Detecting Multi-Purpose Reservoir Operation Induced Time-Frequency Alteration Using Wavelet Transform

Jenq-Tzong Shiau · Chian-You Huang

Abstract It is well recognized that natural flow variability is an inherent characteristic of rivers. Altered natural flow regime caused by anthropogenic regulations would threaten ecosystem biodiversity and deteriorate riverine health. Wavelet transform is a newly-developed tool that extracts dominant modes of variability by decomposing a non-stationary series into time-frequency space, which can be used to detect hydrologic alteration at various scales caused by reservoir operation. Continuous wavelet transform is simultaneously applied to recorded hourly inflow and outflow series of 1998–2008 for the Feitsui Reservoir located in northern Taiwan. Differences between wavelet power spectrum obtained for outflow and inflow series denote severity of hydrologic alteration. Greater spectral alteration is observed at less-than-1-day scales due to peak-load hydropower releases. The spectral alteration gradually declines with increasing scales. Different variation patterns for the yearly time-averaged spectral difference also reveal that the altered spectrum depends on hydrologic conditions. The index of spectral alteration (ISA), defined as the mean absolute deviations of power spectrum for all scales over a certain time period, is proposed to quantitatively assess severity of altered natural flow regime. ISA of 5 can be roughly recognized as the division of dry and non-dry years for the Feitsui Reservoir case. The obtained results offer decision makers useful information to adopt adaptive operating strategies to mitigate negative impacts of altered natural flow regime and derive optimal trade-off between human and environmental needs.

Keywords Natural flow regime · Reservoir operation · Wavelet transform · Index of spectral alteration

1 Introduction

Rapid economic development associated with increasing population in urban areas calls for building a considerable amount of reservoirs to meet a burst of water requirements worldwide. Stable water-supply, irrigation, hydroelectric power production, navigation, and flood-peak

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attenuation provided by reservoir operation are economically rewarding. However, most rivers flowing through metropolitan areas suffer from dam-induced hydrologic alteration. It is widely recognized that altered natural flow regime caused by reservoirs threatens ecosystem biodiversity and deteriorates riverine health (Ligon et al. 1995; Poff et al. 1997; Batalla et al. 2004; Magilligan and Nislow 2005; Graf 2006; Singer 2007; Schmidt and Wilcock 2008; Petts 2009; Botter et al. 2010; García et al. 2011; FitzHugh and Vogel 2011).

Natural flow variability is an inherent characteristic of rivers, which is resulted from integrated hydrologic and climate processes at various temporal scales. Losses of such natural variability are often experienced in the downstream of dams. Reservoir releases according to specific purposes would disrupt the natural cycles and/or create new cycles unrelated to the natural streamflow regime. Variability of regulated streamflow becomes further complex since it comprises natural variability and anthropogenic effects. Understanding impacts of anthropogenic regulations on natural flow regime is an essential component in river management to restore lost natural variability. A commonly used approach to quantify impacts of altered streamflow is comparing pre- and post-impact streamflow series since streamflow records are available at most rivers. Several approaches and hydrologic indicators (Richter et al. 1997; Puckridge et al. 1998; Jowett and Biggs 2006; Arthington et al. 2006; Mathews and Richter 2007; Monk et al. 2007; Shiau and Wu 2008; Gao et al. 2009; Poff et al. 2010) have been developed to characterize impacts of anthropogenic regulations on natural flow regime at multi-temporal scales and a vast literature has applied those approaches to investigate ecologically relevant water-resources problems (Richter et al. 1998; Galat and Lipkin 2000; Maingi and Marsh 2002; Smakhtin et al. 2006; Shiau and Wu 2007, 2009; Xia, et al. 2009; Yang, et al. 2010; Yin and Yang 2011; Suen 2011; Yang, et al. 2012; Chen et al. 2013).

Altered streamflow regime at a specific temporal scale cannot be identified if such temporal-scale hydrologic indicator is not pre-assigned in those previously proposed approaches. Spectral analysis such as wavelet transform provides an alternative method to simultaneously examine hydrologic alterations at multiple temporal scales. Wavelet transform is a mathematical tool for extracting the dominant modes of variability from non-stationary series. Since its computational efficiency, wavelet transform has been increasingly applied in climatology (Kikuchi and Wang 2010; Lim et al. 2013), hydrology (Wang et al. 2011; Niu and Sivakumar; 2013; Sang 2013), oceanography (Thiebaut and Vennell 2010), seismology (Cannata, et al. 2013), and water resources (Ramana et al. 2013; Sahay and Srivastava 2014). However, few studies are devoted to examine hydrologic alteration induced by reservoir operation using wavelet transform. White et al. (2005) had conducted wavelet analyses to examine the hydrologic structure of the Colorado River at Lees Ferry influenced by the Glen Canyon Dam. Steel and Lange (2007) analyzed water temperature data from the Willamette River basin (U.S.A.) to detect impacts of multi-purpose reservoir operation on water temperature at multi-temporal scales using wavelet analysis. Zolezzi et al. (2009) proposed an integrated approach of wavelet transform analysis and range of variability approach (RVA) to assess hydrologic alteration of the Adige River (Italy) caused by hydropower production at multiple temporal scales.

This study aims to assess alteration of natural flow regime influenced by the multi-purpose Feitsui Reservoir located in northern Taiwan at multiple temporal scales using wavelet transform. Feitsui Reservoir, situated 30 km southeast of the Taipei City, is a stable water-supply source of the Taipei metropolitan area and also provides flood-mitigation and hydropower-generation purposes. Hydrologic alteration caused by Feitsui Reservoir had been comprehensively explored by previous studies (Shiau and Wu 2010, 2013). However, simultaneous examination of hydrologic alteration at multi-temporal scales for the Feitsui Reservoir is never addressed in literature. Wavelet transform is thus employed in this study to detect

time-frequency alteration of natural flow regime caused by multi-purpose operation of Feitsui Reservoir. In addition, an index of spectral alteration (ISA) is also proposed in this work to represent severity of hydrologic alteration caused by reservoir operation.

