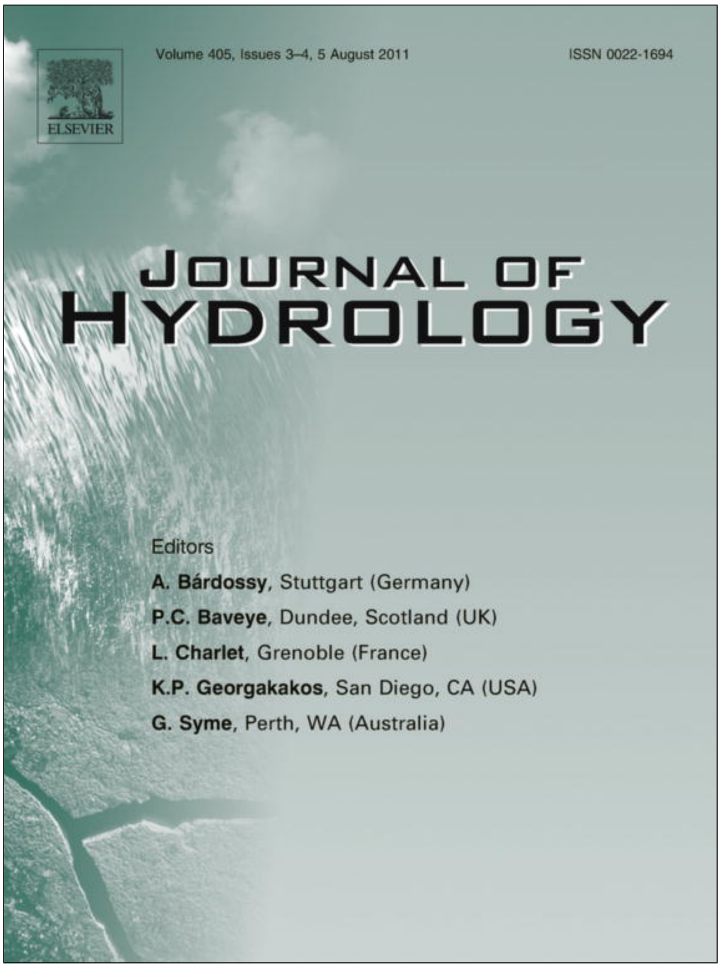
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The impacts of river regulation and water diversion on the hydrological drought characteristics in the Lower Murrumbidgee River, Australia

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SUMMARY

This study demonstrated that the Standardised Flow Index (SFI) was a simple and useful tool to research, monitor and manage hydrologic drought in a highly regulated river system, the Murrumbidgee River in southeast Australia. To validate the applicability of the theory underlining the widely used Standardised Precipitation Index (SPI) to river discharge data, we investigated the probability distribution of the time series of monthly river discharge month by month using long-term (over 100 years) river flow records. Our results showed that the Gamma probability distribution function was adequate to describe and model the skewed river flow data. The generalised additive models (GAM) with Locally Estimated Scattersplot Smoothing (LOESS) additive terms were applied to the computed SFI and SPI sequences to investigate the impacts of river regulation and water diversion on the duration and magnitude of hydrologic droughts in Lower Murrumbidgee River from 1890. The results revealed that upstream regulations had successfully reduced the drought severity at Wagga Wagga, a weir located downstream of the two major dams but immediately upstream of the major irrigation areas. However, the hydrological benefits of river regulation gradually disappeared as the river travels downstream and more and more water abstracted. At Balranald, the end valley weir, hydrologic drought was progressively aggravated during the modelling period, and the impacts were greater during drier periods. The results of the study highlighted the importance of balancing the needs between upstream and downstream water users in river management.

1. Introduction

Drought is described as a "creeping disaster" by Lake (2006) in the sense that, unlike other natural hazards like floods and earthquakes, its onset and termination are difficult to determine (Burton et al., 1978; Mckee et al., 1993; Steinemann, 2003). It is a recurring phenomenon that has significant economic, social and environmental impacts (Wilhite, 2000). Drought not only affects aquatic and terrestrial ecosystems (Milena et al., 2001; Lake, 2003; Humphries and Baldwin, 2003; Bond et al., 2008) but many economic and social sectors including agriculture, transportation, and urban water supply (e.g. EurAqua, 2004; ABS, 2008). It is difficult to develop a single definition of drought (Heim, 2002) due to the range of sectors affected by drought, its diverse spatial and temporal distribution, and human water demands.

Wilhite and Glantz (1985) defined four types of drought: meteorological or climatological, agricultural, hydrological, and socioeconomic. The definitions are generally accepted in the literature of drought science (e.g. American Meteorological Society, 1997). All droughts begin as meteorological droughts caused by precipitation deficits. A lasting meteorological drought can develop quickly into soil moisture shortage which results in reduction of agricultural production (agricultural drought). A prolonged meteorological drought can also develop further into hydrological drought – a deficit in surface water and/or groundwater supply, which reduces streamflow, groundwater, reservoir, and lake levels. Socioeconomic drought is defined in term of its consequences, associating with the supply and demand of some economic good with elements of meteorological, agricultural, and hydrological drought (Wilhite and Glantz, 1985).

