

# A Real-time Flood Monitoring Index Based on Daily Effective Precipitation and its Application to Brisbane and Lockyer Valley Flood Events

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**Abstract** An objective index for flood monitoring is pragmatic tool for flood early warning systems. This study investigates a novel Flood Index ( $I_F$ ) based on Effective Precipitation ( $P_E$ ) for quantifying floods in Brisbane and Lockyer Valley. Using daily precipitation ( $P$ ) data as an input, the  $I_F$  was determined by calculating  $P_E$  using exponentially-decaying time-reduction function considering gradual depletion of water resources over the passage of time and comparing and normalizing the  $P_E$  per day with the means and standard deviations of yearly maximums in the hydrological period. Start of flood was identified for  $I_F \geq 0$ , severity ( $I_F^{acc}$ ) assessed by running-sum on consecutively positive  $I_F$ s duration ( $D_F$ ) as number of days with positive  $I_F$  and peak danger ( $I_F^{max}$ ) as maximum  $I_F$ . The ability of  $I_F$  for flood warning was verified with river height and discharge rates. The most severe flood was recoded in January 1974 in Brisbane ( $I_F^{acc} = 118$ ,  $I_F^{max} = 4.4$ ,  $D_F = 104$  days) with return period ( $T$ ) = 106.2 years. Next was the December 2010–January 2011 event ( $I_F^{acc} = 61.8$ ,  $I_F^{max} = 2.6$ ,  $D_F = 89$  days) with  $T = 53$  years. For Lockyer Valley, December 2010–January 2011 was the most severe ( $T = 104.4$  years). Consequently, we advocate the practicality of the daily  $I_F$  for flood risk assessments where severity, peak danger, duration or return periods are to be considered.

**Keywords** Flood risk · Flood index · Brisbane and lockyer valley floods

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## 1 Introduction

Water-related hazards are an ever-increasing challenge. Current trends in water resource sectors are necessitating the development of scientific tools with practical applications in 21st century (Yevjevich 1991). In Australia, 93 % of building damage from 1900 to 2003 were attributable to cyclones/floods that were most deadly after heatwaves/drought (Coates 1996; Crompton et al. 2008). From 1971 to 2003, floods accounted for >29 % of natural disasters with annual costs over \$US240 million (BTRE 2002). Impacts were exacerbated by 50 % of dwellings in 7 km coastal zone (Chen et al. 2013; Chen and McAneney 2006; Coates 1996; Yeo 2002). Thus, flood recurrence should be viewed as a normal hydrologic feature; the potential danger of which emanates not only from floods' direct effects but also how warning systems are implemented for vulnerability assessment to individuals (Wilhite et al. 1998). Consequently, new tools that convey ability to monitor floods are useful tenets for early warning.

In the twentieth century, Australia witnessed several floods that impacted agriculturally critical Murray-Darling Basin (Roche et al. 2013). Severe events occurred in 1954, 1955, 1956, 1959, 1971 and 1974, with New South Wales (Hunter) flood (February 1955) and Queensland (Brisbane) flood (January 1974) particularly catastrophic (Box et al. 2013; van den Honert and McAneney 2011). Notable floods occurred in Todd River (Alice Springs) (March 1910), Latrobe river (Victoria) (December 1934), Charleville (April 1990), north-eastern Victoria (October 1993) and Katherine (January 1998) (Huq 1980; Yeo 2002). Notwithstanding this, the December 2010–January 2011 flood was catastrophic with damages similar to January 1974 and mid-1950 events (Keogh et al. 2011; NCC 2011; van den Honert and McAneney 2011). In the former, 56,200 insurance payouts totaling \$US2.08 billion (van den Honert and McAneney 2011).

The Standardized Precipitation Index (*SPI*) (McKee et al. 1993) is widely adopted for drought/flood assessment (Du et al. 2013; Hayes et al. 1999; Seiler et al. 2002; Umran Komuscu 1999) although it was designed for drought studies (Wilhite 1996; Wilhite et al. 2000). *SPI* is a probability-based index that compares the cumulative precipitation in a specific period with its mean value. With only monthly precipitation (*P*) as an input, the *SPI* has no issues of parameter calibration, and is thus suitable for flood monitoring (Yuan and Zhou 2004). For example, Seiler et al. (2002) adopted the *SPI* for flood study in Argentina to explain evolution of flood over 25-year period, Du et al. (2013) used it to show the correlation with river discharge and Rauf and Zeepongsekul (2014) used it for rainfall severity and duration studies in Australia.

There is no doubt that flood possibility assessment should be based on how remaining quantity of water due to heavy rain fluctuates over time (Ma et al. 2014) and whether the Flood Index ( $I_F$ ) can reciprocate changing hydrological conditions. Also importantly, how this water volume is distributed is crucial for detecting flood danger (Collier 2007; Lu 2009, 2012; Lu et al. 2013; Nosrati et al. 2011). Flood monitoring should be based on antecedent *P* in a given period, which is not achievable by *SPI* as it is calculated monthly. Even if a flood had occurred, an index is not available until last day of monthly period when statistical analyses of cumulative *P* are completed. As *SPI* has monthly timescale and all days in a hydrological period are assigned equal weighting, *P* recorded in days before that period is not considered objectively. *SPI* assesses flood situation over long-term but is unable to do so over short timescales (e.g., daily). However, operational decision-making require quantification of daily risk using an index that encapsulates start, danger, duration and strength of flood, including time-dependent variability (Lu 2009).

It is also of obvious interest that start/end date of flood event and monitoring spontaneous, short-term or chronic flooding situations, be part of a monitoring system (Charalambous et al. 2013; Lu 2009). *SPI* and other indices focus on  $P$  distribution on monthly or annual scales, ignoring the far more pertinent shorter scales (e.g., weekly, daily). This is problematic for detection of flash-style or short-term events (Collier 2007). A weighted contribution of single day's rainfall or series of heavy rainfall events distributed unevenly is potentially more useful for closer assessment of risk (Lu 2009). Additionally, if  $P$  data alone is used for flood monitoring, changes in water reserves that are important in elevating or reducing the flood risk are not considered objectively (Lu 2009, 2012; Lu et al. 2013).

The novelty of this paper is to testify the practicality of the daily Flood Index ( $I_F$ ) (Byun and Wilhite 1999; Byun and Jung 1998; Nosrati et al. 2011) for flood detection in Brisbane (27.81°S; 152.67°E) and Lockyer Valley (27.55°S; 152.34°E).  $I_F$  is based on Effective Precipitation ( $P_E$ ) deduced from weighted  $P$  over annual cycle where each day's  $P_E$  is based on time-reduction function that places greater emphasis on recent (vs. older) rainfall. A depletion rate is applied on rainfall (since snowfall does not occur in study region), meant to account for hydrological processes (e.g., run-off, evaporation, infiltration). In previous studies (An and Kim 1998; Lee 1998), time-reduction function concurred with rainfall-runoff model output, accounting for declining water resources over time.  $I_F$  is a metric representing deficits/surpluses of water resources per day, in case of a flood, it exhibits a peak to correspond to elevated Available Water Resources Index (*AWRI*) per day reflected by heavy rainfall (Byun and Lee 2002). While  $I_F$  was used in flood studies in Korea (Byun and Jung 1998) and Iran (Nosrati et al. 2011), its application in Australia is new. The purpose of this investigation is threefold:

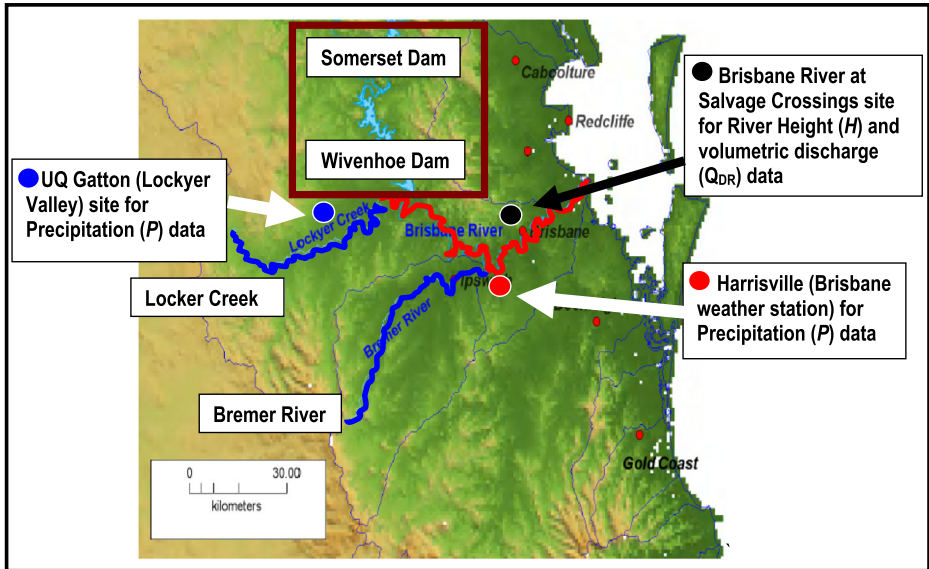
- i. To evaluate  $I_F$  for detecting flood danger and verify its performance with flood parameters (e.g., Australian Height Datum,  $H$ , river discharge rate,  $Q_{DR}$  and dam headwater elevation).
- ii. To quantify flood onset ( $t_{\text{onset}}$ ) and termination ( $t_{\text{end}}$ ) dates and severity ( $I_F^{\text{acc}}$ ), peak danger ( $I_F^{\text{max}}$ ) and duration ( $D_F$ ) including the ability of  $I_F$  for ranking flood events.
- iii. To assess flood return periods and their seasonality.

This paper is structured as follows. Materials and Methods detail precipitation and hydrological data, study area and calculation process of  $I_F$ . In Results and Discussion we present and discuss the findings to demonstrate the usefulness of  $I_F$  in quantifying flood events. In Conclusion that follows, we aver that, compared to other indices used on monthly timescale (e.g., *SPI*), the daily  $I_F$  is a better practical tool for quantification of flood events.

## 2 Materials and Methods

### 2.1 Study Area and Dataset

The study region (Fig. 1) is prone to flooding. Floods occurred throughout Brisbane River, sub-catchments of its tributaries, Lockyer Creek and Bremer River. This is the longest (309 km) in southeast Queensland and extends south to merge with Stanley River downstream of Somerset Dam running into Wivenhoe Lake (van den Honert and McAneney 2011). In order to compute  $I_F$  for flood analysis we acquired rainfall data from Australian Bureau of Meteorology (Haylock and Nicholls 2000). The site closest to Brisbane (Harrisville, 152.67°E;



**Fig 1** a topographical view of study region with location of weather stations (Harrisville and UQ Gatton) in Brisbane and Lockyer Valley, hydrological station (Brisbane River), Wivenhoe dam and major tributaries of Brisbane River system. Modified after van den Honert and McAneney (2011)

27.81°S) and Lockyer Valley (UQ Gatton, 152.34°E; 27.55°S) were selected, where flood events have been prominent (Box et al. 2013; van den Honert and McAneney 2011). Table 1 shows geographical and hydrological characteristics of study sites.

All rainfall data were collated from hourly observations (Jones et al. 2009; Lavery et al. 1997; Suppiah and Hennessy 1998). Quality checks included Standard Normal Homogeneity Test where data were adjusted for inhomogeneities caused by external factors (e.g., station relocation, instrumental errors, adverse exposure to sites) (Alexandersson 1986; Torok and

**Table 1** The hydrological statistics of the study sites

ID	Station name	Location	Elevation (m)	missing data	Precipitation, $P$ (mm year <sup>-1</sup> )		
					Average	Max	Min
— Weather stations —							
40094	Brisbane*	27.81°S, 152.67°E	61	0.58%	830.5	1410.4	357.3
40082	Lockyer Valley**	27.55°S, 152.34°E	89	0.29%	719.7	1093.5	358.7
— Hydrological station —							
<b>Brisbane River Height, <math>H</math> (m AHD), 1959 – 2012</b>							
143001C	Brisbane River at Salvage Crossings	27.44°S, 152.67°E	20	4.54%	Average	Max	Min
					1.450	24.43 [On 12 January 2011]	0.85 [18 August 1978]
<b>Other Details</b>					<b>Brisbane River Discharge Rate, <math>Q_{DR}</math> (ML day<sup>-1</sup>)</b>		
					Site commenced	01/10/1958	
Catchment Area					10170 km <sup>2</sup>		
Distance from stream mouth					131.1 km		
					2.98 × 10 <sup>3</sup>	8.24 × 10 <sup>2</sup> [On 12 January 2011]	50.00 [On 03 July 2008]

\* Also known as Harrisville Post Office; Opened 1896; \*\* Also known as University of Queensland (UQ) Gatton; Opened 1897

Nicholls 1996). Statistical correction removed gross single-day errors. Rather than making adjustments in means, daily records were adjusted for discontinuities at 5, 10, ..., 95 percentiles. Missing data (<0.6 %) were deduced from artificial rainfall based on cumulative distributions. Brisbane River height ( $H$ ) and discharge ( $Q_{DR}$ ) were acquired from Water Monitoring Data Portal (Department of Environment and Resource Management <http://watermonitoring.dnrm.qld.gov.au/host.htm>) (DNRM 2014). Also, headwater elevation and outflows from the Wivenhoe dam (152.61°S; 27.39°S) were obtained for January 2011 flood period (van den Honert and McAneney 2011). Subsequently, the data were used to validate the flood detection response of the  $I_F$ .

## 2.2 Theory of Flood Index

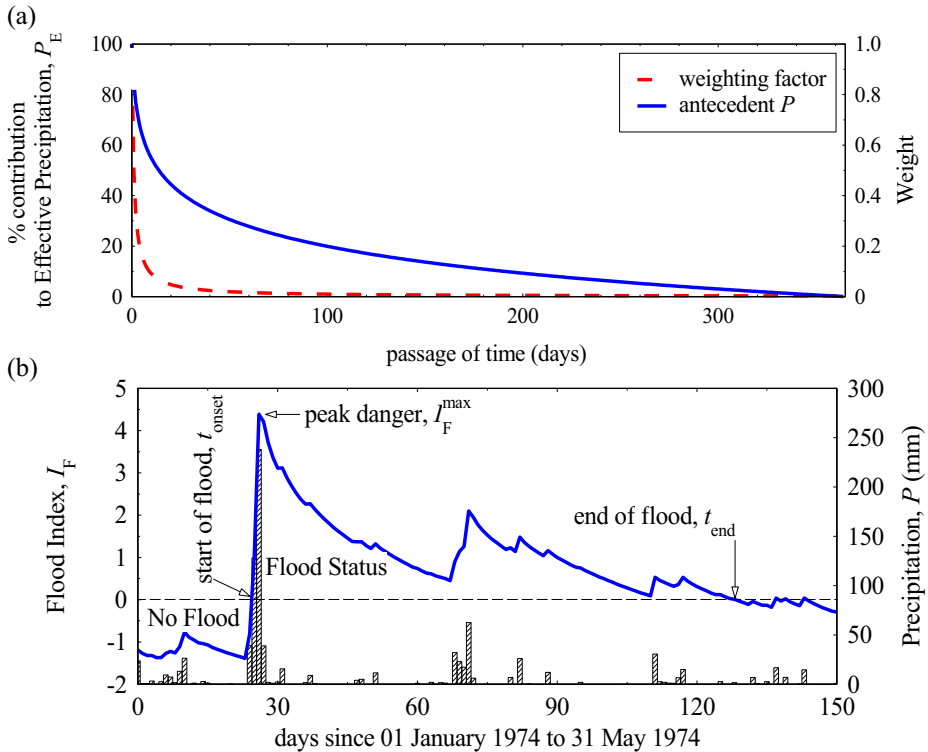
Data were analyzed using FORTRAN software (<http://atmos.pknu.ac.kr/~intra3/>) (Byun and Wilhite (1999). Consistent with recent works (Lu 2009), our method used the logic that flood danger on any day is assessed by superimposing current day's  $P$  on antecedent days' extent of flood. In this study,  $I_F$  was derived from daily Effective Precipitation ( $P_E$ ), the summed value of rainfall for current and antecedent day determined by a time-dependent reduction function (Byun and Jung 1998). Suppose  $P_m$  was the rainfall recorded on any day,  $m$  ( $1 \leq m \leq 365$ ) and  $N$  is the duration of summation of preceding period,  $P_E$  for that (current  $i^{\text{th}}$ ) day was:

$$\begin{aligned}
 P_{E_i} &= \sum_{N=1}^D \left[ \frac{\sum_{m=1}^N P_m}{N} \right] \\
 &= P_1 + \frac{P_1 + P_2}{2} + \frac{P_1 + P_2 + P_3}{3} + \dots + \frac{P_1 + P_2 + P_3 + \dots + P_{365}}{365} \\
 &= P_1 \left( 1 + \frac{1}{2} + \frac{1}{3} + \dots + \frac{1}{365} \right) + P_2 \left( \frac{1}{2} + \frac{1}{3} + \dots + \frac{1}{365} \right) + \dots + P_{365} \left( \frac{1}{365} \right) \\
 &\approx P_1 + 0.85P_2 + 0.77P_3 + \dots + 4.23 \times 10^{-4}P_{365}
 \end{aligned}
 \tag{1a-d}$$

Equations (1a-d) define the degree by which  $P_m$  is converted into  $P_E$  for  $i^{\text{th}}$  day but more importantly, the model considers antecedent  $P$  with reduced weights. That is,  $P_E$  will accumulate 100 % of precipitation received a day before,  $\approx 85$  % of that received 2 days before,  $\approx 77$  % of that received 3 days before, and so on, to  $\approx 0.0423$  % of precipitation 365 days before the  $i^{\text{th}}$  day (Fig. 2a). Clearly the model puts highest weight on present rainfall whereas previous days' contributions decrease gradually up annual cycle ( $N=365$  days, ignoring leap year for simplicity).<sup>1</sup>

Unlike rainfall-runoff models, our logic requires no parameter estimation, yet it describes systematically changes in water reserves due to present ( $i^{\text{th}}$ ) and antecedent  $P$ , whilst considering general effects of a water balance model (Lu 2009). Notably the reduced size of weighting over time signifies loss of water resources due to hydrological processes (e.g., runoff), which also assumes that other topographical influences (e.g., catchments size, shape, vegetation cover or slope) are absorbed into the  $P_E$ . The decay of water resources peaks first few days after rainfall event (An and Kim 1998; Lee 1998;

<sup>1</sup> For any given leap year, the  $P$  value was added to the  $P$  value for March 01st.



**Fig 2** a The ratio of weighted contribution of raw precipitation ( $P$ ) into effective precipitation ( $P_E$ ) over annual cycle ( $N=365$  days). b An example of flood monitoring using the daily Flood Index ( $I_F$ ) from 01 January–31 May 1974

Lu 2009). From this standpoint, flood danger is expected to be greatly influenced by recent downpour but cumulative (lesser) effect of antecedent rainfall, is also considered in an objective manner (Lu 2009, 2012; Lu et al. 2013).

Based on the  $P_E$ , Available Water Resources Index ( $AWRI$ ) (Byun and Lee 2002; Kim et al. 2009) which represents the accumulated  $P$  over an annual cycle is

$$AWRI = \frac{P_E}{W} \tag{2}$$

$$W = \sum_{n=1}^{n=D} \frac{1}{n} \tag{3}$$

Where  $W$  ( $\approx 6.48$ ) equals weight factor applied as an exponentially decay time-reduction function to the accumulation of precipitation for  $N$  ( $\approx 365$ ) days. This concurs with physical reasoning of reduction in water resources in rainfall-runoff models (Jakeman and Hornberger 1993; Lee and Huang 2013) and flood studies (Lu 2009, 2012). Our equation is less complex than rainfall-runoff models, advantageous for assessing surplus/deficit of water reserves that likely trigger flood situations. If  $AWRI$  is larger than normal, water resources are considered to be relatively abundant, indicating the flood possibility (Han and Byun 2006).

The  $I_F$  a standardized metric calculated as

$$I_F = \frac{P_E - \frac{1915}{2012} \overline{P_E^{\max}}}{\sigma\left(\frac{1915}{2012} \overline{P_E^{\max}}\right)} \quad (4)$$

where,  $\frac{1915}{2012} \overline{P_E^{\max}}$  and  $\sigma\left(\frac{1915}{2012} \overline{P_E^{\max}}\right)$  are means and standard deviations of yearly maximum daily  $P_E$  across the recorded hydrological period (1915–2012). Flood is identified using the criterion whether  $I_F > 0$ , severity,  $I_F^{acc}$  is the sum of positive  $I_F$  from flood onset [ $t_{onset}$ , i.e., first day when  $I_F > 0$  or daily  $P_E$  exceeds the normal ( $\frac{1915}{2012} \overline{P_E^{\max}}$ )] to its end ( $t_{end}$ , last day  $I_F > 0$ , before dropping below 0, or day before  $P_E$  drops to being less than to the normal) and peak danger,  $I_F^{\max}$  = maximum  $I_F$  between  $t_{onset}$  and  $t_{end}$ , while duration,  $D_F$  = number of days between onset/end date. These are concordant with the running-sum approach Yevjevich, (1967)

$$I_F^{acc} = \sum_{t=t_{onset}}^{t=t_{end}} I_{F_t} \quad \text{where } I_{F_t} > 0 \quad (5)$$

$$I_F^{\max} = \max(I_F)_{t_{onset}-t_{end}} \quad (6)$$

$$D_F = t_{end} - t_{onset} \quad (\text{days}) \quad (7)$$

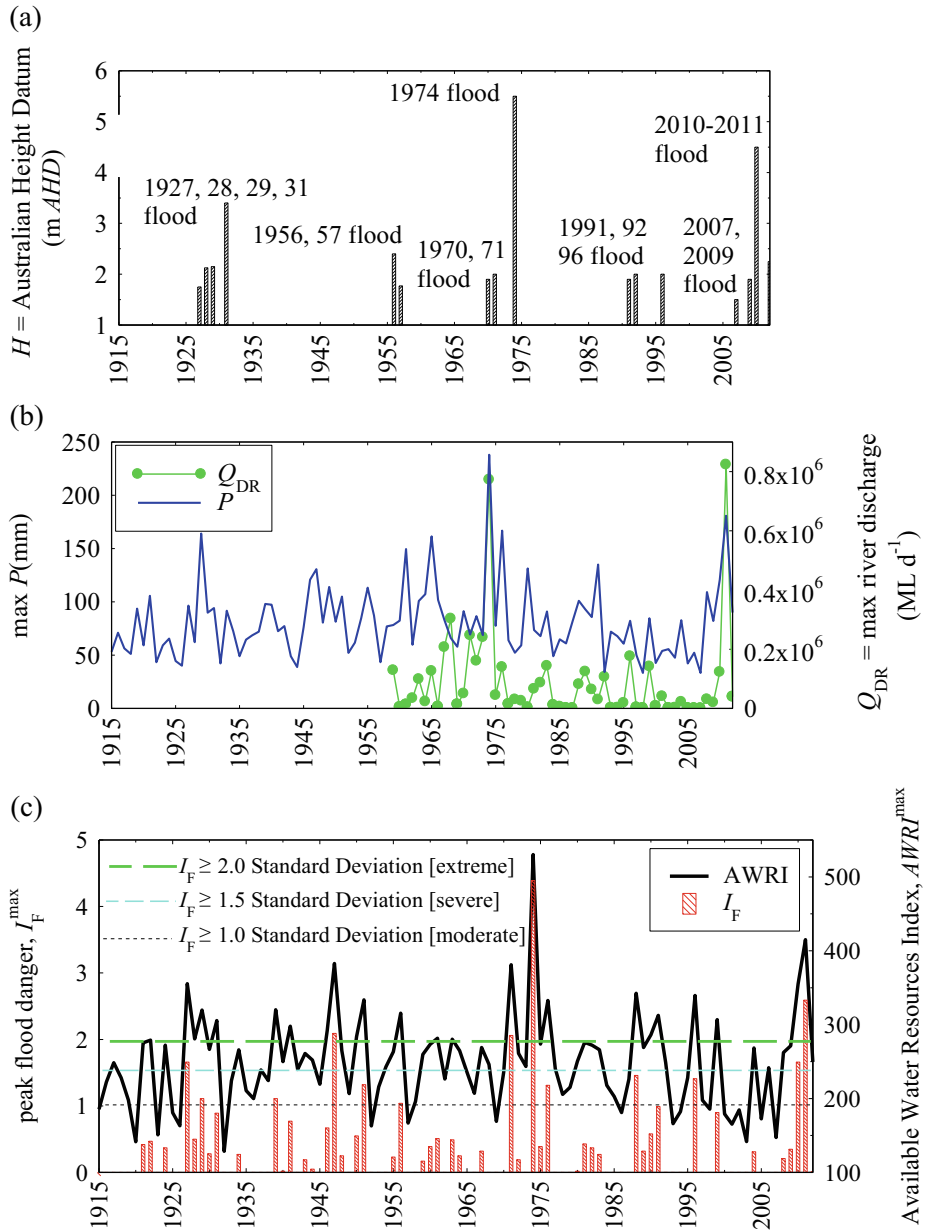
where,  $I_{F_t}$  is the index of flood for the day  $t$  during a period of flooding, i.e., when  $I_F > 0$  and  $t_{onset} \leq t \leq t_{end}$ .