The remainder of this paper is organized as follows. Section 2 presents a brief introduction of wavelet transform theorem. Section 3 summarizes operating rules of the Feitsui Reservoir and the hourly flow records during the period of 1998–2008 used for wavelet analysis. Results and discussions are given in the Section 4, which is followed by the Section 5 of conclusions.

2 Methodology

2.1 Wavelet Transform

Wavelet transform is a mathematical tool to determine both the dominant modes of variability and how the modes varying with time by decomposing a non-stationary series into time-frequency space (Torrence and Compo 1998). Due to efficiency in time-frequency localization, the wavelet transform provides a flexible time-scale window that narrows when focusing on small-scale features and widens when focusing on large-scale features (Kumar and Foufoula-Georgiou 1997). Continuous wavelet transform of a discrete series is briefly described in this section. Detailed description of wavelet transform theorem can be referred to Lau and Weng (1995), Kumar and Foufoula-Georgiou (1997), and Torrence and Compo (1998).

For a discrete series x_n ($n=0, 1, ..., N-1$) observed at a fixed time interval δt, the continuous wavelet transform is defined as the convolution of the series x_n with a set of dilated and translated wavelet functions Ψ, which is written as

$$W_n(s) = \sum_{k=0}^{N-1} x_k \Psi^* \left(\frac{(k-n)\delta t}{s} \right)$$ (1)

where Ψ^* is the complex conjugate of Ψ; s denotes the scale, i.e., the width of the wavelet, a larger value of s meaning more data included in calculation; Ψ is the wavelet function which is dilated in scale and translated in time from a mother wavelet functions Ψ_0 through $\Psi(t,s) = \frac{1}{s^{1/2}} \Psi_0\left(\frac{t'-t}{s}\right)$

A wavelet function must have zero mean and be localized in both time and frequency space (Farge 1992). Choice of the wavelet function depends on its shape similar to signals for analysis. Since the Morlet wavelet function well describes the wave-like signals such as streamflow, it is commonly used for streamflow analysis (Nakken 1999; White et al. 2005; Kang and Lin 2007; Adamowski et al. 2009; Zolezzi et al. 2009). The complex Morlet wavelet function is

$$\Psi_0(\eta) = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\eta^2/2}$$ (2)

where ω_0 is the nondimensional frequency, the value of 6 is taken in this study to satisfy the admissibility condition (Farge 1992); η denotes the nondimensional time parameter.

In order to have fast computational efficiency, Torrence and Compo (1998) had indicated that the convolution shown in equation (1) can be calculated as the inverse Fourier transform of the product of the Fourier transformed x_n and Ψ, which is given by

$$W_n(s) = \sum_{k=0}^{N-1} \widehat{x}_k \widehat{\Psi}^* (s\omega_k) e^{i\omega_k n\delta t}$$ (3)

where $\widehat{x_k}$ is the discrete Fourier transform of x_n and is calculated as

$$\widehat{x}_k = \frac{1}{N}\sum_{n=0}^{N-1}x_n e^{-2\pi ikn/N} \tag{4}$$

ω_k is the angular frequency and defined as

$$\omega_k = \begin{cases} \dfrac{2\pi k}{N\delta t} \text{ when } k \leq \dfrac{N}{2} \\ -\dfrac{2\pi k}{N\delta t} \text{ when } k > \dfrac{N}{2} \end{cases} \tag{5}$$

$\widehat{\Psi}(s\omega)$ in equation (3) is the discrete Fourier transform of $\Psi(t/s)$ and needed to be normalized to have unit energy in order that the derived wavelet transforms at each scale s are directly comparable to each other.

$$\widehat{\Psi}(s\omega_k) = \left(\frac{2\pi s}{\delta t}\right)^{1/2} \widehat{\Psi}_0(s\omega_k) \tag{6}$$

Since the complex Morlet wavelet function is adopted, the obtained wavelet transform W_n (s) is also a complex. The wavelet power spectrum (WPS) is thus defined as $|W_n(s)|^2$ to describe the distribution of energy among the modes of variability. By varying the wavelet scale s and translating along the time index n, the power spectrum diagram is constructed to show both the amplitude of any features versus the scale and how this amplitude varies with time. Choice of scales is determined by the fractional powers of two for convenience. That is,

$$s_j = s_0 2^{j\delta j}, \;\; j = 0, 1, ..., J \tag{7}$$

where s_0 is the smallest scale and $2\delta t$ is used in this study; δj is the scale interval and 1/50 is used to obtain finer resolution in power spectrum; J determines the largest scale for spectrum analysis. Steel and Lange (2007) suggested using 10 % of observation at most to determine this largest scale.

2.2 Index of Spectral Alteration

In this study, wavelet transform is simultaneously applied to reservoir inflow and outflow series to detect effects of reservoir operation on alteration of natural flow regime. Differences between wavelet power spectrum (WPS) obtained for reservoir inflow and outflow series denote hydrologic alteration caused by reservoir operation. To simplify and quantify assessing procedure, the index of spectral alteration (ISA) is proposed to represent severity of altered natural flow variability, which is defined as

$$ISA = \frac{1}{(n_2-n_1+1)(J+1)}\sum_{j=0}^{J}\sum_{n=n_1}^{n_2}\left| \left|W_{n,A}(s_j)\right|^2 - \left|W_{n,N}(s_j)\right|^2 \right| \tag{8}$$

where $|W_{n,A}(s)|^2$ and $|W_{n,N}(s)|^2$ denote the WPS of reservoir outflow (altered streamflow) and inflow (natural streamflow), respectively.

The value of ISA represents mean absolute deviations of outflow WPS from inflow WPS for all scales over a certain time period. Null value indicates that natural flow regime is not

disturbed, i.e., outflow series is identical to inflow series. Greater ISA implies severe alteration caused by reservoir operation. However, the value of ISA also depends on magnitude and seasonal variability of inflow, purposes and operating policies of reservoir, and capacity of reservoir. This proposed index can be applied to different time periods to compare severity of hydrologic alteration caused by different reservoir operating polices adopted to cope with various hydrologic conditions.

