              | [-0.45%]| [0%] | [0.9%]  | [1.8%]  | [2.6%]  | [3.2%]   |

Table S21.2 Ratio and percentage changes between updated stationary versus EC-generated DSI for Windsor Airport for different durations

| Duration     | 2-year | 5-year | 10-year | 25-year | 50-year | 100-year |
|--------------|--------|--------|---------|---------|---------|----------|
| 15-min       | 0.97   | 0.98   | 1.00    | 1.04    | 1.08    | 1.12     |
|              | [-3.0%]| [-1.94%]| [0.32%] | [4.2%]  | [7.5%]  | [11.1%]  |
| 30-min       | 0.98   | 1.01   | 1.03    | 1.05    | 1.07    | 1.09     |
|              | [-1.56%]| [0.79%]| [2.6%]  | [4.9%]  | [6.7%]  | [8.5%]   |
| 1-hour       | 1.01   | 1.01   | 1.02    | 1.03    | 1.04    | 1.05     |
|              | [1.04%]| [0.99%]| [1.5%]  | [2.7%]  | [3.7%]  | [4.8%]   |
| 2-hour       | 1.07   | 1.06   | 1.03    | 1.0    | 0.97    | 0.94     |
|              | [6.9%]| [5.5%] | [3.3%]  | [-0.3%] | [-3.4%] | [-6.8%]  |
| 6-hour       | 1.03   | 1.04   | 1.05    | 1.07    | 1.08    | 1.09     |
|              | [2.4%]| [3.7%] | [4.7%]  | [6.1%]  | [7.2%]  | [8.4%]   |
| 12-hour      | 1.00   | 1.01   | 1.04    | 1.07    | 1.10    | 1.14     |
|              | [-0.26%]| [1.4%]| [3.5%]  | [6.8%]  | [9.5%]  | [12.3%]  |
| 24-hour      | 1.00   | 1.01   | 1.01    | 1.02    | 1.03    | 1.03     |
|              | [0.45%]| [0.7%] | [1.2%]  | [2.1%]  | [2.6%]  | [3.2%]   |
Table S2.1 Ratio and percentage changes between updated nonstationary versus EC-generated DSI for Kingston P. Station for different durations

| Duration | 2-year | 5-year | 10-year | 25-year | 50-year | 100-year |
|----------|--------|--------|---------|---------|---------|----------|
| 15-min   | 1.00   | 1.00   | 1.00    | 0.99    | 0.98    | 0.96     |
|          | [-0.2%]| [0.5%]| [-0.03%]| [-1.3%]| [-2.5%]| [-3.9%]  |
| 30-min   | 0.98   | 0.98   | 0.97    | 0.95    | 0.94    | 0.93     |
|          | [-1.8%]| [-2.5%]| [-3.4%]| [-4.78%]| [-5.93%]| [-7.13%] |
| 1-hour   | 1.00   | 0.97   | 0.95    | 0.91    | 0.88    | 0.86     |
|          | [0.1%]| [-2.8%]| [-5.68%]| [-9.8%]| [-13.3%]| [-16.8%] |
| 2-hour   | 0.96   | 0.95   | 0.97    | 1.01    | 1.05    | 1.10     |
|          | [-4.5%]| [-4.9%]| [-2.84%]| [1.18%]| [4.9%]| [8.82%]  |
| 6-hour   | 0.99   | 0.98   | 0.99    | 1.03    | 1.06    | 1.09     |
|          | [-1.04%]| [-1.98%]| [-0.56%]| [2.5%]| [5.4%]| [8.6%]  |
| 12-hour  | 0.98   | 0.96   | 0.97    | 1.00    | 1.03    | 1.07     |
|          | [-2.08%]| [-4.1%]| [-3.1%]| [-0.3%]| [2.8%]| [6.1%]  |
| 24-hour  | 0.98   | 0.98   | 0.99    | 1.01    | 1.03    | 1.05     |
|          | [-1.5%]| [-1.6%]| [-0.7%]| [1.2%]| [3.1%]| [4.9%]  |

