Australasian Journal of Water Resources

ISSN: 1324-1583 (Print) 2204-227X (Online) Journal homepage: http://engineersaustralia.tandfonline.com/loi/twar20

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AUSTRALASIAN JOURNAL OF WATER RESOURCES, 2018
https://doi.org/10.1080/13241583.2018.1446677

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Large floods in South East Queensland, Australia: Is it valid to assume they occur randomly?

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ABSTRACT
Flood frequency analysis and existing engineering practice assumes that flood events are randomly distributed. However, as understanding of large-scale ocean-atmospheric processes and associated hydroclimatic variability (and change) increases, the assumption that flood events are random seems unlikely to be valid. This paper examines historical flood data from 10 major catchments in South East Queensland (SEQ), Australia with the aim of testing for non-random patterns in the timing of the largest flood events. The results show that most (~80%) large floods in the study catchments have occurred within sets of 5-year periods separated by 35 years of lower flood risk. This finding is consistent with previous studies that have reported 20- to 40-year cycles in rainfall, flooding and drought across most of eastern Australia. Based on these insights, an explanation for the nominal 40-year cycle in SEQ flooding is proposed, and implications for describing and managing flood risk are discussed.

ARTICLE HISTORY
Received 2 June 2017
Accepted 26 February 2018

KEYWORDS
Non-stationarity; flood risk; climate variability; climate change; flood cycles

1. Introduction

1.1. Background

The first half of the 1970s was a time of many severe floods in South East Queensland (SEQ; Figure 1) (Middelmann, Harper, and Lacey 2000; Bureau of Meteorology 2014). That decade was followed by extensive floodplain studies and development projects in the 1980s. A small group of engineers from Queensland Government departments, modelling laboratories and principal consultants in Queensland steered and conducted most of these flood studies and development projects. Meeting each other as frequently as they did, at different river, creek and estuarine communities throughout SEQ, the group came to refer to itself as 'the Roadshow'.

Floodplain development approvals required favourable recommendations from regulators in several government departments which were organised by a committee set up by the former Coordinator-General's Department. The committee system of coordinating the response by regulators to floodplain development proposals was also used to evaluate modelling conducted by the developers and their consultants. Such studies and reviews included were conducted for catchments including the Maroochy River (Maroochy River Flood Study Technical Supervising Committee 1980–1985), Mooloolah River (Mooloolah River Hydraulic Model Technical Committee 1976–1983), Pine River (Advisory Body Responsible Authority Review of Environmental Impact Assessment Study Pine Waters Canal Estate 1983–1984), Brisbane River and its tributaries (Approvals City of Brisbane (Flood Mitigation Works Approval) Act 1980–1986), and Nerang River (Joint Technical Steering Committee of Nerang River Flood Study 1984–1987). This experience of analysis and evaluation of the hydrology of these catchments provided a regional, multi-catchment perspective to the hydrology of SEQ (McMahon 2011, 2012). From this experience and perspective, the Roadshow engineers noticed that three large flood events had occurred about 40 years apart:

- February 1893, the largest on record for Brisbane River;
- February 1931, the largest on record for Pine River and also large for Brisbane River;
- January 1974, the largest on record for Nerang River and also large for Brisbane River.

In the 1980s, based on the idea that large floods in SEQ follow a nominal 40-year cycle with sets of 5-year period of high flood risk separated by 35 years of lower flood risk, some of the Roadshow speculated that: (i) the next '1974 flood' could come in 2013, plus or minus a few years (McMahon 2011, 2012); (ii) there would be a Royal Commission the next time a '1974 flood' occurred; and (iii) some Roadshow members would still be in practice

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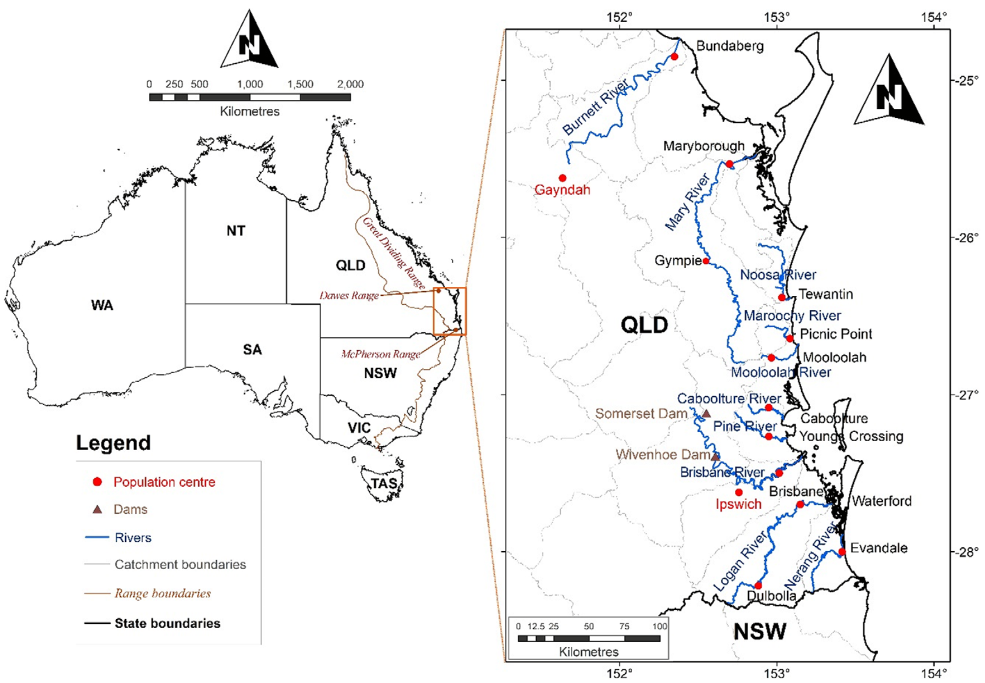