For any flood,  $I_F$  is a time-varying signal where significantly low (high) rainfall yields negative (positive) value (Byun and Wilhite 1999; Kim and Byun 2009; Nosrati et al. 2011). Fig. 2b exemplifies practicality of the  $I_F$  for detecting  $t_{onset}$  and  $t_{end}$  and flood properties ( $I_F^{acc}$ ,  $I_F^{\max}$  and  $D_F$ ). Arguably, changes in  $I_F$  and  $P$  for catastrophic floods in January 1974 are in agreement where spurts in rainfall, as reflected by responsive changes of  $I_F$ .

### 3 Results and Discussion

As Brisbane City is built on a flood plain, floods have been recorded as far back as 1840s (Roche et al. 2013). In this study, we focus on floods in 20th Century where reliable data were available, and employed the  $I_F$  for analyzing floods over 1915–2012. Figure 3a displays annual time-series of flood periods based on  $I_F$  and *AWRI* for Brisbane River, with precipitation ( $P$ ), Australian Height Datum ( $H$ ) and river discharge ( $Q_{DR}$ ). Note that river height ( $H$ ) expressed in units of m *AHD* are altitude measurements equivalent to elevations above median sea level (van den Honert and McAneney 2011).

Based on recorded  $H$ , major flood years were identified, in particular, 2010–2011, 2007–2009, 1991, 1992, 1996, 1974, 1970–71, 1974, 1956–57 and 1927–31, among the others. Out of these, the largest  $H$  was identified for 1974, followed by 2010–2011 and 1927–31. To demonstrate how well  $I_F^{\max}$  represented flood events captured by  $H$ , the annual maximum values of  $Q_{DR}$  and  $P$  along with  $I_F^{\max}$  and  $AWRI^{\max}$  are included (Fig. 3). Note that *AWRI* is the total available water resources index (Eq. 2), and is thus, a flood possibility indicator.



**Fig 3** Annual analysis of flood events: (a) Australian Height Datum (m AHD) for Brisbane River (van den Honert and McAneney 2011), (b) maximum precipitation,  $P$  (left) and maximum river discharge,  $Q_{DR}$  (right), (c) Peak danger,  $I_F^{\max}$  (left) and Available Water Resources Index,  $AWRI^{\max}$  (right) for Brisbane

However, the Flood Index ( $I_F$ ) is a normalized form of  $AWRI$  where hydrological means of yearly maximum and standard deviations of effective precipitation are used. Whereas  $I_F$  is mainly the index for flood detection,  $AWRI$  is used as supplementary parameter for quantifying the extent of flood possibility.



Notably, peaks in  $H$  identified for major floods agreed with peaks in  $I_F^{\max}$  and  $AWRI^{\max}$ . For example, severe (1971) flood registered the highest  $H=5.5$  m  $AHD$ , coinciding with highest annual  $I_F^{\max}$  ( $\approx 4.4$ ). Likewise, second severe event ( $H \approx 4.5$  m  $AHD$ ) in 2010–2011 flood yielded second highest  $I_F^{\max}$  ( $\approx 2.6$ ). Interestingly, highest  $H$  and  $I_F^{\max}$  corresponded to highest river discharge ( $\approx 772.84 \times 10^3$  MLd $^{-1}$  for 1974 flood and  $\approx 123.26 \times 10^3$  ML d $^{-1}$  for 2010–2011 flood). Similarly, largest  $AWRI^{\max}$  ( $\approx 530$  mm) was recorded in 1974, with second largest ( $\approx 415$  mm) in December 2010–January 2011 event (Fig. 3a–c). A scatterplot of maximum  $P$ ,  $Q_{WL}$  and mean  $Q_{DR}$  for Brisbane River (Appendix A1) yielded linear correlation with  $I_F^{\max}$ . This verified that annual  $I_F^{\max}$  was in parity with published literature, precipitation and  $Q_{DR}$  and  $H$  for floods analyzed over 1915–2012.

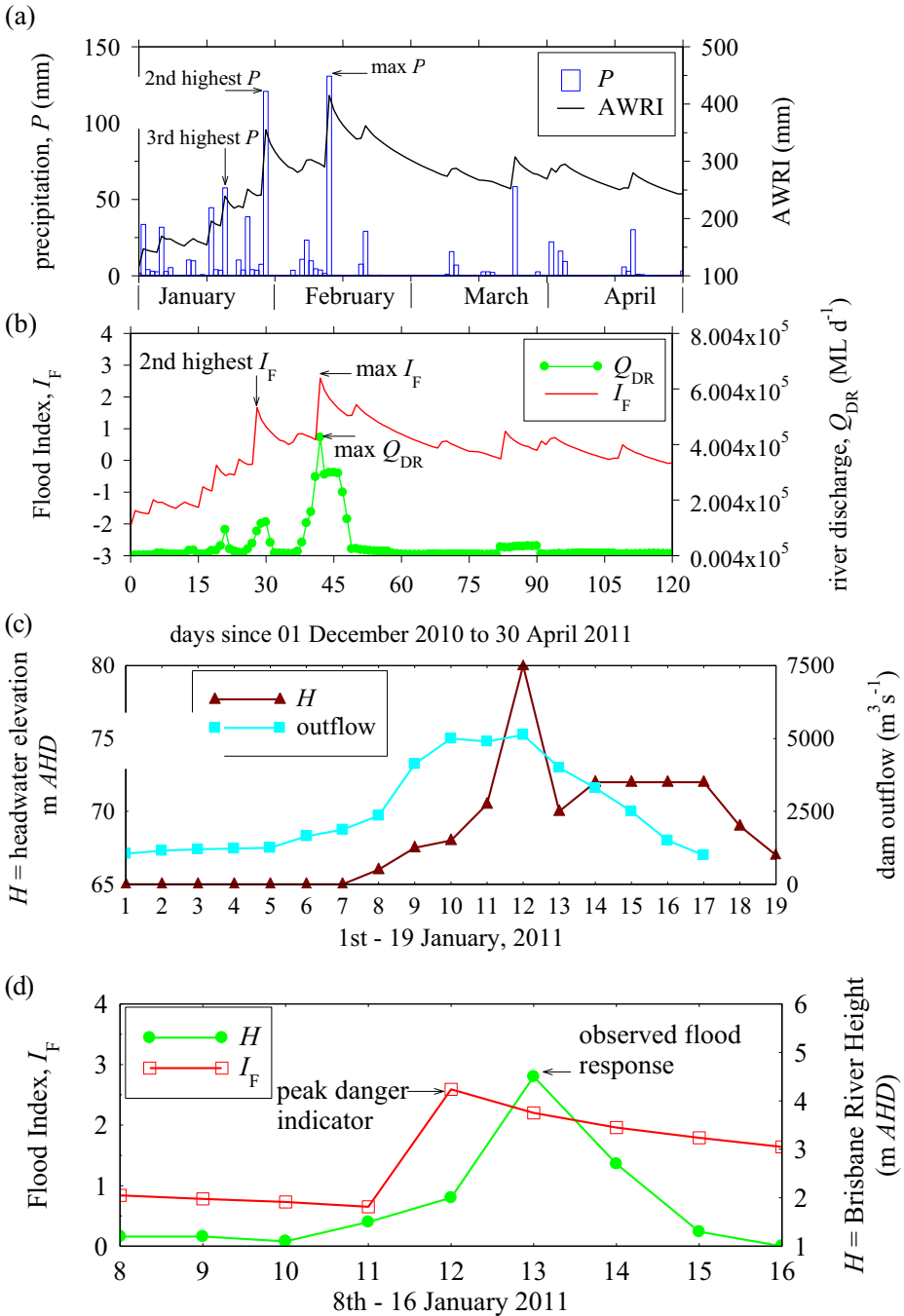
When analyzing floods, daily monitoring of flood is appealing for decision-makers in risk assessment issues. In Australia later half of 2010 and early 2011 was characterized by one of the four strongest La Niñas since 1900. Wet conditions were associated with extreme rainfall events and widespread flooding (Keogh et al. 2011). A plot of daily  $I_F$ ,  $AWRI$ , mean  $Q_{DR}$  and  $P$  for Brisbane River between 01-December 2010 and 31 March 2011 showed good agreement of the fluctuations in  $I_F$  and those of other parameters (Fig. 4). In particular, maxima in  $P$  (Fig. 4a) coincided with maxima in  $I_F$  and  $Q_{DR}$  (Fig. 4b). Likewise, peak of second highest precipitation coincided with second highest  $I_F$  and  $Q_{DR}$ . Clearly, this indicates that  $I_F$  was responsive to fluctuations in  $P$  and  $Q_{DR}$  during the December 2010–January 2011 flood.