Table S2.2 Ratio and percentage changes between updated stationary versus EC-generated DSI for Kingston P. Station for different durations

| Duration | 2-year | 5-year | 10-year | 25-year | 50-year | 100-year |
|----------|--------|--------|---------|---------|---------|----------|
| 15-min   | 0.97   | 0.97   | 0.97    | 0.96    | 0.95    | 0.95     |
|          | [-2.8%]| [-2.7%]| [-3.1%]| [-4.0%]| [-4.8%]| [-5.7%]  |
| 30-min   | 0.98   | 0.97   | 0.96    | 0.95    | 0.93    | 0.92     |
|          | [-2.5%]| [-3.2%]| [-4.1%]| [-5.7%]| [-7.1%]| [-8.5%]  |
| 1-hour   | 0.99   | 0.96   | 0.93    | 0.90    | 0.87    | 0.85     |
|          | [-1.5%]| [-4.5%]| [-7.3%]| [-11.4%]| [-14.7%]| [-18.1%] |
| 2-hour   | 0.97   | 0.95   | 0.95    | 0.96    | 0.97    | 0.98     |
|          | [-3.3%]| [-5.1%]| [-4.9%]| [-4.1%]| [-3.0%]| [-1.8%]  |
| 6-hour   | 0.99   | 0.98   | 0.99    | 1.01    | 1.03    | 1.06     |
|          | [-1.2%]| [-2.2%]| [-1.4%]| [0.8%]| [2.9%]| [5.3%]  |
| 12-hour  | 1.0    | 0.98   | 0.99    | 1.01    | 1.04    | 1.07     |
|          | [0.3%]| [-1.5%]| [-0.8%]| [1.4%]| [3.9%]| [6.5%]  |
| 24-hour  | 0.99   | 1.0    | 1.01    | 1.02    | 1.04    | 1.06     |
|          | [-0.5%]| [-0.4%]| [0.7%]| [2.3%]| [3.9%]| [5.6%]  |
Table S23.1 Ratio and percentage changes between updated nonstationary versus EC-generated DSI for London International Airport for different durations

| Duration | 2-year | 5-year | 10-year | 25-year | 50-year | 100-year |
|----------|--------|--------|---------|---------|---------|----------|
| 15-min   | 0.92   | 0.96   | 1.0     | 1.08    | 1.1     | 1.21     |
|          | [-9.2%]| [-4.3%]| [0.45%]| [7.1%]  | [12.3%]| [17.4%]  |
| 30-min   | 0.92   | 0.89   | 0.90    | 0.92    | 0.94    | 0.97     |
|          | [-9.3%]| [-12.3%]| [-11.7%]| [-9.2%]| [-6.4%]| [-3.3%]  |
| 1-hour   | 0.88   | 0.88   | 0.91    | 0.98    | 1.05    | 1.12     |
|          | [-13.3%]| [-13.3%]| [-9.3%]| [-1.9%]| [4.3%]| [10.8%]  |
| 2-hour   | 0.92   | 0.93   | 0.95    | 0.98    | 1.0     | 1.03     |
|          | [-8.9%]| [-7.8%]| [-5.8%]| [-2.5%]| [0.12%]| [2.9%]   |
| 6-hour   | 0.93   | 0.92   | 0.92    | 0.92    | 0.93    | 0.94     |
|          | [-7.2%]| [-9.0%]| [-9.1%]| [-8.4%]| [-7.5%]| [-6.3%]  |
| 12-hour  | 0.95   | 0.97   | 0.98    | 1.01    | 1.03    | 1.05     |
|          | [-5.6%]| [-3.4%]| [-1.8%]| [0.5%]| [2.5%]| [4.3%]   |
| 24-hour  | 0.92   | 0.94   | 0.94    | 0.94    | 0.94    | 0.93     |
|          | [-9.3%]| [-6.2%]| [-5.9%]| [-6.7%]| [-7.6%]|          |