Figure 1. The SEQ study area (approximately indicated by the orange box) and the 10 catchments analysed in this study.

and required to stand before such a commission. This Roadshow speculation was realised with large SEQ flood events in January 2011 and January 2013 – with the 2011 floods resulting in a Queensland Government Flood Commission of Inquiry (QFCI, www.floodcommission.qld.gov.au/). This suggests that the occurrence of large floods in SEQ may not be random – as is assumed in existing engineering practice and floodplain development policies. Research conducted before and after the 1980s Roadshow speculation reinforces the suggestion of non-randomness in flood occurrence (refer to Section 1.2 for further details).

1.2. History

Given scientific understanding and engineering methodology and guidelines in the 1980s, thinking a hydrometeorological phenomenon like flooding could be non-random may have seemed radical at worst or unusual at best. So, was the Roadshow alone in its idea of physically based regularity of large SEQ flooding?

Clement Wragge (1852–1922), commonly regarded as an eccentric polymath, set up an extensive network of weather stations around Queensland in the 1880s and 1890s. Using data from these weather stations, and training provided by Wragge, Inigo Jones (1872–1954) developed long-term weather forecasts based on the 11- and 22-year sunspot cycles. Regarding flooding, Jones (1931) followed the Bruckner Cycle for solar activities, which he determined to be 35 years long, but which has since been found to vary from 35 to 45 years (Raspopov et al. 2000). Although Jones failed to have his methods recognised as soundly based by any substantial body of accredited scientific opinion, he was widely recognised for his successes, especially by farmers and other practitioners (http://adb.anu.edu.au/biography/jones-inigo-owen-539).

The principal international hydrology textbook for the 1970s and 1980s, Chow (1964, 8–11), mentions ‘periodicity’ and defines it as a regular or oscillatory form of variations in hydrologic phenomena. Studies were quoted where technically trained professionals had detected regular cycles in hydrological data provided to them (Chow 1964, 9–46). The 11-year sunspot cycle was the only cycle that enjoyed some acceptance regarding an explanation for this periodicity, but Chow (1964, 40–46) stated that quantitative investigations into the relationships between sunspot cycles and this hydrological periodicity failed to demonstrate any statistical significance. Whether this means that there is no causal relationship between sunspot cycles and hydroclimatic variability on Earth, or that the statistical testing methods used were inadequate, remains an open research question (Franks 2002; Gray et al. 2010; Kiem 2014). Despite the physical mechanisms and causal relationships being a matter of controversy (a scientific debate which continues today), Chow (1964) accepts that the occurrence of hydrologic extremes is not random, quoting the work of Hurst, Black, and Simaika (1965) on the 1300 year (622–1921 A.D.) Nile River flood record. Hurst, Black, and Simaika (1965) noted that both wet and dry years appeared to occur in groups.

In Australia, John Ward and colleagues, from the then Queensland Irrigation and Water Supply Commission, recognised the statistical difference between large and common floods in Queensland and supposed there would be a physical driver (or drivers) for this (Ward and Harman 1972). John Ward also argued that flood frequency distributions at a location differ because higher flows originate from a variety of different rainfall mechanisms – at the time, minimal insight was available into what those different rainfall mechanisms were. More recent work by Klingaman (2012) provides comprehensive details on rainfall mechanisms for Queensland (see Figure 2) and as such (i) provides useful insights into the physical drivers behind the different flood frequency distributions that John Ward described in the 1970s and (ii) also potentially explains the non-randomness of large floods in SEQ suggested by the 1980s Roadshow.

In the 1990s, drought modelling and investigations in Queensland (Stone and Auliciems 1992; Brook and Carter 1996) brought to notice cyclical phenomenon in sea surface temperatures and ocean-atmospheric processes that potentially provides an explanation for the Roadshow idea of physically based regularity of large floods in SEQ. French (1999) also noticed an irregular clustering of flood events for a median of 9 years (range 7–16 years) and observed that the perturbations in climate which are longer than a year were, at the time, not taken into account when assessing flood frequency or designing infrastructure to manage surface water resources.