The relationship between the different types of drought is complex, requiring some numerical standard for comparing drought measurements from region to region, as well as for comparing past drought events. In the twentieth century, a number of drought indices, such as Palmer Drought Severity Index (PDSI), and the per cent of normal, deciles, Crop Moisture Index (CMI), Surface Water Supply Index (SWSI), and the Standardised Precipitation Index (SPI), were developed to identify the severity and duration of drought, and to improve techniques for early drought warning and mitigation (Heim, 2002; Lloyd-Hughes and Saunders, 2002). Of these indices, PDSI proposed by Palmer (1965) and SPI developed by McKee et al. (1993) are the most widely used. They are

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adopted and integrated in large-scale drought watch programs in the United States (NOAA, 2009), Canada (AAFC, 2009), Europe (DMCSEE, 2009; Eu Watch Programme, 2009), Africa (Rouault and Richard, 2003; Ntale and Gan, 2003), and Asia (e.g. Bordi et al., 2004; Min et al., 2003). In Australia, drought is normally defined as meteorological and is determined by the rainfall deciles, calculated from ranked rainfall data (Gibbs and Maher, 1967).

The SPI has several advantages over other indices to characterise drought (Hayes et al., 1999; Lloyd-Hughes and Saunders, 2002), and was considered as the most robust and effective tool for drought monitoring and mitigation by some researchers (e.g. Vicente-Serrana, 2006). The primary advantage is its simplicity: the SPI requires only rainfall time series to calculate two parameters, therefore, the algorithm to compute SPI is relatively easier than others. In contrast, to calculate PSDI not only precipitation and temperature but also several site-specified empirical relationships are needed (Palmer, 1965). Furthermore, the SPI represents different temporal and spatial scales on a statistically comparable basis; that is an SPI value is the same in terms of cumulative probability across locations and time periods (McKee et al., 1993; Guttman, 1998; Hayes et al., 1999; Wu et al., 2005). The SPI can be computed with different time scales (i.e. 1, 2, 6 , . . . , months), and can be used to monitor short-term drought such as soil moisture deficit and long-term water resource such as streamflow and reservoir levels (McKee et al., 1995).

Most of the indices mentioned above are derived from meteorological observations (primarily precipitation and sometimes, temperature). These data are usually readily available throughout the world, which partially explains the variety of such indices and the general popularity of this approach. Droughts may also and should, wherever possible, be assessed and monitored using other types of data (e.g. river flow). McKee et al. (1993) suggested that the procedure for precipitation could be adapted to other variables such as river flow and reservoir storage. Shukla and Wood (2008) developed a Standardised Runoff Index (SRI) by applying the SPI concept to runoff data simulated from a hydrological model, and concluded that SRI was a useful counterpart for depicting hydrologic aspects of drought. While the runoff-based SRI is useful to investigate the impacts of human activities on the catchment such as changing land cover on hydrologic drought, it does not account for the impacts of river regulation and water extraction.

In river management, droughts are often referred to as periods of low flow. Smakhtin (2001) reviewed the analyses and indices for low stream flow, and this is not repeated here. Some of these analyses focus on the frequency of flow minima or on how fast the flow in a river recedes in the absence of rain. Others, like flow duration curves, are somewhat similar to the precipitation deciles, which ranks the long-term record form highest to lowest to construct a cumulative distribution (Gibbs and Maher, 1967). Generally, these analyses do not allow the start and end of dry periods to be determined directly (Smakhtin, 2001). In the drought context, the most relevant type of hydrological analyses is perhaps the analysis of continuous periods (spells or runs) during which a flow in a river stays below some pre-defined threshold(s), which are often referred to as reference discharge or truncation level (cf. Fleig et al., 2006).

In this study, we investigated the long-term meteorological drought history from 1889 to 2007 in the Murrumbidgee Catchment, New South Wales, Australia, using the SPI. Furthermore, we apply the theory and concept underlying the SPI in defining a Standardised Flow Index (SFI) taking advantage of the existing long-term river gauge records. Specifically, the study's purpose is to answer the four questions:

1. Has the meteorological drought (SPI) changed in Murrumbidgee Catchment over the past 100 years?
2. Can hydrological drought in Murrumbidgee River be described by Standardised Flow Index (SFI)?
3. What is the relationship between SPI and SFI?
4. What are the impacts of river regulation on hydrological drought?

To distinguish the two related indices, drought based on SPI was referred as meteorologic or climatologic as the SPI considers only rainfall in isolation from hydrological context, and droughts derived from SFI were termed as hydrologic.