Table S23.2 Ratio and percentage changes between updated stationary versus EC-generated DSI for London International Airport for different durations

| Duration | 2-year | 5-year | 10-year | 25-year | 50-year | 100-year |
|----------|--------|--------|---------|---------|---------|----------|
| 15-min   | 0.92   | 0.94   | 0.95    | 0.97    | 0.98    | 1.0      |
|          | [-8.9%]| [-6.8%]| [-5.2%]| [-3.2%]| [-1.7%]| [-0.1%]  |
| 30-min   | 0.93   | 0.94   | 0.97    | 1.02    | 1.07    | 1.13     |
|          | [-7.6%]| [-6.2%]| [-3.1%]| [2.2%]| [6.6%]| [11.2%]  |
| 1-hour   | 0.88   | 0.87   | 0.89    | 0.92    | 0.95    | 0.99     |
|          | [-13.1%]| [-14.8%]| [-12.9%]| [-8.9%]| [-5.1%]| [-1.05%] |
| 2-hour   | 0.92   | 0.92   | 0.93    | 0.94    | 0.95    | 0.97     |
|          | [-8.4%]| [-8.3%]| [-7.5%]| [-5.9%]| [-4.8%]| [-3.4%]  |
| 6-hour   | 0.94   | 0.94   | 0.96    | 0.98    | 1.0     | 1.02     |
|          | [-6.4%]| [-5.8%]| [-4.4%]| [-2.1%]| [0.08%]| [2.3%]   |
| 12-hour  | 0.95   | 0.96   | 0.96    | 0.96    | 0.96    | 0.96     |
|          | [-5.3%]| [-4.6%]| [-4.3%]| [-4.1%]| [-3.8%]| [-3.8%]  |
| 24-hour  | 0.92   | 0.96   | 0.96    | 0.97    | 0.96    | 0.96     |
|          | [-8.7%]| [-4.5%]| [-3.9%]| [-3.8%]| [-3.8%]| [-4.4%]  |
Table S2.1 Ratio and percentage changes between updated nonstationary versus EC-generated DSI for Trenton Airport for different durations

| Duration | 2-year | 5-year | 10-year | 25-year | 50-year | 100-year |
|----------|--------|--------|---------|---------|---------|----------|
| 15-min   | 0.99   | 0.99   | 1.01    | 1.07    | 1.13    | 1.19     |
|          | [-0.67%] | [-1.11%] | **[1.45%]** | **[6.56%]** | **[11.13%]** | **[16.0%]** |
| 30-min   | 0.99   | 0.99   | 1.01    | 1.04    | 1.07    | 1.10     |
|          | [-1.32%] | [-0.54%] | **[1.11%]** | **[3.9%]** | **[6.3%]** | **[8.88%]** |
| 1-hour   | 0.97   | 0.94   | 0.96    | 1.0     | 1.04    | 1.09     |
|          | [-3.2%] | [-5.93%] | [-4.23%] | [0%]    | **[4.0%]** | **[8.5%]** |
| 2-hour   | 0.99   | 0.95   | 0.95    | 0.96    | 0.97    | 0.99     |
|          | [-1.5%] | [-5.29%] | [-5.54%] | [-4.3%] | [-2.8%] | [-0.9%] |
| 6-hour   | 0.99   | 1.00   | 1.03    | 1.08    | 1.12    | 1.18     |
|          | [-0.53%] | [0.13%] | **[2.6%]** | **[7.1%]** | **[11.1%]** | **[15.3%]** |
| 12-hour  | 1.00   | 1.02   | 1.03    | 1.06    | 1.09    | 1.12     |
|          | [0%]   | [1.5%] | **[3.3%]** | **[6.04%]** | **[8.5%]** | **[10.9%]** |
| 24-hour  | 1.02   | 1.03   | 1.03    | 1.03    | 1.03    | 1.03     |
|          | **[1.93%]** | **[3.05%]** | **[3.02%]** | **[2.9%]** | **[2.9%]** | **[2.5%]** |