More recent work investigating the characteristics and impacts of large-scale ocean-atmospheric processes (e.g. El Niño/Southern Oscillation [ENSO] and the Interdecadal Pacific Oscillation [IPO]) has demonstrated strong links between these processes and eastern Australian rainfall variability (Kiem and Franks 2001; Verdon et al. 2004; Gallant et al. 2012), flood risk (Kiem, Franks, and Kuczera 2003; Kiem, Franks, and Verdon 2006; Micevski, Franks, and Kuczera 2006; Kiem and Verdon-Kidd 2013; Stevens and Kiem 2014; Verdon-Kidd and Kiem 2015) and drought risk (Kiem and Franks 2004; Verdon-Kidd and Kiem 2009; Kiem et al. 2016). Klingaman (2012) focused specifically on large-scale climate processes that influence rainfall in Queensland and explained that ENSO, IPO and the Madden-Julien Oscillation were most important but that they operate on different temporal scales as illustrated in Figure 2.

1.3. Aim and scope

The aim of this paper is to determine whether the Roadshow suggestion that large flood events in SEQ do not occur randomly is credible.

This is done by: (i) testing for the existence and strength of a perceived pattern in the timing of the large flood events in SEQ (i.e. testing the Roadshow hypothesis of a nominal 40-year flood cycle); and (ii) identifying, in line with previous work on climate-informed flood frequency analysis (e.g. Kiem, Franks, and Kuczera 2003; Kiem, Franks, and Verdon 2006; Kwon, Brown, and Lall 2008), physical mechanisms which might explain non-randomness in the largest flood events experienced in SEQ.

The analysis is limited to floods occurring from 1890 to 2014 in the 10 major SEQ catchments illustrated in Figure 1. While some information does exist prior to 1890 – mostly anecdotal or documented but some measured flow records – we limit our study to floods occurring from 1890 following the opinion in Cossins (1975), that pre-1890 flow records are mostly unreliable.

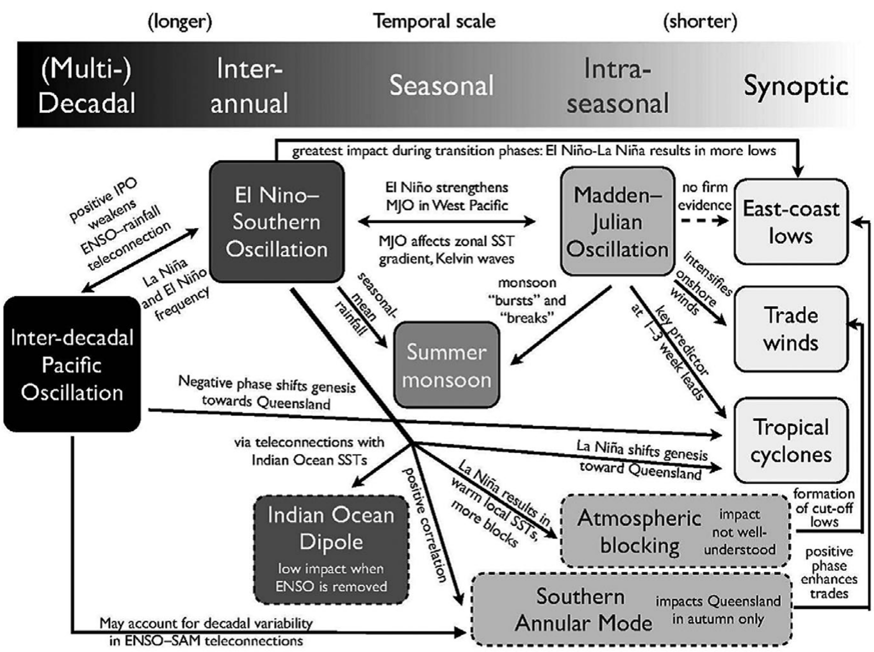

Figure 2. Conceptual diagram of remote drivers of Queensland rainfall (Klingaman 2012).

2. Data

2.1. Study catchments

The SEQ study area (Figure 1) is a 63,200 km^2 region bounded by orographic features – the Dawes Range to the north, the Great Dividing Range to the west and the McPherson Range (eastern part of the Queensland–New South Wales border) to the south. This is consistent with the definition of SEQ used by the 1980s Roadshow (see Section 1.1 for details).

Table 1 summarises important characteristics of the 10 study catchments. The 10 study catchments range in size from 196 km^2 (Mooloolah River) to 33,000 km^2 (Burnett River), with measured flow records from less than 30 years (Noosa River) to over 100 years (Burnett River, Mary River and Brisbane River).

