1.1 *Hydropeaking Event Detection Algorithm*

To fulfill OBJ 1, a new algorithm, Hydropeaking Event Detection Algorithm (HEDA), was developed in R (R Core Team, 2021) to automate feature extraction of high-resolution hydropeaking flow with limited subjective decisions. HEDA consists of three modules: Data Preparation, Vector Angle, and Clean Noise (Fig. 3). The first module, Data Preparation, starts with hourly flow records (15-minute records were converted to hourly records by taking the mean flow within the same hour) of the interest period (e.g., post-dam period) in CSV format. The flow record of each site is then split into dry (June-September) and wet (October-May) season datasets to optimize the performance of HEDA as hydropeaking tends to occur more frequently in the dry season while precipitation and snowmelt in other seasons can disturb the hydropeaking signals. Data smoothing strategies such as Gaussian filtering or locally estimated smoothing were not applied as these strategies (1) are unable to quickly process a large amount of data; (2) potentially mark peaking events as noise; and (3) degrade or destroy the peaking pattern (SI II). Instead, the flow record was smoothed with two steps. First, based on observation, intensive small fluctuations always occur at base and peaking discharge, thus flow records were truncated by 10th and 90th percentile of discharge during the whole period to remove these fluctuations (SI II). Second, flow variations ($\Delta q_i = Q_{i+1} - Q_i$) smaller than threshold X were assigned zero to avoid mischaracterizing small fluctuations as peaks due to measurement errors. Threshold X consists of a global (γ) and local static ($\alpha_1 * Q_{ave}$) threshold (Eq.1). The global threshold (γ) acted as a consistent standard to all the sites. Threshold values of γ was initialized based on the minimum rise/fall rate found in the literature (2.8 m^3/s/hr) and finalized to be γ = 1.1 m^3/s. The local static threshold ($\alpha_1 * Q_{ave}$) was a consistent standard to one site. The α_1 was assigned 0.03 by evaluating the range of Q_{ave} at 33 sites and the relative difference between all the thresholds ($T3_t$) used in this study (SI II).

$$X = \max(\gamma,\ \alpha_1 * Q_{ave}) \tag{1}$$

The second module, Vector Angle, involves the identification of change points in flow time series (Fig. 3). Among the flow record, consecutive data points (T_n,Q_n) and (T_{n+1}, Q_{n+1}) were treated as a Euclidean Vector $\overrightarrow{q_n}$ ($\Delta t_n,\ \Delta q_n$), a quantity that has a magnitude and a direction. The magnitude of a vector is the distance between the two data point ($|\overrightarrow{q_n}| = \sqrt{(\Delta t_n)^2 + (\Delta q_n)^2}$ while direction is from its tail (T_n,Q_n) to its head (T_{n+1}, Q_{n+1}) (Fig. 2). The vector angle (θ_{n+1}) between two continuous vectors ($\overrightarrow{q_n}, \overrightarrow{q_{n+1}}$) was used to identify change points instead of the first derivative of $q(t)$ to avoid excluding change points outside the range of the designated rise/fall rate ($\tan\theta = \Delta q_n/\Delta t_n$) can be excluded (Eq.2). The threshold value of θ was tested from 30° to 70° (70° was set based on the threshold of the minimum rise/fall rate (2.8m^3/s/hr).) and finally set as 60° because it amounts to a rise/fall rate of 1.7m^3/s/hr. This value was set to be lower than 2.8m^3/s/hr which was used as a mitigation standard of hydropeaking the American river (SI II) (Young et al. 2011). After $q(t)$ with θ > 60° were identified, change points were grouped into four categories based on the symbol of Δq_{n+1} (+, 0, -) which separated hydropeaking processes into four groups (points 1-4 in Fig. 3). Points 1 and 4 are always followed by a rising discharge while point 3 is followed by a falling discharge. Point 2 indicates the start of either a peak or base flow discharge. The sequence of point 2 followed by point 4 (base-flow pair) indicates base flow while the combination of point 2 and 3 (peak pair) indicates a peak discharge.

$$\theta_{n+1} = \cos^{-1}(\Delta {t_n}^2 * \Delta {t_{n+1}}^2 + \Delta {q_n}^2 * \Delta {q_{n+1}}^2) / \sqrt{\Delta q_n * \Delta {t_n}^2 + \Delta q_{n+1} * \Delta {t_{n+1}}^2} \tag{2}$$

In the Clean Noise module, three layers of correction (position, repetition and difference) clean change points identified incorrectly. In the position layer, change points are excluded if they occur in the wrong position. For example, both point 3 and the peak pair represent the peaking discharge whose value (position) should be close to the daily maximum discharge. If the peaking discharge is close to the daily minimum discharge, change points are removed since they are in the wrong positions. The second layer, Repetition, cleans repeated points generated in the first layer. Before getting to the third layer, the first and second layers need to be repeated to make sure change points that violated the former two rules are removed. The last layer, Difference, evaluates whether Δq_i is large enough to be identified as a peaking event based on a daily amplitude threshold described below.

Within the three layers, three thresholds were used, $T1(\mathrm{t})$, $T2(\mathrm{t})$, and $T3(\mathrm{t})$, (Eq.3-5 and Fig. 3). In the position layer, two dynamic thresholds ($T1(\mathrm{t})$ and $T2(\mathrm{t})$) that were updated daily were used for each river to identify the relatively high and low discharge. The threshold value of high discharge was defined as the difference between maximum daily flow ($Q_{max}(\mathrm{t})$) and 30% (α_2) of the daily maximum amplitude ($Q_{max}(\mathrm{t}) - Q_{min}(t)$) while that for low discharge was defined as the sum of daily minimum flow ($Q_{min}(t)$) and 30% (α_2) of the daily maximum amplitude. In the repetition and difference layers, $T3(\mathrm{t})$ was used as the standard to evaluate whether flow variation can be counted as a rise/fall process. $T3(\mathrm{t})$ consists of a local static threshold ($\alpha_3 * Q_{ave}$) and a dynamic threshold ($\alpha_4 * (Q_{max}(\mathrm{t}) - Q_{min}(t))$) that were updated daily for each river to reflect the evolvement evolution of climate, seasonality, and river size flow, all of which that are highly related to hydropower operation. To decide what fraction of Q_{ave} to be used, tests were run within a reference range (30%-100%) gained from literature with both Q_{ave} and amplitude available (Zimmerman et al. 2010, Hauer et al. 2012, Capra et al. 2017). Finally, 70% of Q_{ave} ($\alpha_3 = 0.7$) was selected as the threshold value because outputs of HEDA didn't change beyond this fraction. To identify different intensities of rise/fall process of each site, 50% of the daily maximum amplitude was used (SI II).

$$T1(\mathrm{t}) = Q_{max}(\mathrm{t}) - \alpha_2 * (Q_{max}(\mathrm{t}) - Q_{min}(t)) \quad (3)$$

$$T2(\mathrm{t}) = Q_{min}(\mathrm{t}) + \alpha_2 * (Q_{max}(\mathrm{t}) - Q_{min}(t)) \quad (4)$$

$$T3(\mathrm{t}) = \max\left(\alpha_3 * Q_{ave} \,, \, \alpha_4 * (Q_{max}(\mathrm{t}) - Q_{min}(t))\right) \quad (5)$$

The performance of HEDA was assessed with visual examination, with 500 change points of each hydropeaking site plotted and visually checked. The error rate of HEDA was calculated by dividing the number of wrongly identified change points by 500.