Table S2.2 Ratio and percentage changes between updated stationary versus EC-generated DSI for Trenton Airport for different durations

| Duration | 2-year | 5-year | 10-year | 25-year | 50-year | 100-year |
|----------|--------|--------|---------|---------|---------|----------|
| 15-min   | 1.01   | 1.03   | 1.07    | 1.16    | 1.25    | 1.35     |
|          | **[1.38%]** | **[2.78%]** | **[6.8%]** | **[13.9%]** | **[19.9%]** | **[26.06%]** |
| 30-min   | 0.98   | 1.01   | 1.04    | 1.09    | 1.13    | 1.18     |
|          | [-1.63%] | [0.8%] | **[3.7%]** | **[8.1%]** | **[11.7%]** | **[15.4%]** |
| 1-hour   | 0.95   | 0.91   | 0.91    | 0.94    | 0.97    | 1.01     |
|          | [-4.8%] | [-9.8%] | [-9.4%] | [-6.4%] | [-3.1%] | [0.7%] |
| 2-hour   | 0.96   | 0.94   | 0.96    | 1.0     | 1.05    | 1.10     |
|          | [-3.7%] | [-5.95%] | [-4.1%] | [0.45%] | **[4.6%]** | **[9.1%]** |
| 6-hour   | 0.98   | 0.98   | 0.99    | 1.03    | 1.06    | 1.11     |
|          | [-1.97%] | [-2.3%] | [-0.82%] | **[2.69%]** | **[6.0%]** | **[9.5%]** |
| 12-hour  | 1.00   | 1.05   | 1.09    | 1.15    | 1.21    | 1.27     |
|          | [-0.3%] | **[4.41%]** | **[8.1%]** | **[13.04%]** | **[17.1%]** | **[21.1%]** |
| 24-hour  | 1.03   | 1.05   | 1.05    | 1.05    | 1.04    | 1.04     |
|          | **[2.87%]** | **[4.51%]** | **[4.6%]** | **[4.3%]** | **[4.2%]** | **[3.6%]** |
Table S25.1 Ratio and percentage changes between updated nonstationary versus EC-generated DSI for Stratford WWTP for different durations

| Duration | 2-year | 5-year | 10-year | 25-year | 50-year | 100-year |
|----------|--------|--------|---------|---------|---------|----------|
| 15-min   | 1.05   | 1.08   | 1.06    | 1.02    | 0.99    | 0.96     |
|          | [5.03%]| [7.02%]| [5.6%]  | [2.4%]  | [-0.76%]| [-4.35%]|
| 30-min   | 0.96   | 1.00   | 1.07    | 1.19    | 1.31    | 1.45     |
|          | [-3.99%]| [0.33%]| [6.6%]  | [16.2%] | [23.72%]| [31.2%]  |
| 1-hour   | 0.90   | 0.94   | 1.03    | 1.19    | 1.36    | 1.57     |
|          | [-10.9%]| [-6.1%]| [2.6%]  | [16.2%] | [26.5%] | [36.4%]  |
| 2-hour   | 0.97   | 0.98   | 1.06    | 1.21    | 1.37    | 1.56     |
|          | [-3.3%]| [-1.9%]| [5.3%]  | [17.4%] | [26.8%] | [36.04%]|
| 6-hour   | 0.89   | 0.84   | 0.86    | 0.93    | 1.01    | 1.11     |
|          | [-12.3%]| [-19.4%]| [-16.1%]| [-7.2%] | [1.09%] | [9.8%]   |
| 12-hour  | 0.90   | 0.83   | 0.84    | 0.90    | 0.97    | 1.06     |
|          | [-11.5%]| [-20.7%]| [-18.9%]| [-2.9%] | [5.9%]  | 11.04%   |
| 24-hour  | 0.84   | 0.79   | 0.80    | 0.87    | 0.94    | 1.03     |
|          | [-19.02%]| [-27.2%]| [-24.3%]| [-15.6%]| [-6.8%] | [2.6%]   |