It was observed that gradual rise in  $P$  in first 40 days of the period was mimicked well by changes in  $AWRI$  (Fig. 4a), i.e.,  $AWRI$  rose with each notable rainfall event, as depicted by bars representing rainfall per day.  $I_F$  and  $Q_{DR}$  also showed similar trends (Fig. 4b). From day 42 to 83 of the hydrological period,  $P$  exhibited a significant decline with majority days being almost rainless (Fig. 4a). This dry period led to an “exponential-like decay” in  $AWRI$  and  $I_F$  although occasional rainfall events appeared to reciprocate the trend (Fig. 6b). Quite clearly, our model of  $P_E$  (Eqs. 1, 2 and 3) was responsive to dynamical changes in hydrological conditions, and was thus, able to provide crucial information about potential flood risks.

According to sources (Babister and Retallick 2011; Box et al. 2013; O’Brien 2011; Seqwater 2011; Van Vuuren et al. 2011), the December 2010–January 2011 flood’s climax occurred on January 13, 2011 with major flooding around Brisbane River and Lockyer Valley. Reports pointed out the crucial role of residual water from Wivenhoe dam as a primary cause of floods (Seqwater 2011). In Fig. 4c, d, we showed the daily  $P$ ,  $I_F$  and  $AWRI$  between January 8 and 16, 2011 alongside the parameters typical of Wivenhoe dam’s hydrological state (i.e., headwater elevation, volumetric outflow and Brisbane River’s  $H$  (O’Brien 2011; Seqwater 2011; van den Honert and McAnaney 2011). Our interest in doing so was to monitor flood danger using daily changes in  $I_F$  and other indicators of flood situation.

As per Fig. 4c, d, the greatest flood risk was indisputably indicated by peaked  $I_F$  ( $\approx 2.60$ ) on January 12, 2011 with 130 mm rainfall (equivalent  $AWRI=415$  mm). While maximum outflow ( $\approx 7500$  m $^3$  s $^{-1}$ ) in Wivenhoe dam was attained on January 12, it was only the next day (January 13) that headwater elevation and Brisbane River’s  $H$  peaked (72.55 m and 4.55 m  $AHD$ ; Fig. 4c, d). Accordingly,  $I_F$  was considerably responsive in replicating subtle changes in hydrological state of Wivenhoe dam and Brisbane River, and therefore was highly instrumental in reflecting flood danger.

To demonstrate the efficacy of  $I_F$  in estimating accumulated stress caused by flood events, the severity ( $I_F^{acc}$ ), peak danger ( $I_F^{\max}$ ), and duration ( $D_F$ ) parameters were derived using running-sum approach (Yevjevich, 1967) (Eqs. 5, 6 and 7). Here the  $D_F$  should be interpreted with caution, as this property represents all days with  $I_F > 0$ , but it is not meant to measure the



**Fig 4** Assessment of December 2010–January 2011 event in Brisbane: (a) precipitation ( $P$ ) and Available Water Resources Index (AWRI), (b) Flood Index ( $I_F$ ) and maximum river discharge ( $Q_{DR}$ ), (c) Volumetric outflow from Wivenhoe Dam (m<sup>3</sup>s<sup>-1</sup>) and headwater elevation (m AHD) due to excess water released in January 2011, (d) pinnacle of flood event in terms of the  $I_F$  and Brisbane River height ( $H$ ). Note: Headwater elevation, dam outflow and river height were digitized from O’Brien (2011), Seq (2011) and van den Honert and McAneney (2011)

period (length) of reported inundations. Out of all events identified from 1915–2012, ten severe cases were ranked in order of  $I_F^{acc}$  (Eq. 7; Table 2a, b). For both locations, severity-based ranking was consistent with ranking based on  $I_F^{max}$  and  $D_F$ . In agreement with annual flood analysis (Fig. 3), 1974, 2010, 1971, 1947 and 1956 stood out as iconic flood years. For Lockyer Valley, 2010, 1996, 1971, 1974 and 1988 had severe floods. With respect to floods in Brisbane, the 1974 flood outweighed other events based on flood indicators ( $I_F^{acc}=118$ ,  $I_F^{max}=4.4$  and  $D_F=104$  days). This was confirmed by water-intensive properties for January 1974 event ( $AWRI^{tot}=33,446$  mm,  $P=715$  mm and  $I_F^{max}=530$  mm).

Another flood dubbed as the worst in Brisbane started on December 29, 2010 (Keogh et al. 2011; NCC 2011; van den Honert and McAneney 2011). The flood indicators recorded  $I_F^{acc}=61.3$ ,  $I_F^{max}=2.6$  and  $D_F=89$  days, which were less than half in magnitude compared to the January 1974 event. Similarly, December 2010–January 2011 event's water-intensive properties were  $\approx 25\%$  lower than January 1974. However, worst flood in Lockyer Valley was recorded in December 2010 with similar  $I_F^{acc}$ ,  $I_F^{max}$  and  $D_F$  as coeval event in Brisbane. However, total  $AWRI$  and maximum  $P$  for Lockyer Valley in December

**Table 2** Ranking of flood events over 98-years based on Flood Index ( $I_F$ ) according to severity,  $I_F^{acc}$  (accumulated  $I_F$ ); peak danger,  $I_F^{max}$  (maximum  $I_F$  from  $t_{onset}$  and  $t_{end}$ ) and duration,  $D_F$ . Acronyms:  $AWRI^{tot}$ ≡total Available Water Resources Index;  $P^{tot}$ ≡total precipitation and  $AWRI^{max}$ ≡maximum Available Water Resources Index