3 A Case Study – The Feitsui Reservoir System in Taiwan

The Feitsui Reservoir, located in northern Taiwan, dames the Peishih Creek (the north fork of the Hsintien Creek) and is situated approximately 30 km southeast of the Taipei City (see Fig. 1). Finished in 1987, Feitsui Reservoir serves as the stable water-supply source of the Taipei metropolitan area. With an active capacity of 336 million m^3 and installed hydroelectric capacity of 70 MW, the Feitsui Reservoir also provides for flood-peak attenuation and peak-load hydroelectric power generation.

The mean daily flows of the Peishih Creek (inflow of the Feitsui Reservoir) and the Nanshih Creek (south fork of the Hsintien Creek) for the 1998–2008 period are 34.2 and 40.4 m^3/s, respectively. The annual domestic demands for the downstream metropolitan areas are approximate 1 billion m^3 per year. Unregulated streamflow of the Nanshih Creek merged with releases from the Feitsui Reservoir are used to meet this domestic demand (TFRA 2004). The releases for domestic requirements from Feitsui Reservoir also pass through the installed hydroelectric power plant for peaking hydropower generation, with mean annual production of 220 GWh.

The hourly inflow records of the Feitsui Reservoir for the 1998–2008 period are employed to represent the natural streamflow, which are shown in the top panel of Fig. 2. The same period of hourly outflows from Feitsui Reservoir, including domestic, hydropower production,
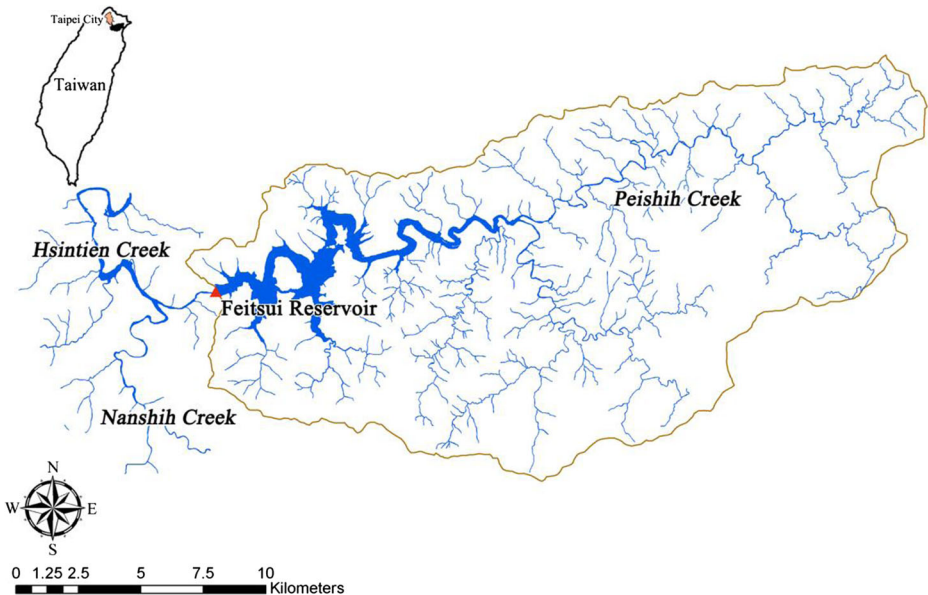

Fig. 1 Location map of the Feitsui Reservoir and the Hsintien Creek system in Taiwan
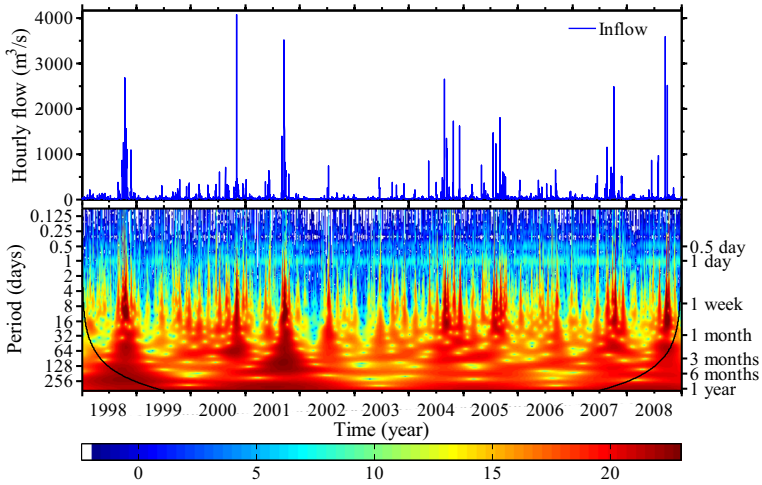
Fig. 2 The hourly inflow series (1998–2008) of the Feitsui Reservoir, Taiwan (*top panel*) and the corresponding wavelet power spectrum (*bottom panel*)

and man-made compelling flood releases, are used to represent the altered streamflow, which are shown in the top panel of Fig. 3.