Table S25.2 Ratio and percentage changes between updated stationary versus EC-generated DSI for Stratford WWTP for different durations

| Duration | 2-year | 5-year | 10-year | 25-year | 50-year | 100-year |
|----------|--------|--------|---------|---------|---------|----------|
| 15-min   | 1.0    | 1.01   | 1.03    | 1.04    | 1.05    | 1.07     |
|          | [-0.1%]| [1.4%] | [2.47%] | [3.97%] | [5.1%]  | [6.3%]   |
| 30-min   | 0.95   | 0.96   | 0.99    | 1.04    | 1.09    | 1.15     |
|          | [-5.25%]| [-4.5%]| [-1.45%]| [3.89%] | [8.5%]  | [13.2%]  |
| 1-hour   | 0.92   | 0.91   | 0.94    | 1.0     | 1.06    | 1.14     |
|          | [-8.7%]| [-10.03%]| [-6.7%]| [-0.06%]| [5.8%]  | [12.05%]|
| 2-hour   | 0.92   | 0.88   | 0.91    | 0.98    | 1.05    | 1.15     |
|          | [-8.7%]| [-13.6%]| [-10.2%]| [-2.18%]| [5.1%]  | [12.7%]  |
| 6-hour   | 0.89   | 0.82   | 0.84    | 0.88    | 0.94    | 1.01     |
|          | [-12.3%]| [-21.3%]| [-19.7%]| [-13.1%]| [-6.45%]| [0.8%]   |
| 12-hour  | 0.89   | 0.81   | 0.82    | 0.86    | 0.92    | 0.99     |
|          | [-12.4%]| [-22.7%]| [-21.9%]| [-15.7%]| [-8.86%]| [-1.3%]  |
| 24-hour  | 0.84   | 0.79   | 0.80    | 0.84    | 0.90    | 0.97     |
|          | [-19.02%]| [-27.2%]| [-25.5%]| [-18.5%]| [-11.4%]| [-3.1%]  |
### Table S26.1 Ratio and percentage changes between updated nonstationary versus EC-generated DSI for Fergus Shand dam for different durations

| Duration | 2-year | 5-year | 10-year | 25-year | 50-year | 100-year |
|----------|--------|--------|---------|---------|---------|----------|
| 15-min   | 1.05   | 1.02   | 1.01    | 1.01    | 1.01    | 1.02     |
|          | [4.5%] | [1.8%] | [1.21%] | [1.1%]  | [1.3%]  | [1.75%]  |
| 30-min   | 1.02   | 0.98   | 0.98    | 1.00    | 1.02    | 1.05     |
|          | [2.1%] | [-2.05%] | [-1.89%] | [0.06%] | [2.3%]  | [4.8%]   |
| 1-hour   | 0.99   | 0.94   | 0.95    | 0.99    | 1.03    | 1.08     |
|          | [-0.8%] | [-6.5%] | [-5.4%] | [-1.4%] | [2.8%]  | [7.4%]   |
| 2-hour   | 0.91   | 0.92   | 0.96    | 1.05    | 1.13    | 1.23     |
|          | [-10.4%] | [-9.0%] | [-3.9%] | [4.7%]  | [11.6%] | [18.7%]  |
| 6-hour   | 0.94   | 0.97   | 0.99    | 1.02    | 1.05    | 1.07     |
|          | [-6.2%] | [-3.0%] | [-0.7%] | [2.2%]  | [4.3%]  | [6.6%]   |

### Table S26.2 Ratio and percentage changes between updated stationary versus EC-generated DSI for Fergus Shand dam for different durations