Rank	Onset Date $t_{onset}$	Flood Properties			Water Intensive Properties		
		Severity $I_F^{acc}$	Peak Danger $I_F^{max}$	Duration $D_F$ (days)	$AWRI^{tot}$ (mm)	Precip. $P^{tot}$ (mm)	$AWRI^{max}$ (mm day <sup>-1</sup> )
Brisbane							
1	26-Jan-1974	118.1	4.4	104	33446	715	530
2	29-Dec-2010	61.3	2.6	89	26073	528	415
3	26-Jan-1971	58.3	2.1	66	20162	402	381
4	13-Feb-1947	56.6	2.1	79	23284	482	383
5	09-Feb-1956	25.7	1.0	53	14834	333	315
6	23-Jan-1927	18.6	1.7	26	7658	317	355
7	04-Apr-1988	15.1	1.5	23	6694	223	342
8	03-May-1996	11.1	1.4	17	4942	184	339
9	10 Mar-1939	8.0	1.1	17	4741	206	320
10	31-Jan-1951	6.2	1.3	12	3384	114	334
Locker Valley							
1	26-Dec-2010	62.1	2.80	81	23103	472	422
2	02-May-1996	61.5	3.62	52	16285	415	477
3	20-Jan-1971	49.1	1.80	72	20129	414	355
4	26-Jan-1974	43.3	2.96	42	12725	336	432
5	05-Apr-1988	19.9	1.38	34	9284	230	327
6	11-Jan-1968	19.6	2.04	26	7391	218	371
7	18-Feb-1950	17.0	1.17	32	8624	199	312
8	17-Feb-1928	16.6	1.26	29	7892	185	318
9	11-Mar-1939	12.7	1.28	21	6865	222	319
10	10-Feb-1992	10.1	1.37	24	6288	270	326

2010–January 2011 event was 10 % lower than the coeval Brisbane flood. Also, interestingly, flood ranks for two sites were independent of each other, with distinct ranking sequences for two stations (Table 2a, b).

Figure 5 a, b shows boxplot of  $I_F$  and  $AWRI$  for ten worst events in Brisbane according to quartile summaries ( $Q_1$  lower quartile,  $Q_2$  median,  $Q_3$  upper quartile). Outliers beyond the whiskers are largely represented  $I_F^{max}$  for each event. Evidently, significant number of outliers recorded for January 1974, December 2010–January 2011 and February 1947 events should be interpreted as indicators of severe flood, confirmed by large  $I_F$  and  $AWRI$ . On this basis, the flood danger in January 1974 outweighed December 2010–January 2011 event. Also interestingly, the quartiles and range of  $I_F$  was larger for January 1974 compared to December 2010–January 2011 event.

For five worst events in Brisbane from 1915–2012, the distribution statistics ( $Q_1$ ,  $Q_2$ ,  $Q_3$ ) and minimum, maximum and standard deviations ( $\sigma$ ) deduced from time-series data using  $t_{onset}$  and  $t_{end}$  were checked (Tables 3 and 4). Consistent with boxplots (Fig. 5a, b), the statistics demonstrated that January 1974 flood was the worst of all in Brisbane. Except  $P$  values, which were zero for  $Q_1$ ,  $Q_2$ ,  $Q_3$  and the minimum, the distribution of flood indicators were larger for January 1974 compared to December 2010–January 2011 event. Interestingly, ranking based on maximum  $P$  concurred with ranking based on  $AWRI^{max}$  and  $I_F^{max}$  (Figs. 4 and 5). This certified ability of  $I_F^{max}$  as a flood danger indicator capable of detecting anomalously high rainfall, and consequently, elevated water resources that trigger a flood.

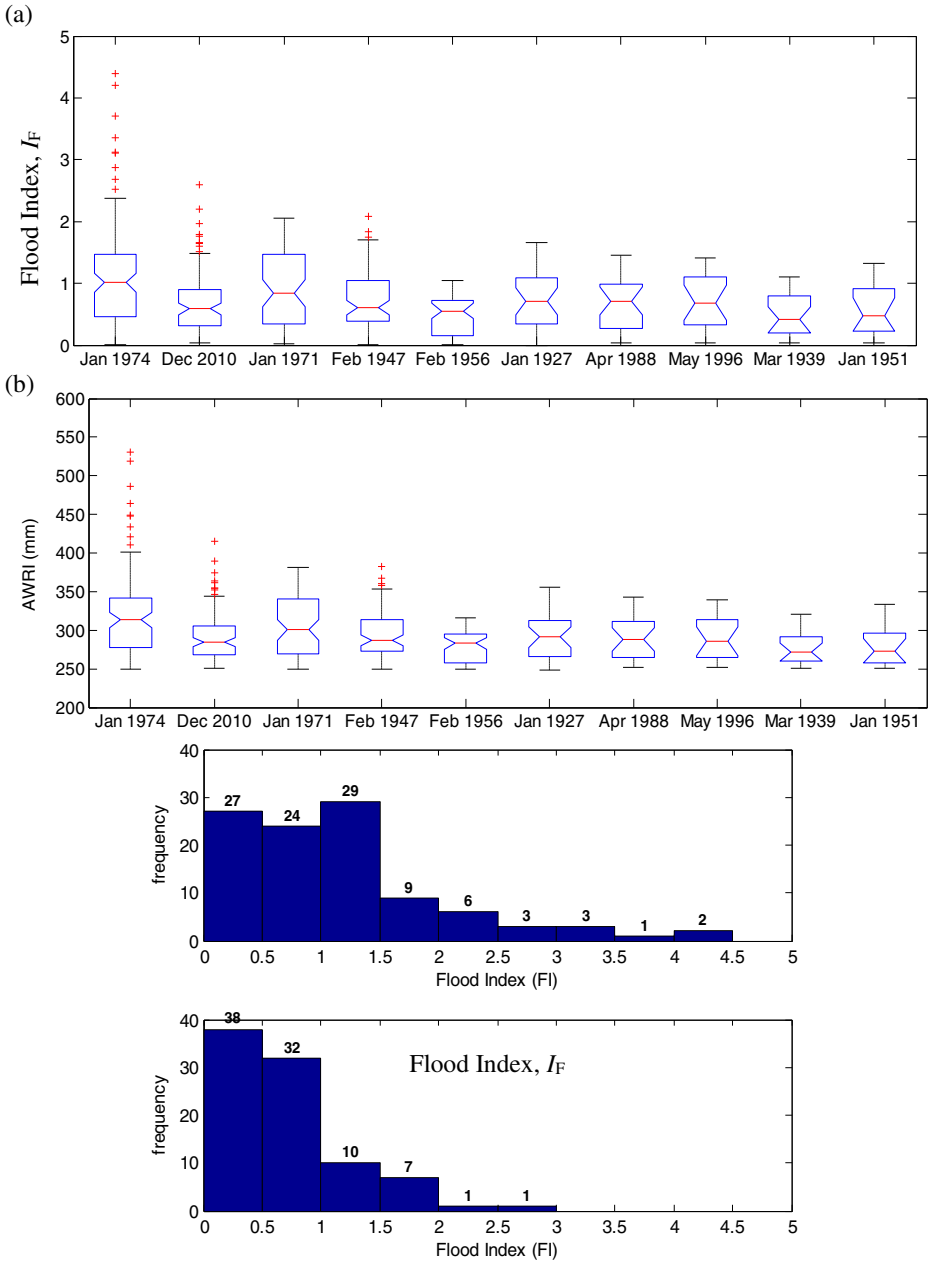
As  $I_F$  represents potential flood danger we analyzed the region’s two worst events based on data from respective  $t_{onset}$  to  $t_{end}$ . Figure 5c shows a histogram of  $I_F$  categorized by the level of severity ( $I_F = 0$  to 4.5 in increment of 0.5) for January 1974 ( $D_F=104$  days) and December 2010–January 2011 ( $D_F=89$  days) events. Tables 3 and 4 shows percentage of days in  $I_F$  categories. Number of days between  $0 < I_F \leq 0.5$  category was undoubtedly higher for December 2010–January 2011 compared to January 1974 event ( $\approx 42.7$  % vs. 26.0 %, respectively), as was the case for days when  $0.5 < I_F \leq 1.0$  (36.0 % vs. 23.1 %, respectively). However, when more severe flooding ( $I_F > 1.0$ ) was considered, the frequency was higher for January 1974 (27.9 %, 8.7 % and 14.4 %, for  $1.0 < I_F \leq 1.5$ ,  $1.5 < I_F \leq 2.0$ , and  $I_F > 2.0$ ) relative to December 2010–January 2011 event (11.2 %, 7.9 % and 2.2 %, respectively). Large percentages of days agreed with more severe floods in January 1974 relative to December 2010–January 2011 event.