To clearly demonstrate differences between inflow and outflow series, hourly inflow and outflow series for the period of January 24–March 12, 2000 are shown in the top panel of Fig. 4. This hourly flow hydrograph shows three typical outflow patterns according to different inflow conditions. Subdaily mild variability of natural inflow replaced by a periodically hydropeaking daytime 8-h release is evidently observed during non-flood periods. Small floods are totally stored and continuous 24-h release for hydropower generation is implemented during post-storm high pool-level periods. Man-made compelling flood release for flood-
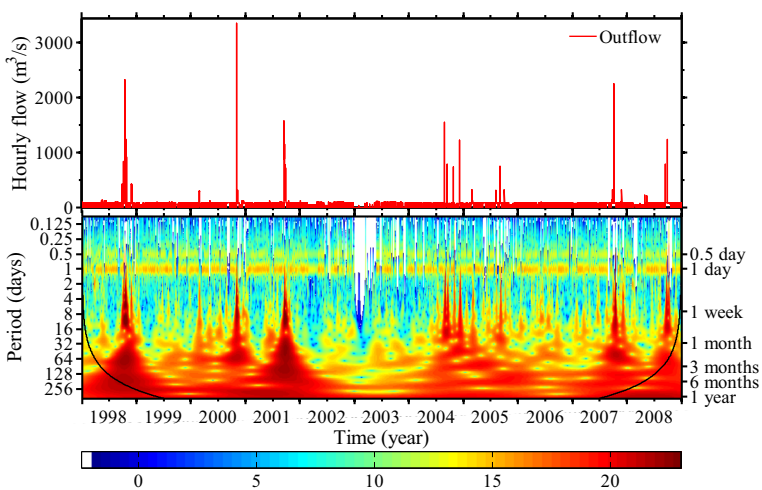

Fig. 3 The hourly outflow series (1998–2008) of the Feitsui Reservoir, Taiwan (*top panel*) and the corresponding wavelet power spectrum (*bottom panel*)
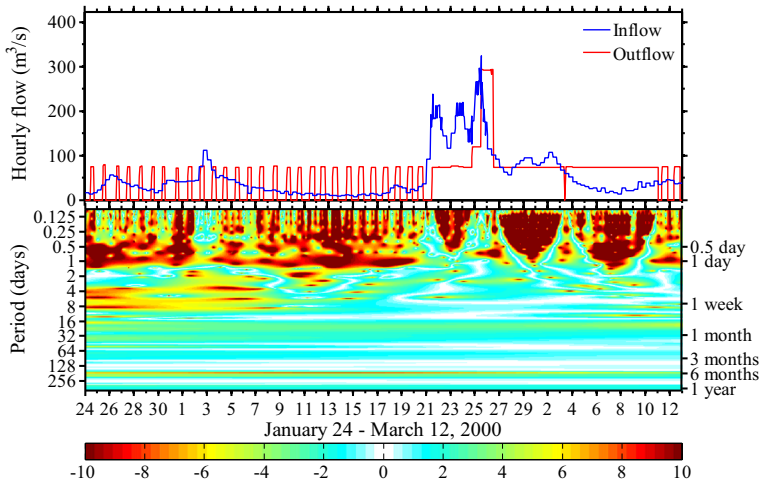
Fig. 4 Recorded inflow and outflow series for the period of January 24 – March 12, 2000 (top panel) and the corresponding spectral differences (*bottom panel*)

peak attenuation is implemented when inflow and pool level exceed predefined flooding thresholds. To quantitatively assess impacts of such complex multi-purpose reservoir operation on natural flow regime, wavelet analysis is conducted to detect time-frequency alteration.

4 Results and Discussions

4.1 Wavelet Analysis of the Multi-Purpose Feitsui Reservoir Operation

The recorded hourly inflow and outflow series for the 1998–2008 period are used to assess impacts of the Feitsui Reservoir operation on the natural flow regime using wavelet transform. A total of 96,432 (=N in equation (3)) hourly streamflow data (δt=1 h) associated with the largest scale of 1.1 years leads to the resulting WPS which are shown in the bottom panels of Figs. 2 and 3 for reservoir inflow and outflow series, respectively. Wavelet power spectrum shown in these figures and thereafter is represented by the base-2 logarithm and expressed in terms of color scale ranging from blue (low power=−2) to red (high power=23). The white swath shown in figures indicates that the logarithmic WPS is less than −2.

Low spectral power of inflow series at scales less than 2 days is clearly observed in the bottom panel of Fig. 2 since mild variation of streamflow occurs in most non-storm periods. The extreme high power (i.e. red swath) at less-than-2-day scales is attributed to floods. Great oscillation of power thus occurs at less-than-2-day scales because streamflow is highly fluctuated between non-flood and flood periods. Spectral power generally increases with increasing scales, i.e., color changes from blue to green, yellow, orange, and then red with increasing scale. In addition, evident temporal fluctuation of WPS at lower scales along the time-axis gradually diminishes with increasing scales, especially when scales exceed 6 months. To better demonstrate the diminished spectral fluctuation with increasing scales, Fig. 5 shows the time variation of WPS of inflow series at 8-h, 1-day, 1-week, 16-day, 1-month, 3-month, 6-month, and 1-year scales. The reduced oscillation of WPS at greater scales is caused by smoothing effect, i.e., more data used in calculation resulting in less oscillation. Slight power
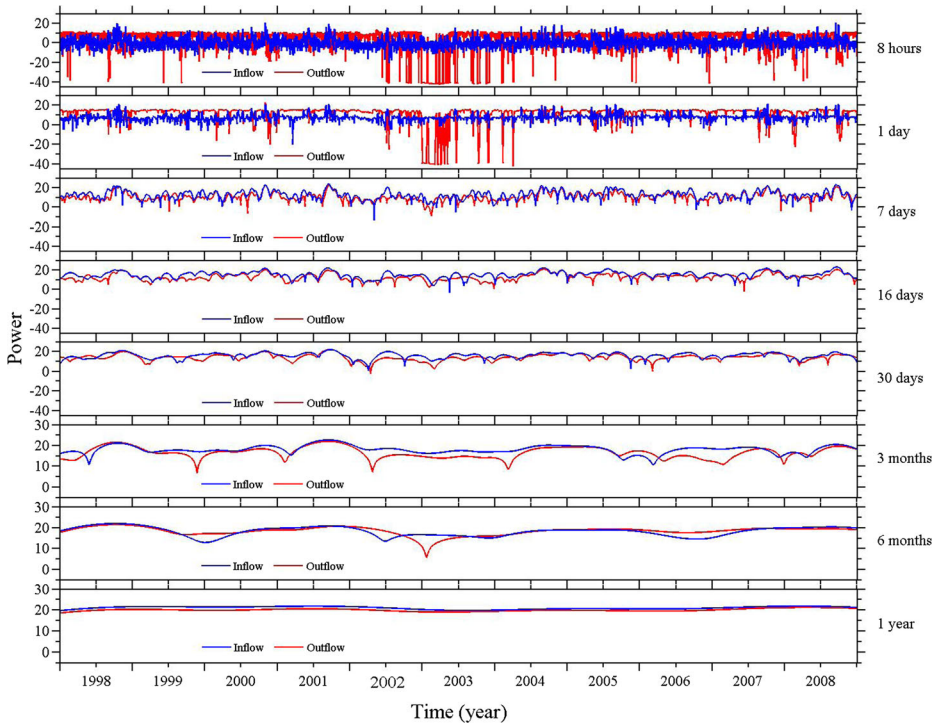
Fig. 5 Time variation of wavelet power spectrum of Feitsui Reservoir inflow and outflow series at various scales