2.2. Flood data

Measured flood records (river heights for the largest floods) were obtained from the Australian Bureau of Meteorology for gauges at downstream population centres in the 10 study catchments (see Table 1 and Bureau of Meteorology [2014]). Gauges at downstream population centres were used for three reasons: (i) downstream records are more representative of flow from the total catchment and thus of the largest flood events to affect that catchment; (ii) the downstream population centres selected have long histories of being affected by flooding and therefore have the data records (and/or anecdotal evidence) required to test the concept of a nominal 40-year flood cycle; and (iii) the flood-prone population centres selected have the most to lose if the existing assumption that large flood events in SEQ occur randomly is incorrect.

Supplementary information was also obtained from Middelmann, Harper, and Lacey (2000), especially relating to flooding at times when records were not available from the Bureau of Meteorology (2014) and to better understand the timing and impacts of dam constructions on the Bureau of Meteorology (2014) flood records. Where dam constructions are known to have affected the flood records this was allowed for by ensuring floods pre-dam and post-dam were used in our analysis (McMahon 2016).

2.3. Selection of large flood events

The largest floods were identified by recorded river heights at downstream population centres with the largest height on record ranked 1. To address the non-uniform length and completeness of flow records, the number of floods selected for each catchment was determined from the number of years of useful records – the largest flood was selected plus one additional event for each 40 years of useful records. For example, the Burnett River had good records for 141 years, so the four (=(141 ÷ 40) + 1, rounded down to the nearest integer) largest floods were selected.

3. Does flood occurrence and magnitude in SEQ align with the Roadshow's 40-year flood cycle hypothesis?

Due to limitations associated with the length of data records (see Section 7.2 for further discussion on this), a simple, non-parametric approach was used to test the hypothesis of a nominal 40-year cycle in SEQ flooding. The approach involved investigating whether the large flood events identified in Section 2.3 occurred during the 5-year target periods that, according to the Roadshow hypothesis, are when the largest floods are to be expected: 1890–1894, 1930–1934, 1970–1974, 2010–2014.

Table 2 shows the timing of the largest flood events occurring in SEQ over the 1890 to 2014 study period. In line with the hypothesis of a nominal 40-year cycle, a column has been given in Table 2 for each of the 5-year target periods when, according to the hypothesis, large floods are expected, and for each of the 35-year periods of lower flood risk that separates them. The largest floods in each catchment are mapped in Table 2 according to their dates of occurrence.

Flood height is only one criterion for the importance of a flood, another is the number of catchments that experienced a large flood. For example, Table 2 shows the flooding events of February 1893 (6 out of 7 catchments where records existed) and January 1974 (6 out of 10 catchments) covered most of the study area, while the February 1931, February 1972, January 2011 and January 2013 floods occurred across two or three catchments. All these floods occurred within the 5-year target periods identified by the nominal 40-year flood cycle hypothesis.

Table 2 clearly shows that the 5-year target periods include the majority (~80%) of large historical floods in SEQ over the 125-year, 1890–2014 study period, where these large floods are defined by a combination of river heights and their spread across several SEQ catchments. Table 2 also shows that, three of the four 5-year target periods experienced more than one large flood. Even though a few large floods occurred outside the 5-year target periods (these are discussed further in Section 7.1) these results suggest that, in the 5-year target periods, SEQ may be more susceptible to large floods and that there is evidence to support the hypothesis of a 40-year cycle in SEQ flooding.

A 5-year target period score was used to indicate the validity of the nominal 40-year flood cycle hypothesis for SEQ. The 5-year target period score was calculated by counting the number of large flood events that occurred within one of the 5-year target periods and expressing that number as a percentage of the total large flood events selected for that catchment.

Table 1. Characteristics of the 10 study catchments listed from north to south.

Catchment (@ gauging station)	Area ('000 km^2)	Period of record (years)	Comments
Burnett (@ Bundaberg)	33	1873–2013 (141)	The construction of dams has some impact on flood records at Bundaberg in the last half of the 141-year data period
Mary (@ Maryborough)	7	1892–2013 (122)	The construction of dams has some impact on flood records at Maryborough in the last ~30–40 years
Noosa (@ Tewantin)	1.9	1987–2014 (28)	Only two large floods in February 1992 and August 2007 have occurred, since the initial flood warning network was installed in 1987. Historical records show the 1968 flood was of greater magnitude so it is considered here as the largest flood on record
Maroochy (@ Picnic Point)	0.6	1892–2013 (34 years available due to 89 year gap 1894–1982)	The construction of dams has some impact on flood records at Picnic Point in the last ~30–40 years
Mooloolah (@ Mooloolah)	0.2	1972–2015 (44)	The construction of dams has some impact on flood records at Mooloolah in the last ~30–40 years
Caboolture (@ Caboolture)	0.4	1966–2015 (50)	
Pine (@ Drapers/Youngs crossing)	0.8	1892–2013 (122)	
Brisbane (@ Port Office/Edward St, Brisbane City)	15	1887–2014 (128)	There is some impact from dam construction on flood records, principally from 1942 (Somerset Dam) and then from 1985 (Wivenhoe Dam)
Logan (@ Waterford)	3.9	1880–2015 (47 years available due to 74 year gap 1894–1967)	Despite no recorded data from 1894 to 1967, there are documented events in Jan 1947 (lower than January 1974 levels at Waterford), in January 1887 (slightly higher than January 1974 levels at Waterford), and in February 1893 (much higher than January 1974 levels at Waterford) (Middelmann, Harper, and Lacey 2000)
Nerang (@ Evandale)	0.4	1892–2014 (123)	Flood records have been significantly affected by dam construction in 1976 and 1989