2. Study site

The Murrumbidgee catchment is the fourth largest in the Murray-Darling Basin, draining an area of over 84,000 km^2 (Fig. 1). The Murrumbidgee Catchment has one of the most diverse climates in the State of New South Wales (NSW), varying from the cooler and wetter high alpine in the east to the hot and dry plains of the west. Its annual rainfall varies from more than 1500 mm in the high country to less than 400 mm on the western plains. Under average climatic conditions about 24% of the rainfall in the 28,000 km^2 river catchment above Wagga Wagga appears as runoff, contributing the majority of the river flow. Below Wagga Wagga, the runoff coefficient is less than 2% (Khan et al., 2004).

The Murrumbidgee River flows from east to west, and is one of most regulated system in Australia. Water resource development in the Catchment can be traced back to the early European settlement. Table 1 listed the major water resource developments in chronological order. The main course of Murrumbidgee has 14 dams and eight large weirs. The large dams include Burrinjuck Dam near Yass, forming a reservoir with a capacity of 10.26 billion cubic metres, and Blowering Dam near Tumut, holding 16.28 billion cubic metres (Murrumbidgee CMA, 2006). These dams control water for the Murrumbidgee Irrigation Area and the Coleambally Irrigation Area situated in the lower Murrumbidgee Catchment (Fig. 1). This study focuses on the lowland reach between Wagga Wagga and Balranald.

As the major water storages are located upstream of Wagga Wagga, and the majority of water diversions occur between Wagga Wagga and Balranald (Fig. 1 and Table 1), the examination of the behaviours and dynamics of hydrological drought at the two stations provides a way to differentiate the effects of water resources development in terms of river regulation (i.e. construction and operation of large dams) and water extraction.

3. Data sources and methods

3.1. Rainfall and river flow data

Monthly rainfall data from 1889 to 2007 at Balranald, Hay and Wagga Wagga were acquired from the Australian Bureau of Meteorology (BOM, 2009). Monthly river discharge for the same period were obtained from the NSW Department of Environment, Climate Change and Water hydrological network gauges No. 410001 (Murrumbidgee River at Wagga Wagga) and No. 4100130 (Murrumbidgee River at downstream of Balranald Weir) (NSW Government, 2009) (Fig. 1).

3.2. Mathematical formulation for SPI and SFI

A number of publications detail the algorithm to compute the SPI (e.g. Guttman, 1999; Wu et al., 2005), and software for computing SPI is available. We used a program developed by the US National Drought Mitigation Centre at University of Nebraska-Lincoln to compute both SPI and SFI. The program is freely