fluctuation along time-axis at 1-year scale can be neglected when comparing with fluctuations of other smaller scales, which is shown in the bottom panel of Fig. 5.

It is worthy to note three significant alterations of outflow WPS (bottom panel of Fig. 3), which include increased power at less-than-1-day scale, reduced power at scales between 1 day and 30 days, and extremely low power occurred in the beginning of 2003. Hydropeaking caused by peak-load type hydropower production leading to violently disturbed streamflow during non-flood periods (see top panel of Fig. 4) causes increasing power at scales less than 1 day. The higher energy swaths (yellow-orange-red region) of inflow spectral power between 1- and 30-day scales slightly reduce since most small floods are totally stored (comparing top panels of Figs. 2 and 3). Extremely low-energy (white swath) in the beginning of 2003 is attributed to severe drought occurs in that period and reservoir operating strategy is changed to drought mode. Water rationing measures implemented in severe drought periods dramatically reduce domestic and hydropower releases. The time variation of outflow WPS at various scales is also shown in Fig. 5. At smaller scales (less than 1 day), outflow WPS has greater oscillation than inflow WPS. This evident oscillation of outflow WPS also diminishes with increasing scales. Reduced spectral difference between outflow and inflow series is observed with increasing scales. Negligible spectral difference at 1-year scale implies that outflow series is highly similar to inflow series at that scale.

Figure 6 shows the spectral difference between reservoir outflow and inflow series, defined as $|W_{n,A}(s_j)|^2 - |W_{n,N}(s_j)|^2$, at various scales for the 1998–2008 period to clearly demonstrate effects of Feitsui Reservoir operation on the WPS alteration. Generally, greater spectral differences (i.e., red swath) are observed at less-than-1-day scales, which are caused by
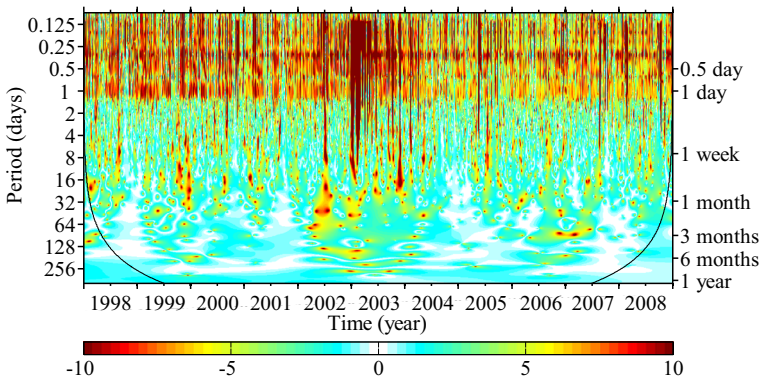
Fig. 6 Spectral differences of recorded hourly outflow and inflow series of 1998–2008 for the Feitsui Reservoir, Taiwan

hydropeaking-type outflow series and mild-variation inflow series. Such phenomenon can be observed by comparing outflow and inflow series associated with corresponding WPS shown in Figs. 2 and 3. Figure 4 also clearly demonstrates greater spectral differences occurred at lower scales for the specific period of January 24−March 12, 2000. This larger spectral difference occurred at lower scales gradually declines with increasing scales due to more data employed in calculation, i.e., smoothing effect. At greater-than-1-year scales, minor spectral difference is attributed to the limited capacity of Feitsui Reservoir that cannot entirely store rare floods, which agrees with results shown in Fig. 5. In addition, extremely high spectral differences (i.e., yellow-orange-red swath) are also noted during severe drought periods such as the period from mid-2002 to mid-2003 at small and moderate scales. This inconsistent variation pattern is caused by implementation of drought operating rules such as water rationing. This fact implicitly implies that spectral differences also depend on the hydrologic condition since it would affect reservoir operating policies.