Table 2. Timing of the largest flood events within the 40-year cycle. Flood events occurring within the 5-year target periods are shown in bold. Superscripts next to each flood event indicate the ranking of that flood event in that catchment (i.e. largest flood in each catchment is ranked 1).

	Five-year target periods, 35 years apart						
Catchment (years of record)	Target period 1890–1894	Off target 1895–1929	Target period 1930–1934	Off target 1935–1969	Target period 1970–1974	Off target 1975–2009	Target period 2010–2014
Burnett (141)	**Jan 90^{2}** **Feb 93a^{3}** **Feb 93b^{4}**						**Jan 13^{1}**
Mary (122)	**Feb 93^{1}**			Mar 55^{2}	**Jan 74^{3}**		**Jan 13^{4}**
Noosa (28)	No record			Jan 68^{1}			
Maroochy (122)	**Feb 93^{1}**			Jan 51^{3}	**Jan 74^{2}**	Feb 92^{4}	
Mooloolah (44)	No record				**Feb 72^{2}**	Apr 89^{1}	
Caboolture (50)	No record				**Feb 72^{2}**		**Jan 11^{1}**
Pine (122)	**Feb 93^{2}**		**Feb 31^{1}**		**Jan 74^{3}**		**Jan 11^{4}**
Brisbane (128)	**Mar 90^{2}** **Feb 93^{1}**				**Jan 74^{3}**		**Jan 11^{4}**
Logan (47)	**Feb 93^{1}**				**Jan 74^{2}**		
Nerang (123)			**Feb 31^{3}**	Feb 54^{2}	**Jan 74^{1}**		**Jan 13^{4}**

Table 3 shows the 5-year target period scores for each study catchment. Table 3 indicates that while the nominal 40-year cycle is not absolute (i.e. there are a few large floods that occur outside the 5-year target periods) the majority of large floods are captured by the 5-year target periods irrespective of catchment size or location. Traditional hydrology in texts and guidelines has recognised these flood-dominated epochs as 'persistence' or as 'trends', but has failed to recognise a cause and, in practice, such clustering of floods and significant rainfall events is rarely considered or robustly dealt with (French 1999; Kiem, Franks, and Kuczera 2003; Kiem, Franks, and Verdon 2006; Johnson et al. 2016).

4. Testing the robustness and statistical significance of the nominal 40-year flood cycle

To further test the hypothesis of a nominal 40-year flood cycle, the normalised flood heights for large floods in the 10 study catchments during the four 5-year target periods are compared with the normalised flood heights in the 35-year off-target periods. Flood heights are normalised by dividing the flood height for each of the individual large floods by the average height of large floods in that catchment. A Student's t-test is then used to assess the statistical significance of any differences identified between the distributions of (i) normalised flood heights within and outside the 5-year target periods and (ii) the proportion of large floods per year within and outside the 5-year target periods.

Table 3. The 5-year target period scores for each study catchment.

Catchment	Area ('000 km^2)	No. of large floods	Five-year target period score (%)
Burnett	33	4	100
Mary	7	4	75
Noosa	1.9	1	0
Maroochy	0.6	4	50
Mooloolah	0.2	2	50
Caboolture	0.4	2	100
Pine	0.8	4	100
Brisbane	15	4	100
Logan	3.9	2	100
Nerang	0.4	4	75
	Sum of the above	Sum of the above	Mean (median) of the 5-year target period scores
Totals and averages	63.2	31	75% (88%)

The normalised flood height within the 5-year target periods is, on average, 41% greater than the normalised flood height outside the 5-year target periods. The number of large floods per year within the 5-year target periods is, on average, 4.9 times greater than the number of large floods per year outside the 5-year target periods or, in other words, there is a 24% chance of a large flood occurring during a 5-year target period compared to only 4.9% chance at other times. All of these results are statistically significant at the 1% level.