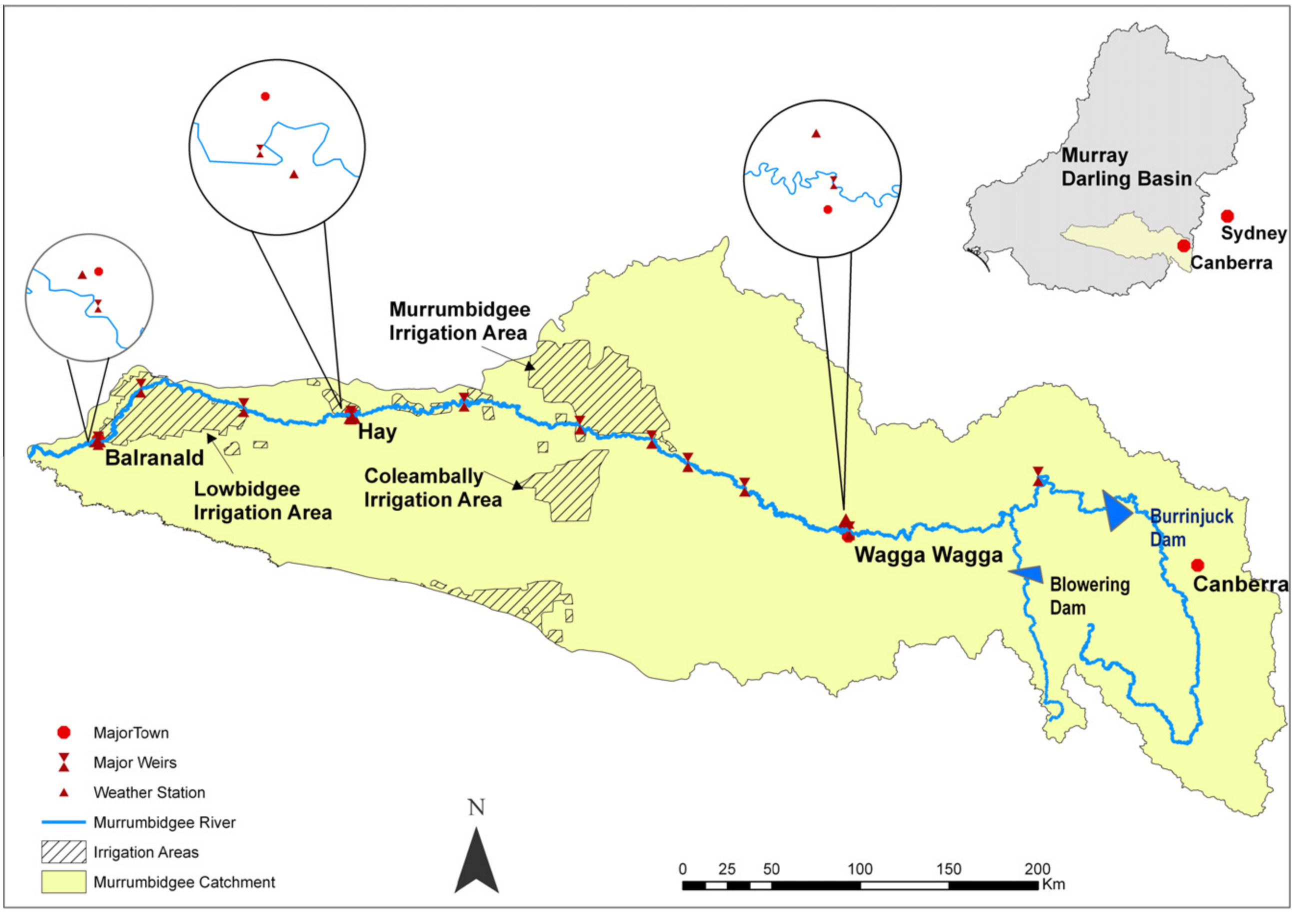

Fig. 1. Murrumbidgee Catchment in NSW, Australia. The River flows from East to West. The two largest dams (Burinjuck and Blowering) control river flow for the major irrigation areas (principal water users), which are located downstream of Wagga Wagga. The insets show the location of the weather and river gauges of which the records are used in this study.

Table 1
Major water resources developments in Murrumbidgee Catchment (modified from Wen, 2009).

Period	Development	Relevant particulars
1855–1902	Deepening of Yanco creek open to increase water diversions from Murrumbidgee	
1880–Present	Pumping water from the Murrumbidgee for irrigation, town water supply, domestic and livestock use	In the period of 1979–1990, average 337.6 million m^3 was extracted annually
1907–1927	Burrinjuck Dam stage 1	951.9 million m^3 capacity
1914–1957	Burrinjuck Dam stage 2, increasing capacity by 8.5 million m^3	Total capacity of Burrinjuck Dam is 1026 million m^3; first supply water to MIA in 1912. From 1979 to 1990, annual mean diversion is 1, 143.5 million m^3
1928	Yanco weir	Capacity of diverting 700,000 m^3/day to irrigation areas and properties along Yanco creek
1958–1968	Snowy–Tumut Hydro-electricity Scheme	Diverts up to 600.0 million m^3 per year from Snowy River to Tumut River (a tributary to Murrumbidgee River)
1965–1968	Blowering dam	Capacity 1626.0 million m^3, storing water diverted from Snowy River system and regulate flow in Tumut River
1912–1927	Murrumbidgee irrigation area (licensed irrigation area about 150,000 ha)	Receives up to 780.0 million m^3 per year diverted from Murrumbidgee River
1956–1962	Coleambally irrigation area main expansion (licensed irrigation area approximately 80,000 ha)	Receives up to 600.0 million m^3 per year from Murrumbidgee River
1936–1940	Maude weir	Diverts water to Lowbidgee Irrigation Area. Mean annual diversion (1970–1982) is 100.4 million m^3
1937–1940	Redbank weir	Diverts water from the Murrumbidge to Lowbidgee Irrigation Area. Mean annual diversion (1970–1982) is 77.7 million m^3
1982	Hay weir	Capacity 13.5 million m^3. Mean annual diversion (1979–1990) is 7.7 million m^3

available (National Drought Mitigation Center, 2000). A summary of the SPI calculation procedures can be found in the on line Supplementary material.

As SPI is normalised and represents a cumulative probability in relation to the base period for which the Gamma parameters were estimated, the interpretation is universal, i.e. comparable for different regions and periods. The classification of drought in Table 2 follows Mckee et al. (1995).

We computed SPI at three time scales with 3, 6 and 12 month lagging windows for the Wagga Wagga and Lower Murrumbidgee regions using the rainfall records from BOM. To compute SPI over different time-scales, moving-average smoothing (by 3, 6 and 12) was applied to the original monthly records. We arranged the monthly river flow time series according to calendar year. The SPI for the Lower Murrumbidgee region was based on the simple average of monthly rainfalls at Wagga Wagga, Hay and Balranald. Although less significant compared to rainfall at upstream, (Khan et al., 2004), local rainfall also contributes to river flow gauged at Balranald (Wen, 2009). Therefore, regional SPI instead of SPI at Balranald was used to investigate the impacts of the water resource management on hydrologic drought at Balranald. Because the 12-month SPI best matches the recorded historical droughts in the region, it was the choice for further analysis.

After verifying that the Gamma probability distribution function fits reasonably well with the monthly river discharge time series (see Section 4.1), we computed the standardised river flow index (SFI) at three time scales (3-month, 6-month and 12-month) in the same way as for SPI. In this study, we used the 12-month time scale to investigate the hydrological drought as it re-visualised the recorded major droughts.