4.2 Time-Average Wavelet Power Spectrum Analysis

To simplify the hour-based wavelet analysis and examine spectral differences over a yearly period, the yearly time-averaged spectral differences at various scales are calculated as $\frac{1}{(n_2-n_1+1)} \sum_{n=n_1}^{n_2} \left| \left|W_{n,A}\left(s_j\right)\right|^2 - \left|W_{n,N}\left(s_j\right)\right|^2 \right|$ and shown in Fig. 7. A similar variation pattern, i.e., greater spectral alteration at smaller scales and less spectral alteration at larger scales, is observed for all years. However, severe spectral alteration, especially at smaller scales, are noted for years 2002 and 2003, which are recognized as dry years during the 1998–2008 period. Fig. 7 is in line with the spectral differences at various scales shown in Fig. 6, but it offers a useful and simple way to show various variation pattern of spectral alteration for different years and different scales. Regardless of hydrologic conditions, spectral difference increases from approximate 5 (in a range of 4.4−6.0) at 2-h (smallest) scale to a peak difference at 4- to 8-h scale, and then declines to less than 4 when the scale exceeds 2 days. A scale of 2-day can be considered as a division to separate high and low spectral differences. Spectral differences form a peak or plateau when the scale is less than 2-day, and a slightly declined plain at greater-than-2-day scales.
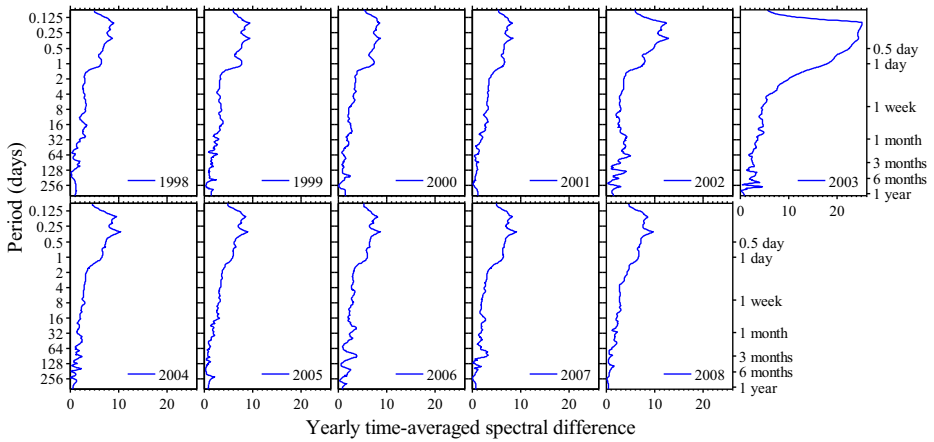
Fig. 7 Yearly time-averaged spectral difference of Feitsui Reservoir for each year over the period of 1998–2008

Time variations of the values of index of spectral alteration (ISA) associated with annul runoff for each year are shown in Fig. 8. A clear opposite variation pattern between ISA and annual runoff is observed. The greatest ISA of 9.5 occurred in 2003 is associated with the lowest annual runoff of 538.7 million m^3. The second and third lowest annual runoff of 549.7 and 721.8 million m^3 in 2002 and 1999 have second and third greatest ISAs of 5.0 and 4.1, respectively. The ISA of other years ranges between 3.6 and 3.8, while annual runoff has a range of 888.1−1587.1 million m^3. This result reveals that hydrologic wet and normal years would result in similar spectral alteration and ISA, which is attributed to the same releasing rules being used to guide reservoir operation. Extremely severe spectral alteration associated with greater ISA occurred in dry years is caused by drought-mode operation rules. During extreme low-inflow periods such as end of 2002 to beginning of 2003, intermittent releases for hydropower production are implemented due to low pool level. Reservoir inflow is generally conserved for future use and unregulated streamflow from the Nanshih Creek is used with top priority to meet domestic requirement. Water rationing measure is implemented for reducing domestic releases during continuous and prolonged droughts would further increase spectral alteration. Greater spectral differences are thus observed in drought years for all scales when comparing with results of wet and normal years.

It is difficult to determine the boundary ISA for dry and non-dry years due to the short length of 11 years. Since years of 2002 and 2003 are recognized as dry years, values of ISA for
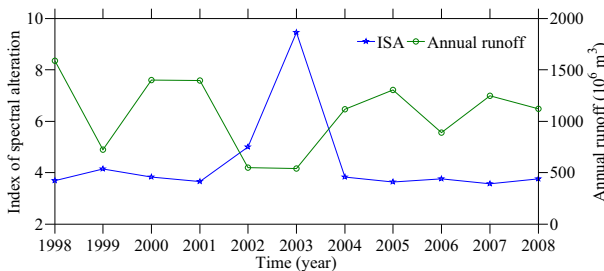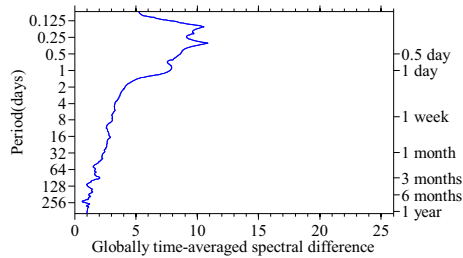

Fig. 8 Time variations of index of spectral alteration (ISA) associated with annual inflow of Feitsui Reservoir for the period of 1998–2008

Fig. 9 Globally time-averaged spectral difference of Feitsui Reservoir for the period of 1998–2008

the wet and normal years are roughly less than 5 for the Feitsui Reservoir case. That is, dry-year category of Feitsui Reservoir case would have ISA greater than 5. Since the value of ISA depends on hydrologic conditions and reservoir characteristics such as capacity, purposes, and operating policies, the ISA of 5 is used as a division of dry and non-dry years for the Feitsui Reservoir case only. In addition, further information such as longer yearly ISAs from simulations is required to determine the general criteria of ISA for high-, moderate-, and low-alteration categories.

The globally time-averaged spectral difference of the 1998–2008 period is shown in Fig. 9, which has a similar variation pattern with those of yearly ones. Spectral difference increases from 5.2 at 2-h scale to a peak value of 10.9 at 8-h scale, and then rapidly declines to 5 at scale between 1 and 2 days. Spectral difference at greater-than-2-day scale further decreases to 1 when the scale reaches 1 year. The ISA of the globally time-averaged spectral difference shown in Fig. 9 is approximate 4.4, which belongs to the non-dry-year category according to the results of the yearly ISAs. The globally time-averaged spectral difference associated with the value of ISA over the entire analysis period offers a simple, but fast and efficient, approach to detect dominant scales of significant alterations and how the alteration varying with scales. However, such results represent long-term average effects and may ignore rare events such as droughts occurred within the analysis period. For example, severe spectral alteration which occurred in drought years such as 2002 and 2003 is not detectable in the globally time-averaged spectral difference shown in Fig. 9. Instead, yearly time-averaged spectral difference associated with the yearly ISA offer more information to describe variation of spectral differences for various scales. It is worth noting that the yearly results also reflect the hydrologic conditions which induce implementation of different reservoir operating rules to cope with such hydrologic conditions.