5. Assessing the sensitivity of the Roadshow's 40-year flood cycle hypothesis to catchment size and length of flood records

Table 1 shows that the sizes of catchments in SEQ are of widely different sizes and of quite different record lengths. A curiosity naturally arises as to whether the most significant floods (i.e. the largest floods in the largest catchments or the largest floods occurring simultaneously in several catchments) are captured by the Roadshow's nominal 40-year flood cycle. To form an answer, a sensitivity analysis was conducted by calculating and comparing the average and median 5-year target period scores for:

- Case A: the baseline case, which is all 10 study catchments shown in Table 1;
- Case B: Case A without the largest catchment (i.e. leaving out the Burnett River catchment);
- Case C: Case A without the catchment with the shortest record (i.e. leaving out the Noosa River catchment);

- Case D: only catchments with records long enough that four large floods were identified following the method described in Section 2.3 (i.e. as with Case A but leaving out Noosa, Mooloolah, Caboolture and Logan catchments).

Table 4 shows the mean and median 5-year target period scores for each of the four cases. Table 4 indicates that while the 5-year target scores change slightly for each of the four cases assessed, the main conclusion, that the largest SEQ floods mostly occur on a nominal 40-year cycle, does not. In other words, Table 4 shows that the 5-year target periods (i.e. 16% of the study period) produce, on average, 72–83% of the large floods across SEQ (with the variation due to the four different cases assessed). Logic suggests, since larger floods produce larger damages, and the floods captured by the 5-year target periods are the largest floods, that these 5-year target periods are also associated with a very large and disproportionate percentage of flood-related property damage and loss, government emergency and assistance expenditures, and loss of lives.

6. Physical explanations for the nominal 40-year cycle in SEQ flooding

To be accepted and acted on, the non-randomness suggested by the results presented in previous sections requires a physical explanation or a credible source or cause. There are some hints:

- All large flood events occurred in the Queensland cyclone season (December to April) and were associated with tropical cyclones that tracked into SEQ.
- Kiem, Franks, and Kuczera (2003) found that 20–40 year flood cycles also exist in most New South Wales catchments. Table 2 emphasises a 40-year cycle, but a 20-year cycle – a series of 5-year period 15 years apart – also captures the majority (84%) of floods shown in Table 2. This again suggests that, while further research is required to clarify the exact length and cause(s) of the cycle, it is unlikely that large floods in SEQ are randomly distributed.
- Section 1.2 and Figure 2 summarise previous investigations which demonstrate strong links between ENSO, IPO and flooding across most of eastern Australia, including SEQ (e.g. Kiem, Franks, and Kuczera 2003; Kiem, Franks, and Verdon 2006; Micevski, Franks, and Kuczera 2006).

Table 4. The mean and median 5-year target period scores for all study catchment (Case A) and three other subsets of Case A to test the sensitivity of the 40-year flood cycle hypothesis.

Cases	Mean (median) 5-year target period score
Case A: the baseline case (all 10 catchments as per Table 1	75% (88%)
Case B: Case A without the largest catchment (i.e. leaving out Burnett)	72% (75%)
Case C: Case A without the catchment with the shortest record (i.e. leaving out Noosa)	83% (100%)
Case D: only catchments with four large floods identified (i.e. as with Case A but leaving out Noosa, Mooloolah, Caboolture, Logan)	79% (75%)

The macro-climate effect most likely to offer a physical explanation for cyclic or non-random flooding is the IPO, the multidecadal ENSO-like pattern of Pacific climate variability (Power et al. 1999). As noted by Gallant et al. (2012), two characteristics distinguish the IPO from ENSO: the persistence of IPO epochs (15–30 years on average based on the instrumental record) and the fact that the sea surface temperature anomalies associated with the IPO are evident across most of the Pacific Ocean while sea surface temperature anomalies associated with ENSO are generally confined to the tropical Pacific. The IPO regulates the eastern Australian climate indirectly by modulating both the magnitude and frequency of ENSO impacts (Power et al. 1999; Kiem, Franks, and Kuczera 2003; Verdon et al. 2004). The greatest effect of this modulation is a magnified response of rainfall and streamflow to La Niña events during a cool IPO phase, and this is associated with a significant elevation in flood risk across most of eastern Australia (Kiem, Franks, and Kuczera 2003; Kiem, Franks, and Verdon 2006; Micevski, Franks, and Kuczera 2006; Kiem and Verdon-Kidd 2013; Stevens and Kiem 2014; Verdon-Kidd and Kiem 2015). Conversely, during the warm (i.e. positive) IPO phase wet events are less frequent and not as wet as they are during the IPO cool phase which results in an increased risk of drought across most of eastern Australian (Kiem and Franks 2004; Verdon-Kidd and Kiem 2009; Kiem et al. 2016).