| Duration | 2-year | 5-year | 10-year | 25-year | 50-year | 100-year |
|----------|--------|--------|---------|---------|---------|----------|
| 15-min   | 1.05   | 1.02   | 1.02    | 1.02    | 1.02    | 1.03     |
|          | [4.5%] | [2.2%] | [1.73%] | [1.86%] | [2.27%] | [2.86%]  |
| 30-min   | 1.03   | 0.97   | 0.97    | 0.98    | 1.00    | 1.03     |
|          | [2.4%] | [-2.74%] | [-3.1%] | [-1.60%] | [0.36%] | [3.76%]  |
| 1-hour   | 0.99   | 0.93   | 0.94    | 0.97    | 1.01    | 1.05     |
|          | [-1.03%] | [-7.1%] | [-6.48%] | [-3.02%] | [0.67%] | [4.86%]  |
| 2-hour   | 0.94   | 0.92   | 0.94    | 0.97    | 1.00    | 1.03     |
|          | [-6.3%] | [-8.44%] | [-6.95%] | [-3.47%] | [-0.31%] | [3.19%]  |
| 6-hour   | 0.96   | 0.97   | 0.99    | 1.01    | 1.03    | 1.05     |
|          | [-4.36%] | [-2.7%] | [-1.1%] | [1.12%] | [2.79%] | [4.53%]  |
Figure S15. Estimated nonstationary versus EC-generated IDFs for return periods $T = 2, 5, 10, 25, 50$ and 100-year for the urbanized and moderately locations in Southern Ontario. The updated and EC IDFs are shown using solid and dotted lines respectively.
SI 5 Statistical Significance of Nonstationary versus Stationary DSI

The (statistically) significant differences in DSI is computed using the statistical test for the difference between two means or the standardized z-statistics, which is given by (Madsen et al., 2009; Mikkelsen et al., 2005)

\[ z = \frac{\hat{z}_T^{NonSta} - \hat{z}_T^{Sta}}{\sqrt{0.5(\text{var}\{\hat{z}_T^{NonSta}\} + \text{var}\{\hat{z}_T^{Sta}\})}} \]  

(5.1)

Where \( \hat{z}_T^{NonSta} \) is the \( T \)-year DSI obtained from the best selected nonstationary model, \( \hat{z}_T^{Sta} \) describes the same but with the best stationary model. The denominator indicates predictive uncertainty; \( \text{var}\{\hat{z}_T^{NonSta}\} \) and \( \text{var}\{\hat{z}_T^{Sta}\} \) are the estimated variance obtained from the \( T \)-year event estimates and corresponding 95% credible interval. The z-statistic can be interpreted as statistically equivalent to quantiles of standard normal distribution, \( i.e. \), \( z = \pm 1.64 \) correspond to 10% significance levels. The null hypothesis of the test assumes the \( T \)-year event estimate obtained using the best fitted nonstationary model is significantly different from its best fitted stationary counterpart.
Table S27. Z-statistics* between best selected nonstationary and stationary model for 2-year return period

| Duration | Toronto  | Hamilton | Oshawa | Windsor | Kingston | London | Trenton | Stratford | Fergus Shand |
|----------|----------|----------|--------|---------|----------|--------|---------|-----------|--------------|
| 15-min   | -0.038   | -0.362   | 0.251  | -0.354  | 0.297    | -0.032 | -0.265  | 0.521     | 0.000        |
| 30-min   | -0.050   | -0.126   | 0.244  | 0.011   | 0.068    | -0.158 | 0.030   | 0.118     | -0.037       |
| 1-hour   | -0.331   | 0.151    | 0.127  | -0.288  | 0.158    | -0.009 | 0.161   | -0.168    | 0.016        |
| 2-hour   | -0.170   | 0.041    | -0.012 | -0.153  | -0.128   | -0.041 | 0.246   | 0.371     | -0.324       |
| 6-hour   | 0.389    | -0.147   | 0.195  | 0.151   | 0.021    | -0.088 | 0.183   | 0.000     | -0.154       |
| 12-hour  | 0.214    | -0.073   | -0.031 | 0.088   | -0.266   | -0.038 | 0.032   | -0.032    | -             |
| 24-hour  | 0.000    | -0.108   | 0.044  | -0.116  | -0.116   | -0.049 | -0.126  | 0.000     | -             |

*The standardized Z-statistic is positive (negative) with an increasing (decreasing) trend, and statistically significant at 10% significance level when $|z| > 1.64$.