The statistical return period ( $T$ ) was estimated by quantitative assessment of flood recurrence (Kim et al. 2003). Variables were assumed to be independent and identically distributed (Chow et al. 1988) so a flood’s  $T$  value was the inverse of exceedance probability,  $p=P(X > x_T)$

$$T = \frac{1}{p (X > x_T)} = \frac{1}{1-p (X \leq x_T)} \tag{8}$$

where,  $x_T$  was the magnitude of event with return period  $T$  and random variable  $X$  was the severity parameter denoted by  $I_F^{acc}$ . In accordance with Eagleson (1972) and Willems (2000), time-series of independent events were converted to equivalent distribution for annual exceedance time-series using partial-duration-series. If marginal cumulative distribution of flood severity,  $I_F^{acc}$  for a given threshold level, was denoted by  $F_D(I_F^{acc})$ , the return period of flood severity,  $T_D(I_F^{acc})$  of the given event was

$$T_D = \frac{N}{n(1-F_D(I_F^{acc}))} = \frac{1}{\theta(1-F_D(I_F^{acc}))} \tag{9}$$



**Fig 5** a, b Distribution of flood parameters for top ten events in Brisbane in terms of Flood Index,  $I_F$  and Available Water Resources Index,  $AWRI$ , (c, d) Comparison of the frequency (days) with  $I_F$  for January 1974 and December 2010–January 2011 events

where,  $\theta = n / N$  and  $n =$  total number of events ( $D_F$ ) during  $N (=98)$  years. In Eq. (9), the cumulative probability was estimated using mean rank approximation:

**Table 3** Distribution statistics of flood event parameters for five major events in Brisbane using time-series of  $I_F$

Statistic	January 1974 Flood			December 2010–January 2011 Flood			January 1971 Flood			February 1947 Flood			February 1956 Flood		
	$P$	$AWRI$	$I_F$	$P$	$AWRI$	$I_F$	$P$	$AWRI$	$I_F$	$P$	$AWRI$	$I_F$	$P$	$AWRI$	$I_F$
Lower Quartile, $Q_1$	0.0	278.1	0.46	0.0	268.9	0.31	0.0	270.6	0.34	0.0	273.6	0.39	0.0	258.1	0.15
Median, $Q_2$	0.0	313.3	1.01	0.0	285.7	0.58	0.7	301.6	0.83	0.0	287.4	0.60	0.0	283.8	0.55
Upper Quartile, $Q_3$	0.0	278.1	0.46	0.0	268.9	0.31	0.0	270.6	0.34	0.0	273.6	0.39	0.0	258.1	0.15
Minimum	0.0	249.5	0.01	0.0	250.4	0.03	0.0	249.8	0.02	0.0	249.6	0.01	0.0	249.7	0.01
Maximum	238.0	<b>530.3</b>	<b>4.39</b>	130.8	<b>415.1</b>	<b>2.59</b>	69.3	381.2	2.06	76.2	382.9	2.09	69.6	315.5	1.04
Standard Dev., $\sigma$	27.5	57.9	0.90	20.2	34.2	0.61	12.2	38.9	0.53	14.6	30.3	0.47	13.1	19.9	0.31

**Table 4** Comparing the two severe floods (January 1974, December 2010–January 2011) based on start ( $t_{onset}$ ) and end ( $t_{end}$ ) dates

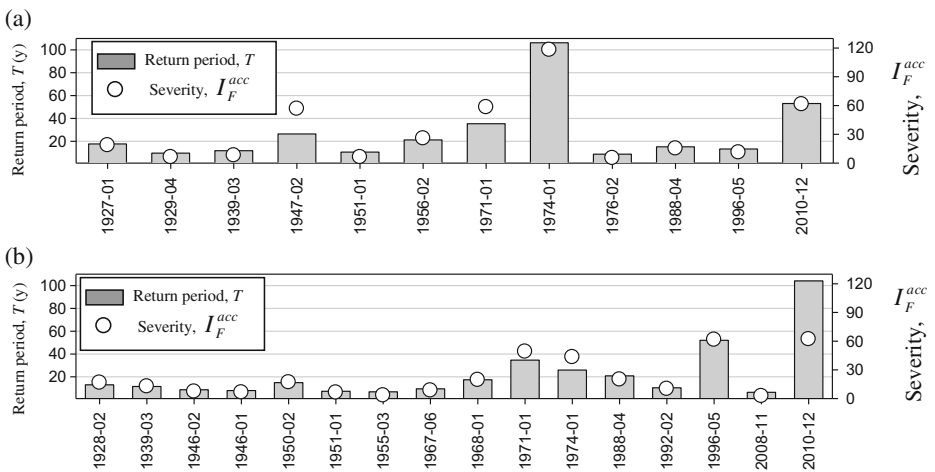
Flood Event	% of the $I_F$ in various thresholds of severity				
	$0 \leq I_F \leq 0.5$	$0.5 < I_F \leq 1.0$	$1.0 < I_F \leq 1.5$	$1.5 < I_F \leq 2.0$	$I_F > 2.0$
January 1974 Flood	26.0	23.1	27.9	8.7	14.4
December 2010–January 2011	42.7	36.0	11.2	7.9	2.2

Units:  $P$  (mm);  $AWRI$  (mm);  $I_F$  (non-dimensional)

$$F_D(I_F^{acc}) = \frac{i}{n + 1} \tag{10}$$

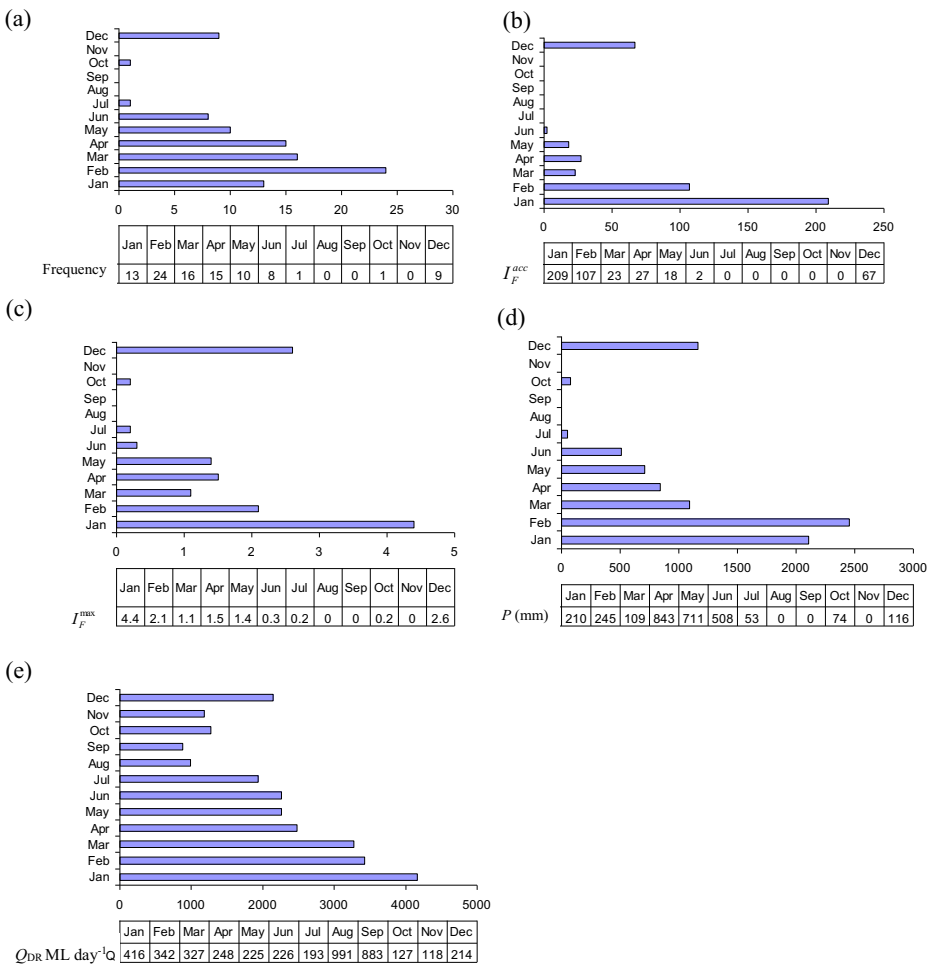
where,  $i$  is the rank order of flood event parameter. On the basis of  $I_F > 0$ , 99 floods were identified in Brisbane and  $T_s$  were computed. However, to analyze only major (severe) events, threshold of  $I_F^{acc} \geq 1$  was applied to all detected flood events.