3.3. Verification of Gamma probability distribution function for monthly river discharge

To apply the SPI framework to river discharge data, a suitable distribution function must be pre-determined. We fitted six distribution functions for the monthly discharge at each gauge for each month: Gamma, generalised Gamma, Gumbel, reverse Gumbel, inverse Gaussian, and generalised inverse Gaussian. These functions are known to perform well with skewed data (Stasinopoulos et al., 2008), which is the case for river discharge data. The modelling was performed using the GAMLSS package (Generalised Additive Models for Location, Scale and Shape) (Rigby et al., 2008) in R environment (R Development Core Team, 2009). For the formula for each PDF, please refer to Stasinopoulos et al. (2008). The six fitted PDFs were compared using the Akaike information criterion index (AIC), which was introduced by Akaike (1974). The definition of AIC is:

$$\mathrm{AIC} = 2k - \frac{N}{n}\ln(L) \tag{1}$$

where k is the number of parameters in the PDF; N is the number of observations; n is the number of time series (one in this case), and L is the maximized log likelihood function for the estimated function. A smaller AIC means better fitting. The formulation of AIC includes a penalty term for additional parameters to avoid over fitting.

As the functions estimate both the distributional scale and shape (skewness but not kurtosis) parameters, the normally used Kolmogorov–Smirnov goodness-of-fit test is invalid. Instead, the adequacy of fit was checked using the worm plot, a de-trended Quantile–quantile (Q–Q) plot, to diagnose the fitted (normalised quantile) residuals (van Buuren, 2007). This worm plot is constructed in the same way as the standard normal Q–Q plot, except that before the plot is generated, the linear trend is removed. This often "spreads out" the plot, thereby allowing the user to detect patterns of deviations (from normal distribution) more easily.

Table 2
Drought classification based on SPI value and the corresponding cumulative probability.

SPI values	Category	Cumulative probability
2.0–3.0	Extremely wet	0.9972–0.9986
1.5–1.99	Very wet	0.9332–0.9972
1.0–1.49	Moderately wet	0.8413–0.9332
−0.99–0.99	Normal	0.1587–0.8413
−1.0 to −1.49	Moderately dry	0.0668–0.1587
−1.5 to −1.99	Severely dry	0.0228–0.0668
−3.0 to −2.0	Extremely dry	0.0014–0.0228

3.4. Modelling the relationship between SFI and SPI

Visual inspection of SPI and SFI time series revealed the departure between the two indices, especially after the middle 1960s (see the on line Supplementary material). The relationship between SFI, SPI and time period was modelled using the generalised additive models with the LOESS (Locally Estimated Scatterplot Smoothing) smoothing technique. LOESS is a "modern" regression modelling method that builds on "classical" methods, such as linear and nonlinear least squares regression (Cleveland and Grosse, 1991). The modelling was performed using the GAMLSS package, and the fitted models were compared used the AIC (Eq. (1)), and the goodness-of-fitting was check using the Q–Q plot.

We fitted four different models considering SFI as responding variable and SPI and Year as explanatory variables. In addition, the seasonal impact was modelled using Month as an explanatory factor variable.

$$\text{Model 1}: \ \mathrm{SFI} \sim \ \mathrm{LOESS(SPI)} + \mathrm{LOESS(Year)} + \mathrm{factor(Month)} \tag{2}$$

$$\text{Model 2}: \ \mathrm{SFI} \sim \ \mathrm{LOESS(SPI)} + \mathrm{LOESS(Year)} \tag{3}$$

$$\text{Model 3}: \ \mathrm{SFI} \sim \mathrm{loss(SPI)} + \mathrm{LOESS(Year)} + \mathrm{LOESS(SPI, Year)} + \mathrm{factor(Month)} \tag{4}$$

$$\text{Model 4}: \mathrm{SFI} \sim \mathrm{LOESS(SPI)} + \mathrm{LOESS(Year)} + \mathrm{LOESS(SPI, Year)} \tag{5}$$

The first two are additive (no interactions between SPI and Year), and the last two fit surfaces for SPI and Year (interactions between SPI and Year considered). The first and third included seasonal impacts while the second and fourth excluded the seasonal factor.

For Balranald, three additional models were fitted using upstream SFI (at Wagga Wagga) as an additional explanatory variable to investigate the relationship between downstream and upstream droughts.

$$\text{Model 5}: \ \mathrm{SFI}_d \sim \mathrm{LOESS}(\mathrm{SFI}_u) + \mathrm{LOESS(Year)} \tag{6}$$

$$\text{Model 6}: \ \mathrm{SFI}_d \sim \mathrm{LOESS}(\mathrm{SFI}_u) + \mathrm{LOESS(SPI)} + \mathrm{LOESS(Year)} \tag{7}$$

$$\text{Model 7}: \ \mathrm{SFI}_d \sim \mathrm{LOESS}(\mathrm{SFI}_u) + \mathrm{LOESS(Year)} + \mathrm{LOESS}(\mathrm{SFI}_u, \mathrm{Year}) \tag{8}$$

where SFI_d and SFI_u are SFI for Balranald and Wagga Wagga, respectively.