Table S28. Z-statistics between best selected nonstationary and stationary model for 10-year return period

| Duration | Toronto  | Hamilton | Oshawa | Windsor | Kingston | London | Trenton | Stratford | Fergus Shand |
|----------|----------|----------|--------|---------|----------|--------|---------|-----------|--------------|
| 15-min   | 0.373    | -0.227   | 0.061  | 0.065   | 0.171    | 0.324  | -0.281  | 0.196     | -0.029       |
| 30-min   | -0.201   | 0.001    | -0.147 | 0.016   | 0.038    | -0.295 | -0.120  | 0.373     | 0.050        |
| 1-hour   | -0.346   | -0.007   | -0.018 | -0.068  | 0.075    | 0.151  | 0.224   | 0.348     | 0.046        |
| 2-hour   | -0.324   | 0.309    | -0.105 | 0.014   | 0.091    | 0.081  | -0.070  | 0.397     | 0.129        |
| 6-hour   | 0.103    | 0.014    | 0.074  | 0.174   | 0.041    | -0.277 | 0.212   | 0.140     | 0.017        |
| 12-hour  | 0.526    | 0.089    | 0.213  | -0.043  | -0.123   | 0.156  | -0.264  | 0.201     | -             |
| 24-hour  | -0.039   | 0.061    | 0.000  | -0.016  | -0.071   | -0.107 | -0.104  | 0.047     | -             |
Table S29. Z-statistics between best selected nonstationary and stationary model for 50-year return period

| Duration | Toronto | Hamilton | Oshawa | Windsor | Kingston | London | Trenton | Stratford | Fergus Shand |
|----------|---------|----------|--------|---------|----------|--------|---------|-----------|-------------|
| 15-min   | 0.569   | -0.144   | -0.137 | 0.287   | 0.081    | 0.636  | -0.287  | -0.214    | -0.032      |
| 30-min   | -0.244  | 0.080    | -0.230 | 0.077   | 0.035    | -0.234 | -0.160  | 0.499     | 0.050       |
| 1-hour   | -0.497  | -0.153   | -0.054 | 0.120   | 0.039    | 0.273  | 0.195   | 0.564     | 0.059       |
| 2-hour   | -0.498  | 0.465    | -0.126 | 0.045   | 0.207    | 0.162  | -0.205  | 0.349     | 0.372       |
| 6-hour   | 0.016   | 0.107    | -0.049 | 0.142   | 0.077    | -0.290 | 0.204   | 0.198     | 0.050       |
| 12-hour  | 0.635   | 0.138    | 0.328  | -0.064  | -0.037   | 0.273  | -0.308  | 0.345     | -           |
| 24-hour  | -0.049  | 0.103    | 0.005  | 0.000   | -0.024   | -0.108 | -0.052  | 0.111     | -           |

Table S30. Z-statistics between best selected nonstationary and stationary model for 100-year return period

| Duration | Toronto | Hamilton | Oshawa | Windsor | Kingston | London | Trenton | Stratford | Fergus Shand |
|----------|---------|----------|--------|---------|----------|--------|---------|-----------|-------------|
| 15-min   | 0.615   | -0.120   | -0.199 | 0.346   | 0.054    | 0.748  | -0.284  | -0.311    | -0.032      |
| 30-min   | -0.249  | 0.098    | -0.239 | 0.092   | 0.035    | -0.208 | -0.166  | 0.529     | 0.046       |
| 1-hour   | -0.531  | -0.192   | -0.059 | 0.175   | 0.031    | 0.309  | 0.182   | 0.613     | 0.062       |
| 2-hour   | -0.534  | 0.510    | -0.127 | 0.051   | 0.236    | 0.185  | -0.231  | 0.327     | 0.441       |
| 6-hour   | -0.002  | 0.130    | -0.083 | 0.130   | 0.087    | -0.280 | 0.200   | 0.209     | 0.058       |
| 12-hour  | 0.652   | 0.148    | 0.355  | -0.067  | -0.010   | 0.302  | -0.311  | 0.390     | -           |
| 24-hour  | -0.052  | 0.110    | 0.007  | 0.000   | -0.018   | -0.104 | -0.041  | 0.127     | -           |
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