5 Conclusions

Wavelet transform is adopted in this study to reveal time-frequency alteration caused by multi-purpose Feitsui Reservoir operation. Continuous wavelet transform is simultaneously applied to hourly inflow and outflow series for the 1998–2008 period. Differences between wavelet power spectrum obtained for outflow and inflow series denote severity of hydrologic alterations. The index of spectral alteration (ISA), defined as the mean absolute deviations of power spectrum for all scales over a certain time period, is proposed to assess the severity of altered natural flow regime. This index offers an efficient and quantitative approach for integrating wavelet power spectrum to compare spectral alteration for various hydrologic conditions.

Significant differences between wavelet power spectrum obtained for outflow and inflow series of Feitsui Reservoir reveal that wavelet transform is a useful tool to detect effects of reservoir operation on natural flow regime. Due to hydropeaking-type releases for peak-load

hydropower production causes violent and periodical oscillation at less-than-1-day scale, significant spectral alteration at such scale is observed for the Feitsui Reservoir case. The spectral alteration gradually declines with increasing scales, which can be ignored when the scale is greater than 1 year. That is, outflow and inflow series have high similarity at greater-than-1-year scales, which is attributed to limited capacity of Feitsui Reservoir.

The yearly time-averaged spectral difference of Feitsui Reservoir indicates that the altered spectrum also depends on the dry and non-dry years since hedging rules are implemented to cope with hydrologic drought condition. The proposed index of spectral alteration (ISA) offers efficient and quantitative information to detect yearly variation of hydrologic alteration. ISA of 5 can be roughly recognized as the division of dry and non-dry years for the Feitsui Reservoir case. This index can also be applied to entire 1998–2008 period to obtain globally time-average spectral difference. However, such outcome obtained from long-term average effect would ignore the rare events such as droughts.

Throughout wavelet analysis, effects of multi-purpose Feitsui Reservoir operation on natural flow regime at various scales and different hydrologic conditions are clearly represented. The obtained results offer decision makers useful information to adopt adaptive operating strategies to mitigate negative impacts of altered natural flow regime. The relationship between the proposed method and other comparing pre- and post-impact series schemes such as the range of variability approach (RVA) is not explored in this work. Furthermore, incorporating environmental flow requirements into reservoir operating rules to derive optimal trade-off between human and environmental needs in terms of minimizing spectral alteration and the proposed ISA is a feasible approach to protect downstream ecosystem diversity and riverine health. These issues remain topics for further extending this research.

References

Adamowski K, Prokoph A, Adamowski J (2009) Development of a new method of wavelet aided trend detection and estimation. Hydrological Processes 23(18):2686–2696

Arthington AH, Bunn SE, Poff NE, Naiman RJ (2006) The challenge of providing environmental flow rules to sustain river ecosystems. Ecological Applications 16(4):1311–1318

Batalla RJ, Gómez CM, Kondolf GM (2004) Reservoir-induced hydrologic changes in the Ebro river basin (NE Spain). Journal of Hydrology 290(1–2):117–136

Botter G, Basso S, Porporato A, Rodriguez-Iturbe I, Rinaldo A (2010) Natural streamflow regime alterations: damming of the Piave river basin (Italy). Water Resources Research 46(6), W06522. doi:10.1029/2009WR008523

Cannata A, Montalto P, Patane D (2013) Joint analysis of infrasound and seismic signals by cross wavelet transform: detection of Mt. Etna explosive activity Natural Hazards and Earth System Sciences 13(6):1669–1677

Chen Q, Chen D, Li R, Ma J, Blanckaert K (2013) Adapting the operation of two cascaded reservoirs for ecological flow requirement of a de-watered river channel due to diversion-type hydropower stations. Ecological Modelling 252:266–272

Farge M (1992) Wavelet transforms and their applications to turbulence. Annual Reviews of Fluid Mechanics 24:395–457

FitzHugh TW, Vogel RM (2011) The impact of dams on flood flows in the United States. River Research and Applications 27(10):1192–1215

Galat DL, Lipkin R (2000) Restoring ecological integrity of great rivers: Historical hydrographs aid in defining reference conditions for the Missouri River. Hodrobiologia 422–423:29–48

Gao Y, Vogel RM, Kroll CN, Poff NL, Olden JD (2009) Development of representative indicators of hydrologic alteration. Journal of Hydrology 374(1–2):136–147

García A, Jorde K, Hanit E, Caamaño D, Parra O (2011) Downstream environmental effects of dam operations: changes in habitat quality for native fish species. River Research and Applications 27(3):312–327

Graf WL (2006) Downstream hydrologic and geomorphic effects of large dams on American rivers. Geomorphology 79(3–4):336–360

Jowett IG, Biggs BJF (2006) Flow regime requirements and the biological effectiveness of habitat-based minimum flow assessment for six rivers. International Journal of River Basin Management 4(3):179–189

Kang S, Lin H (2007) Wavelet analysis of hydrological and water quality signals in an agricultural watershed. Journal of Hydrology 338(1–2):1–14

Kikuchi K, Wang B (2010) Spatiotemporal wavelet transform and the multiscale behavior of the Madden-Julian oscillation. Journal of Climate 23(14):3814–3834

Kumar P, Foufoula-Georgiou E (1997) Wavelet analysis for geophysical applications. Reviews of Geophysics 35 (4):385–412

Lau KM, Weng H (1995) Climate signal detection using wavelet transform: How to make a time series sing. Bulletin of the American Meteorological Society 76(12):2391–2402

Ligon FK, Dietrich WE, Trush WJ (1995) Downstream ecological effects of dams. Bioscience 45(3):183–192

Lim ES, Das U, Pan CJ, Abdullah K, Wong CJ (2013) Investigating variability of outgoing longwave radiation over peninsular Malaysia using wavelet transform. Journal of Climate 26(10):3415–3428

Magilligan FJ, Nislow KH (2005) Changes in hydrologic regime by dams. Geomorphology 71(1–2):61–78