4. Results and discussions

4.1. Probability distribution functions for monthly river flow

In general, the Gamma probability distribution function fits river flow data well for each month at both stations (the on line Supplementary material presented the ranks of fitted PDF and diagnosis worm-plots). For Balranald gauge, of the six distributions fitted, the Gamma was best for 6 months, second best for 1 month, and never worse than third best. No other distribution fitted was best as frequently as the Gamma. In Wagga Wagga, Gamma function is also the appropriate choice.

Amongst fitted functions, the poorest performer is Gumbel for both Balranald and Wagga Stations. This is likely because the probability distribution of river discharge in Murrumbidgee has a positive skewness and Gumbel function fits better for distributions with negative skewness.

4.2. Temporal and spatial characteristics of droughts in the Lower Murrumbidgee Catchment

4.2.1. Comparison of upstream and downstream climatologic drought (SPI)

In general, the two time series of SPI had the same trend, i.e. when there was a climatologic drought in the upstream reaches, drought could be expected downstream, especially for severe and extreme droughts (details of temporal behaviours of SPI and SFI at upstream and downstream gauges can be found in the on line Supplementary materials).

The comparison of SPI between two 40-year periods (1926–1966 and 1967–2007) indicated that the spatial pattern of drought had shifted. Based solely on rainfall record, the frequency of droughts of all categories decreased, especially for moderate ones (e.g. $-1.5 < \text{SPI} < -1$) at Balranald. The frequency for moderate, severe and extreme droughts decreased from 18.09% to 5.69%, from 5.28% to 4.07% and from 2.44% to 2.03%, respectively (Table 3). By contrast, severe and extreme droughts became slightly more frequent at Wagga Wagga (Table 3). This may be caused by a shift of rainfall from the wetter part (upstream) to the drier part (downstream) of the Murrumbidgee Catchment due perhaps to climate change, which was known to have an impact on the spatial distribution of rainfall in Australia (Plummer et al., 1999). A consequence of this likely rainfall shift is the reduction of total water availability in the Murrumbidgee River as the upstream rainfall contributes the majority of runoff to the River (Khan et al., 2004).

4.2.2. Comparison of climatologic (SPI) and hydrologic droughts (SFI) for upstream (Wagga Wagga)

The two drought indices at Wagga Wagga generally matched well until the late 1960s for drought frequency, magnitude and duration (Table 3), especially for server and extreme droughts, validating the usefulness of SFI as a counterpart to SPI for drought study (McKee et al., 1993). The departure of SFI from SPI since the late 1960s was coincident with the completion of Snowy–Tumut Hydro-electricity Scheme which diverts up to 600 million cubic metre of water per year from the Snowy River to the Tumut River (Table 1), a major tributary to the Murrumbidgee. From late 1960s, the climatologic droughts were significantly more frequent, severer and longer-lasting than the hydrologic ones (Table 3), suggesting that water resources development (e.g. dam operation and hydro-electricity scheme) has, to some degree, successfully mitigated drought in terms of making water available for human uses in this section of river (e.g. agricultural irrigation-major irrigation areas located downstream Wagga Wagga, Fig. 1, and town water supply). A previous study also found that river regulations dramatically increased river flow at Wagga Wagga (Wen, 2009).

For river hydrology, the SFI might present a better index for drought study than SPI when long-term records are available as it incorporates rainfall deficits and the influences of water resource management.

4.2.3. Comparison of climatologic (SPI) and hydrologic droughts (SFI) for downstream (Balranald)

In terms of drought frequency and duration, the SFI matched well with the regional SPI with a lag of approximate 2 months for the peaks. For magnitude, however, while the droughts indicated by SFI were less severe than those based on SPI prior to the early 1970s (Table 3), the hydrologic drought became more and more severe than climatologic drought, especially following 1994, since when the Lower Murrumbidgee (and the Murray-Darling Basin in general) experienced the longest drought since European settlement.

A number of reasons may apply to this augmented hydrologic drought (compared to climatologic drought). Firstly, water demand increased during prolonged drought, therefore water diversions from upstream of the Balranald gauge would have increased, reducing the river flow downstream. Secondly, the persistent drought worsens the situation of soil moisture deficit, and consequently reduces the runoff from the catchment as more rainfall is intercepted by soil. Thirdly, the operation of the dam might delay the recovery from drought for downstream regions. After a long period of drought, the water levels in reservoirs and other water storages upstream become low. To ensure the "security water level", dams and regulators may keep shut to intercept the downward flow, resulting artificially prolonged drought downstream, or even deny the opportunity to end drought downstream. The net result is an increased ratio of water diversion/river flow, and an extremely low river discharge downstream.