Figure 3, from Henley et al. (2015), shows the United Kingdom Met Office version of the IPO time series. From Figure 3, and as per previous studies (Power et al. 1999; Kiem, Franks, and Kuczera 2003; Henley et al. 2015) flood dominated IPO negative phases are defined as: ~1870–1895, ~1945–1976, ~1999–present. Comparing these IPO negative phases with Table 2 it is found that, with the exception of 1930–1934, all 5-year target periods (i.e. where almost all observed large flood events occurred) align with IPO negative epochs, usually towards the end of the IPO negative phase. Also note that, while the period 1930–1934 was not associated with a negative IPO phase, a local minima of the IPO occurred around 1932–1935 and ENSO indices were consistently approaching or within La Niña conditions for much of this period. This suggests that while the 1930–1934 period was not associated with an IPO negative phase other large-scale climate conditions were favourable for wet conditions.

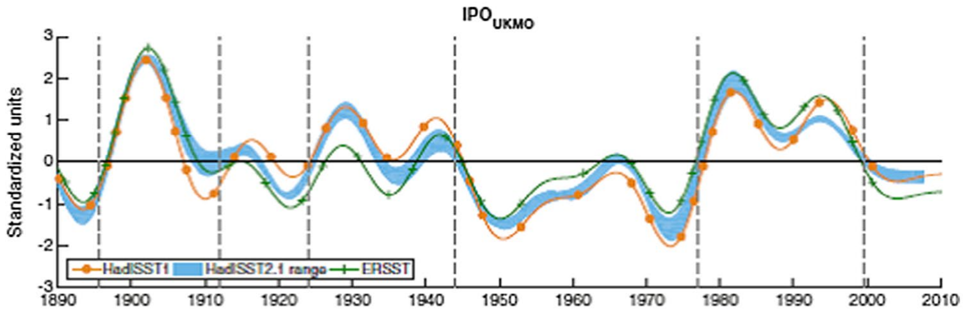

Figure 3. IPO time series (Henley et al. 2015).

7. Discussion

7.1. Exceptions to the Roadshow's 40-year flood cycle hypothesis – large SEQ floods occurring outside the 5-year target periods

From Table 2, it is evident that a few of the large SEQ floods do not align with the nominal 40-year flood cycle. However, as shown in Table 5, the large SEQ floods in the 1950s and 1960s that occur 'off target' all align with IPO negative conditions. Across all catchments 87% (27 out of 31) of large floods occurred during an IPO negative phase and only catchments smaller than 1000 km^2 – Maroochy, Mooloolah, Pine, Nerang and possibly Caboolture (if records had been available) – had a flood in an IPO positive phase. This apparent non-random clustering of large floods is at odds with the assumption that floods are independent and identically distributed (i.i.d.), which is the assumption that underpins current flood frequency analysis and flood risk quantification methodology. This also suggests that design, planning and infrastructure based on methods that assume i.i.d. floods is probably flawed and associated with a false sense of security in epochs where flood risk is elevated (e.g. IPO negative phases).

It should also be noted that recent work utilising palaeoclimate information shows that these IPO cycles, and the multidecadal variability of dry and wet epochs associated with them, have been occurring for at least the last 1000 years (Lough 2007; Vance et al. 2015; Tozer et al. 2016; Croke 2017). This further emphasises that if we want to better understand and manage flood (and drought) risk in Australia then more palaeoclimate research is required to supplement observed hydroclimatic records and to better understand the causes and impacts of the IPO, especially how the IPO and its impacts have varied in the past and how that might change in the future (see Johnson et al. (2016) and Kiem et al. (2016) for further discussion on this issue).

The only two floods not captured by the 5-year target periods or associated with IPO negative epochs were the April 1989 flood in the Mooloolah catchment and the February 1992 flood in the Maroochy catchment. 1988/1989 was a strong La Niña year showing that while La Niña events, and the elevated flood risk associated with them are most likely when the IPO is negative, La Niña events can also occur and elevate flood risk when the IPO is not negative (Kiem, Franks, and Kuczera 2003; Kiem, Franks, and Verdon 2006). The February 1992 flood in the Maroochy catchment does not appear to align with the wet phases of any of the large-scale, interannual to multidecadal climate mechanisms discussed above (and summarised in Figure 2). Further research is required to determine the underlying, large-scale cause(s) of the rainfall that led to this February 1992 flood in the Maroochy catchment but no other.

Table 5. Large South East Queensland floods stratified according to IPO phase. Flood events occurring within IPO negative phases are shown in bold.

	IPO neg	IPO pos	IPO neg	IPO pos	IPO neg	IPO pos	IPO neg
Catchment	~1870–1895	~1897–1910	~1918–1922	~1925–1945	~1945–1976	~1979–1997	~1999–present
Burnett	**Jan 90** **Feb 93a** **Feb 93b**						**Jan 13**
Mary	**Feb 93**				**Mar 55** **Jan 74**		**Jan 13**
Noosa					**Jan 68**		
Maroochy	**Feb 93**				**Jan 51** **Jan 74**	Feb 92	
Mooloolah					**Feb 72**	Apr 89	
Caboolture					**Feb 72**		**Jan 11**
Pine	**Feb 93**			Feb 31	**Jan 74**		**Jan 11**
Brisbane	**Mar 90** **Feb 93**				**Jan 74**		**Jan 11**
Logan	**Feb 93**				**Jan 74**		
Nerang				Feb 31	**Feb 54** **Jan 74**		**Jan 13**