Figure 6 shows return periods of floods based on  $I_F^{acc}$ . There were 12 severe floods in Brisbane with  $T \geq 10$  years. Five events (Feb-1956, Feb-1947, Jan-1971, December 2010–January 2011 & Jan-1974) had  $T > 20$  years and 2 events (December 2010–January 2011 and Jan-1974) were extremely rare ( $T > 50$  years). In particular, Jan-1974 event was the rarest ( $T = 99$  years;  $I_F^{acc} = 118$ ), in agreement with published data that reported recurrence interval ( $T$ ) exceeding 100 years (Middelmann-Fernandes 2010, Smith et al. 1993). For Lockyer Valley, 16 severe events were identified ( $T > 10$  years). Importantly,  $T \approx 99$  years was obtained for December 2010–January 2011 event (Fig. 6b), also in agreement with published literature (van den Honert and McAneney 2011) where a return interval  $> 100$ -years for floods longer than 3 h was reported. However, in contrast to Jan-1974 event in Brisbane ( $T = 99$  years),  $T$  for the same event in Lockyer Valley was 24.5 years. Clearly, the impact of Jan-1974 flood was not as severe in Lockyer Valley as it was in Brisbane, evidenced by larger return period and greater flood severity.



**Fig 6** The statistical return period of flood events based on severity parameter,  $I_F^{acc}$  from 1915 to 2012: (a) Brisbane, (b) Lockyer Valley. Only major floods defined by  $I_F^{acc} \geq 1$  are shown

We tested the ability of  $I_F$  for quantifying flood seasonality. According to Table 2, 7 out of 10 floods occurred from December–February. When seasonality based on  $I_F^{acc}$  vs.  $t_{onset}$  was plotted, the severest event was in February followed by January–March (Appendix Fig A3). A large cluster of floods were recorded between February and May, albeit less severe ( $I_F^{acc} < 10$ ) compared to floods in January–February. By comparison, floods in Lockyer Valley occurred between December–mid June. The severest floods ( $I_F^{acc} > 20$ ) were recorded from December–February. A striking feature was that a large number of events in Lockyer Valley occurred from May–June with virtually no events in Brisbane. This indicates that Lockyer Valley was more prone to floods in second half of the year, although hydrological patterns exhibited generally lower rainfall (Appendix Fig A2). It is pointed out that a severe event ( $I_F^{acc} \approx 61.5$ ) occurred in May in Lockyer Valley whereas for May flood in Brisbane, the severity parameter was relatively small.



**Fig 7** Seasonality of flood events in Brisbane over 1915–2012: (a) frequency (number), (b) severity as per accumulated Flood Index,  $I_F^{acc}$ , (c) peak danger,  $I_F^{max}$ , (d) accumulated precipitation,  $P$ , (e) mean river discharge,  $Q_{DR}$  (ML day<sup>-1</sup>)



Figure 7 investigates the seasonality of flood events based on frequency ( $N$ ),  $I_F^{acc}$  and  $I_F^{max}$  and accumulated  $P$  and river discharge ( $Q_{DR}$ ) over 1959–2012 where reliable data were available. Notably, flood frequency,  $I_F^{acc}$  and  $I_F^{max}$  were the highest between December–May with 87 events in this period compared to 10 outside it. Importantly, the pattern of seasonality paralleled with accumulated  $P$  and mean  $Q_{DR}$  (Fig. 7d, e). Except for frequency that exhibited a peak in February in response to high rainfall (Fig. 7a, d),  $I_F^{acc}$  and  $I_F^{max}$  were found to be elevated in January. This indicated that more severe flood events were likely to occur in January, confirmed emphatically by the mean discharge in Brisbane River (Fig. 7e). Also, flood frequency was the lowest in (dry) winter, as confirmed by magnitudes of  $I_F^{acc}$ ,  $I_F^{max}$  and  $D_F$ . Overall, results provided immensely useful information on the seasonality of flood, particularly for risk assessments.

## 4 Conclusion

A daily Flood Index ( $I_F$ ) has been utilized for analyzing flood events in Brisbane and Lockyer Valley regions, including analysis of flood severity ( $I_F^{acc}$ ), peak danger ( $I_F^{max}$ ) and durations ( $D_F$ ). The following findings are enumerated.

- 1) The maximum  $I_F$  per year ( $I_F^{max}$ ) detected emphatically major flood events during 1974, 2010, 1970, 1971, 1956, 1957, 1927, 1928 and 1929, agreeing well with parameter of  $Q_{WL}$  and  $Q_{DR}$  for Brisbane River. On annual basis, peak in  $I_F^{max}$  coincided with peaks in  $Q_{WL}$  and  $Q_{DR}$ , and exhibited reasonably good linear correlation.
- 2) Based on  $I_F$ , flood danger for December 2010–January 2011 events were analyzed. The climax of this event, which occurred on January 12, 2011 was reflected by peaks in headwater water elevation of Wivenhoe dam (same day), maximum outflow (10th to 12th January 2011) and high  $Q_{WL}$  of Brisbane River around 13th January, 2011. The close coincidence of  $I_F$  and flood indicators certify its excellent ability for detection of flood danger on daily basis.
- 3) By applying the running-sum on  $I_F$ , flood severity ( $I_F^{acc}$ ) was investigated. January 1974 and December 2010–January 2011 events were ranked most severe for Brisbane ( $I_F^{acc} \approx 118.1, 61.3$ ) while for Lockyer Valley, severe events occurred in December 2010–January 2011 and May 1996 ( $I_F^{acc} \approx 62.1, 61.5$ ). Considering peak danger, the magnitude of  $I_F^{max}$  was  $\approx 4.40$  (January 1974) and 2.60 (December 2010–January 2011) for Brisbane and  $\approx 2.80$  (December 2010–January 2011) and 3.62 (May 1996) for Lockyer Valley.
- 4) The return period for January 1974 Brisbane flood was  $\approx 100$  years, rarest of all events in the hydrological period. By contrast, return period for December 2010–January 2011 Brisbane flood was 55 years. In case of Lockyer Valley, return period exceeded 100 years for December 2010–January 2011 event but was less than 40 years for January 1974. Therefore, the probability of flood similar to December 2010–January 2011 in Lockyer Valley was much less than that of a similar event in Brisbane.
- 5) Over 98-years, seasonal pattern of flooding in Brisbane and Lockyer Valley were similar with most flood events recorded from December–May. However, a distinct peak in frequency and severity of floods was evident from January–February, coinciding with high  $Q_{DR}$  in Brisbane River.

In synopsis,  $I_F$  is a robust utilitarian for flood risk monitoring, however, effects of catchment size, shape, vegetation cover and slope which are important for runoff processes, need to be

incorporated. Also, as flash-style inundations generally occur over short timescales (e.g., hourly), an hourly flood monitoring  $I_F$  is another archetype for real-time flood risk assessment. Developing an hourly  $I_F$  is an interesting research and awaits another independent investigation.

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**Conflict of Interest** Authors declare no conflict of interest.

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