4.2.4. Comparison of upstream and downstream hydrologic droughts (SFI)

Fig. 2 presented the comparison between the 12-month SFI for Wagga and Balranald. The inspection of the magnitude and duration of drought events revealed two distinct periods. Until the middle 1960s, negative SFI (i.e. drought events) at Wagga Wagga was noticeably lower (severer) and longer-lasting than those at Balranald. From the middle of 1960s, the opposite pattern was observed: longer, more frequent and severer droughts occurred downstream.

Table 3 compares the drought characteristics at upstream and downstream with basic statistics for two 40-years periods. The total hydrologic drought event (defined by $\text{SFI} \leqslant -1$) frequency increased dramatically from 5.69% to 38.21% for Balranald, but decreased markedly from 20.33% to 3.26% from Wagga Wagga in the same period (Table 3). Furthermore, droughts of all magnitudes showed the same trend. For drought duration, both the maximum and median drought durations increased at Balranald while they remained unchanged at Wagga Wagga.

Table 3
Comparison of climatologic (SPI) and hydrologic (SFI) drought in the Murrumbidgee Catchment before (1926–1966) and after (1967–2007) development at upstream (Wagga) and downstream (Balranald).

Indicator		SPI				SFI			
		Balranald		Wagga		Balranald		Wagga	
		Before	After	Before	After	Before	After	Before	After
Frequency (%)	Moderate (−1.5, −1)	18.09	5.69	8.13	5.89	4.88	17.68	18.09	2.24
	Severe (−1.5, −2)	5.28	4.07	2.85	3.05	0.81	11.99	2.24	1.02
	Extreme (⩽−2)	2.44	2.03	1.83	2.44	0.00	8.54	0.00	0.00
	Total	17.89	11.79	12.80	11.38	5.69	38.21	20.33	3.26
Duration (month)	Max	17	10	15	11	12	77	5	5
	Median	3	3	2	2	1	2	2	2

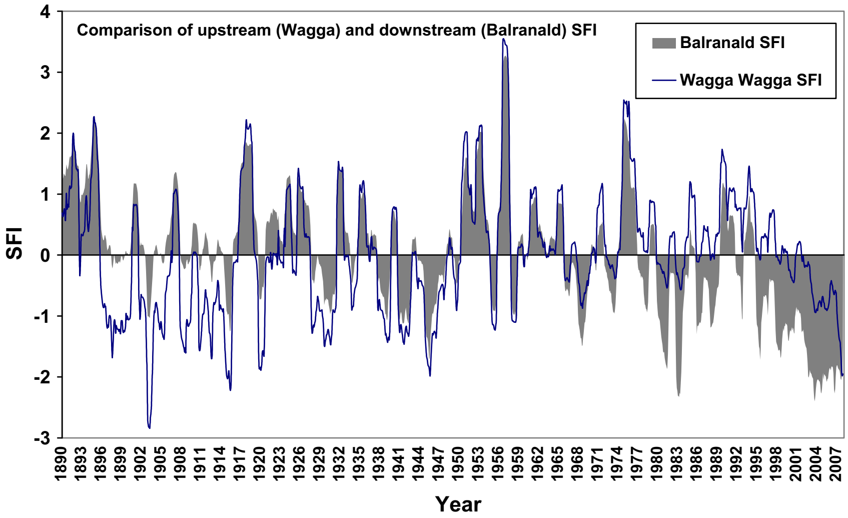

Fig. 2. Time series of Standardised Flow Index (SFI) at Balranald and Wagga Wagga.

4.3. The relationships between SPI and SFI and impacts of water resource development

4.3.1. Wagga Wagga

The residual Q–Q plots indicated that the GAM models fitted the data series reasonably well with a Filliben correlation coefficient of 0.995 (Fig. 3B). The surface models, which consider the interaction between explanatory variables, were slightly better than the simple additive ones based on the global deviance and generalised Akaike information criterion index. In addition, the fitted model coefficients were all comparable (Table 4).

The SFI was positively related to both SPI and Year, and the relationships were significant (Table 4). There was no seasonal pattern in the relationships as the fitted model coefficients for each month were not significantly different from zero (Table 4). The positive relationship with year suggested that the water resource development had successfully mitigated hydrologic drought at Wagga Wagga. The influences of water resource development, which was surrogated in the variable "Year", were clearly shown in the surface plot of Model 4 (right panel, Fig. 4). Under dry conditions, the surface was flat at an early stage indicating a good agreement between the two indices and little human influence. From around