7.2. Categorically proving/disproving the 40-year flood cycle hypothesis

To conduct the more rigorous statistical analysis required to formally prove or disprove, the hypothesis of a nominal 40-year cycle in SEQ flooding at least 25–30 samples of 40-year periods containing annual maximum flow data would be required. That corresponds to 1000–1200 years of data which are obviously not available and is the reason simple tests are used in Sections 3–5. Therefore, while this paper cannot and does not statistically prove that large floods in SEQ conform to a 40-year cycle, it does prove that large flood events in SEQ do not occur randomly. Some form of physically based pattern clearly exists but existing engineering theory and practice assumes there is none. These findings challenge the dominant flood frequency paradigm of randomness.

7.3. Inferences and forecasts

The Roadshow's nominal 40-year flood cycle hypothesis, supported by the results presented above, indicates that there is 72–83% probability (as per Table 4) that the next serious, widespread flooding in SEQ will occur in the years 2050–2054. Based on historical experience, this would be a flood similar in magnitude and impact to the 2011 Brisbane River flood event which, according to Seqwater (2011), was a 0.5–0.05% annual exceedance probability (AEP) flood. These AEP estimates are based on frequency analyses of the event rainfalls, analyses possibly misdirected by an assumption that rainfalls recorded during large events are representative of the duration and intensity of the rainfall and associated flooding that actually occurred. This concern is supported by river height data suggesting the 2011 Brisbane River flood event was more like a 2.5% AEP event and by the analysis presented here which suggests it may actually be more like a 20% AEP (i.e. likely to occur at least once in 2050–2054 and be more like a 1-in-5-year event).

What physics can be added to the statistics? On average, IPO phases last approximately 15–30 years (Kiem, Franks, and Kuczera 2003; Henley et al. 2015). The most recent negative IPO phase started in approximately 2000 and is therefore likely to finish on or shortly after 2020. Based on historical records, the next positive IPO phase is likely to dominate from ~2020 to 2045, so the next negative phase is expected to dominate from begin ~2045 and last for 15–30 years. This would mean that the Roadshow hypothesis-based forecast that the next serious, widespread flooding in SEQ will occur in 2050–2054 would be in line with the occurrence of a negative and thus 'wet' IPO phase. Time will tell whether this forecast eventuates, but, irrespective of what occurs in the future, the results presented here highlight that the historical frequency of large floods in SEQ is not random and that the observed clustering of large floods is strongly linked to real physical processes (e.g. ENSO, IPO). It follows that there is a need to revisit the way flood risk is described and managed so as to account for the non-random nature of flood occurrence – this is especially the case in Australia and other locations that are strongly influenced by interannual to decadal variability associated with processes like ENSO and IPO. Following on from this, in order to ensure future resilience against flooding, it is critical to understand if/how the frequency, magnitude and persistence of ENSO/IPO impacts varies over time (historically and in the future) and if/how the apparent nominal 40-year flood cycle may be impacted.

8. Conclusions

This study shows that the largest floods in SEQ are unlikely to be randomly distributed and that IPO and related concepts provide at least part of the physical explanation for the observed non-randomness. This means a substantial case exists for good practice in flood frequency analyses to separate SEQ flood records into two (or more) populations for which significantly different flood frequency relationships exist. Such practice allows macro-climate effects to be incorporated into flood frequency analyses.

Irrespective of whether the Section 7.3 forecast eventuates, the key point is that what has been recognised for several decades, by the Roadshow and independent researchers, is that flood risk in SEQ is not constant and varies over time. Yet, flood protection infrastructure and management strategies are still designed and operated on the assumption that flood risk is stationary. In short, the realisation that flood risk changes over time provides a fundamental challenge for decision-makers because if i.i.d. and stationarity assumptions continue to be used: (i) resilience, life and adequacy of flood protection and flood evacuation infrastructure are likely to be overestimated in decadal epochs dominated by floods and (ii) properties, assets and local government planning areas designed and/or zoned to deal with floods of a certain probability may find those probabilities significantly underestimated when the next flood-dominated epoch occurs. Such realities necessitate alternatives to current flood hazard estimation practice and identification of ways to deal with the practical implications of (i) the apparent non-random nature of large flood events in SEQ and (ii) the likelihood that the common practice of treating hydrological variables independently from their generating mechanisms is invalid.

Acknowledgements

Thank you to Robert French for his careful reading of earlier versions of this paper and his insightful comments and suggestions. Thanks also to Sedigheh (Sara) Askarimarnani from the Centre for Water, Climate and Land (CWCL) at the University of Newcastle for assisting with the production of Figure 1.

Disclosure statement

No potential conflict of interest was reported by the authors.

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