Maingi JK, Marsh SE (2002) Quantifying hydrologic impacts following dam construction along the Tana river, Kenya. Journal of Arid Environments 50(1):53–79

Mathews R, Richter BD (2007) Application of the indicators of hydrologic alteration software in environmental flow setting. Journal of the American Water Resources Association 43(6):1400–1413

Monk WA, Wood PJ, Hannah DM, Wilson DA (2007) Selection of river flow indices for the assessment of hydroecological change. River Research and Applications 23(1):113–122

Nakken M (1999) Wavelet analysis of rainfall−runoff variability isolating climatic from anthropogenic pattern. Environmental Modelling and Software 14(4):283–295

Niu J, Sivakumar B (2013) Scale-dependent synthetic streamflow generation using a continuous wavelet transform. Journal of Hydrology 496:71–78

Petts GE (2009) Instream flow science for sustainable river management. Journal of the American Water Resources Association 45(5):1071–1086

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD et al (1997) The natural flow regime: A paradigm for river conservation and restoration. Bioscience 47(11):769–784

Poff NL, Richter BD, Arthington AH, Bunn SE, Naiman RJ, Kendy E et al (2010) The ecological limits of hydrologic alteration (ELOHA): A new framework for developing regional environmental flow standards. Freshwater Biology 55(1):147–170

Puckridge JT, Sheldon F, Walker KF, Boulton AJ (1998) Flow variability and the ecology of large rivers. Marine and Freshwater Research 49(1):55–72

Ramana RV, Krishna B, Kumar SR, Pandey NG (2013) Monthly rainfall prediction using wavelet neural network analysis. Water Resources Management 27(10):3697–3711

Richter BD, Baumgartner JV, Wigington R, Braun DP (1997) How much water does a river need. Freshwater Biology 37(1):231–249

Richter BD, Baumgartner JV, Braun DP, Powell J (1998) A spatial assessment of hydrologic alteration within a river network. Regulated Rivers: Research and Management 14(4):329–340

Sahay RR, Srivastava A (2014) Predicting monsoon floods in rivers embedding wavelet transform, genetic algorithm and neural network. Water Resources Management 28(2):301–317

Sang YF (2013) Improved wavelet modeling framework for hydrologic time series forecasting. Water Resources Management 27(8):2807–2821

Schmidt JC, Wilcock PR (2008) Metrics for assessing the downstream effects of dams. Water Resources Research 44(4), W04404. doi:10.1029/2006ER005092

Shiau JT, Wu FC (2007) A dynamic corridor-searching algorithm to seek time-varying instream flow releases for optimal weir operation: Comparing three indices of overall hydrologic alteration. River Research and Applications 23(1):35–53

Shiau JT, Wu FC (2008) A histogram matching approach for assessment of flow regime alteration: Application to environmental flow optimization. River Research and Applications 24(7):914–928

Shiau JT, Wu FC (2009) Regionalization of natural flow regime: Application to environmental flow optimization at ungauged sites. River Research and Applications 25(9):1071–1089

Shiau JT, Wu FC (2010) A dual active-restrictive approach to incorporating environmental flow targets into existing reservoir operation rules. Water Resources Research 46(8), W08515. doi:10.1029/2009WR008765

Shiau JT, Wu FC (2013) Optimizing environmental flows for multiple reaches affected by a multipurpose reservoir system in Taiwan: Restoring the natural flow regime at multiple temporal scales. *Water Resources Research* 49(1), doi:10.1029/2012WR012638, 565–584

Singer MB (2007) The influence of major dams on hydrology through the drainage network of the Sacramento River basin, California. River Research and Applications 23(1):55–72

Smakhtin VU, Shilpakar RL, Hughes DA (2006) Hydrology-based assessment of environmental flows: An example from Nepal. Hydrological Sciences Journal 51(2):207–222

Steel EA, Lange IA (2007) Using wavelet analysis to detect changes in water temperature regimes at multiple scales: Effects of multi-purpose dams in the Willamette River basin. River Research and Applications 23(4): 351–359

Suen JP (2011) Determining the ecological flow regime for existing reservoir operation. Water Resources Management 25(3):817–835

Taipei Feitsui Reservoir Administration (TFRA) (2004) *Regulation Rules of the Feitsui Reservoir*, Taipei, Taiwan

Thiebaut S, Vennell R (2010) Observation of a fast continental shelf wave generated by a storm impacting Newfoundland using wavelet and cross-wavelet analyses. Journal of Physical Oceanography 40(2):417–428

Torrence C, Compo GP (1998) A practical guide to wavelet analysis. Bulletin of the American Meteorological Society 79(1):61–78

Wang W, Hu S, Li Y (2011) Wavelet transform for synthetic generation of daily streamflow. Water Resources Management 25(1):41–57

White MA, Schmidt JC, Topping DJ (2005) Application of wavelet analysis for monitoring the hydrologic effects of dam operation: glen canyon Dam and the Colorado river at lees ferry, Arizona. River Research and Applications 21(5):551–565

Xia XH, Yang ZF, Wu YX (2009) Incorporating eco-environmental requirements in integrated evaluation of water quality and quantity−a study for the yellow river. Water Resources Management 23(6):1067–1079

Yang T, Xu CY, Singh VP, Shao QX, Hao ZC, Tao X (2010) Assessing the impact of human activities on hydrological and sediment changes (1953–2000) in nine major catchments of the loess plateau, China. River Research and Applications 26(3):322–340

Yang N, Mei Y, Zhou C (2012) An optimal reservoir operation model based on ecological requirement and its effect on electricity generation. Water Resources Management 26(14):4019–4028

Yin XA, Yang ZF (2011) Development of a coupled reservoir operation and water diversion model: Balancing human and environmental flow requirement. Ecological Modelling 222(2):224–231

Zolezzi G, Bellin A, Bruno MC, Maiolini B, Siviglia A (2009) Assessing hydrologic alterations at multiple temporal scales: Adige River, Italy. Water Resources Research 45, W12421. doi:10.1029/2008WR007226