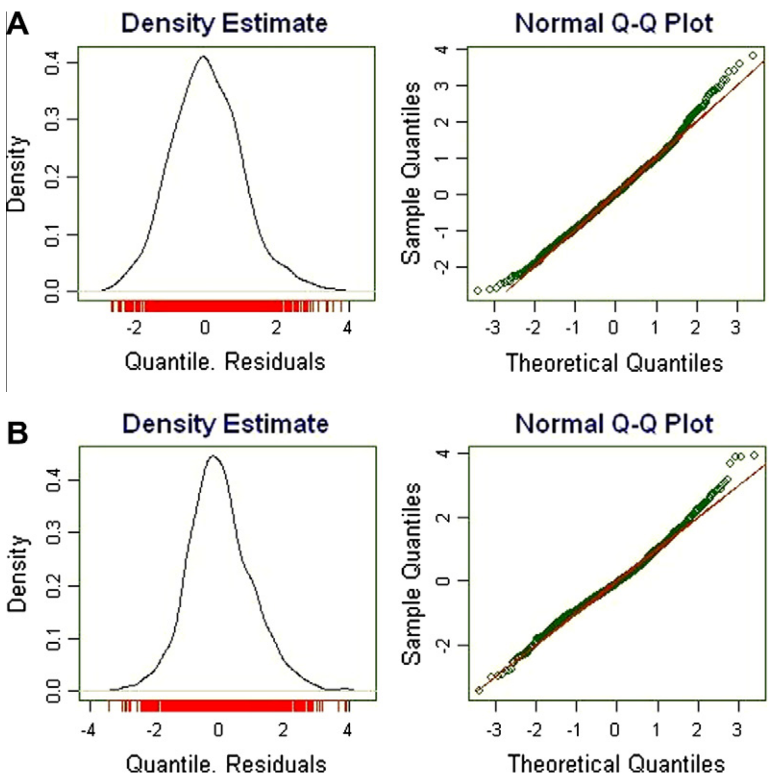

Fig. 3. Summary plots of the surface LOESS model residuals: (A) Model 7 for Balranald, and (B) Model 4 for Wagga Wagga. Both models fit the data well with Filliben correlation coefficient 0.998 and 0.995 for Balranald model and Wagga Wagga model, respectively.

Table 4
Summary of the LOESS models for Wagga Wagga in the order of accuracy (from high to low).

	Df	GD	AIC	Model coefficients		
				Intercept[a]	LOESS (SPI)	LOESS (year)
Model 4	16.52	3174.85	3207.89	−0.00	21.77***	4.46***
Model 3	27.52	3174.77	3229.81	−0.00	21.77***	4.46***
Model 1	9.67	3256.14	3275.47	−0.00	27.74***	4.45***
Model 2	20.67	3256.08	3297.41	−0.00	21.74***	4.45***

GD = Global Deviance; Df = degree of freedom; AIC = generalised Akaike Information Criterion index.
Parameters for each month were not listed as none was significant at 90% level ($p > 0.90$).
The factor month is not significant in any model, therefore not reported in the table.
Refer to the method section for model formula (Eqs. (2)-(5)).
*** Significant level: 99.9%.
[a] Log transformed.

1920s to 1970s, an uphill surface was apparent indicating the progressively improved hydrologic condition brought in by the major resource development projects upstream of Murrumbidgee (e.g. the construction of Burrinjuck and Blowering Dams, and the Snowy Hydro-electricity Scheme, Table 1). The ridge of the surface appeared under normal to slightly wet condition (0 < SPI < 1) (right panel, Fig. 4) suggesting the maximum hydrological benefits could be achieved under these condition. From the end of 1970s to the end of modelling period, a gentle downhill was noticeable suggesting that the increasing water demand was exhausting the drought mitigation capacity. This may suggest that the current water engineering facility upstream of Wagga Wagga has reached its peak capacity to mitigate drought, therefore any further water allocation upstream (e.g. more diversion of water to accommodate the growth of Canberra) would exacerbate hydrologic drought downstream of Wagga Wagga, where the major irrigation areas are located. A contour plot of the model (left panel, Fig. 4) illustrated the development stages by identifying the switches in the SPI and SFI relationship.

Comparing to dry period, the model surface was generally smoother indicating less influence of river regulation on flow in wet years.

A potential criticism of the use of "year" as a proxy for water resources development in the analysis, therefore the attributing the attenuation of hydrologic drought at Wagga Wagga to water resources development, is that other human activities such as land clearing for agricultural production, farm dams in catchment and urbanisation, are all correlated with "Year". While it is true that all these activities have impacts on river hydrology, the effects are likely to be negative. For example, Croke et al. (2004) found that decreasing in catchment forest cover would reduce river flow under dry conditions.

4.3.2. Balranald

All models fitted the SFI with SPI in the lower Murrumbidgee region and recording year reasonably well (Table 5 and Fig. 4A), and the factor variable (Month) had no significant effects on model performance (Table 5) as in the case of Wagga Wagga station. The goodness-of-fit was comparable for each model although the surface models were slightly better based on global deviance and AIC (Table 5).

All fitted models showed that the SFI was significantly positively related to SPI, which is reasonable as more rainfall means more flow in the stream. However, the significantly negative relationship with sampling year was opposite to the Wagga Wagga model, indicating the negative impacts of water resource development – extracting water from the Murrumbidgee Channel in this reach of river. The surface plot clearly illustrated the impacts of water diversion on the magnitude of hydrologic drought (right panel, Fig. 5). The gentle downhill surface till around 1960s showed the gradually increase in the severity of hydrologic drought. A much steeper downhill surface from early 1960s overlapped with the expansion of Coleambally Irrigation Area and the introduction

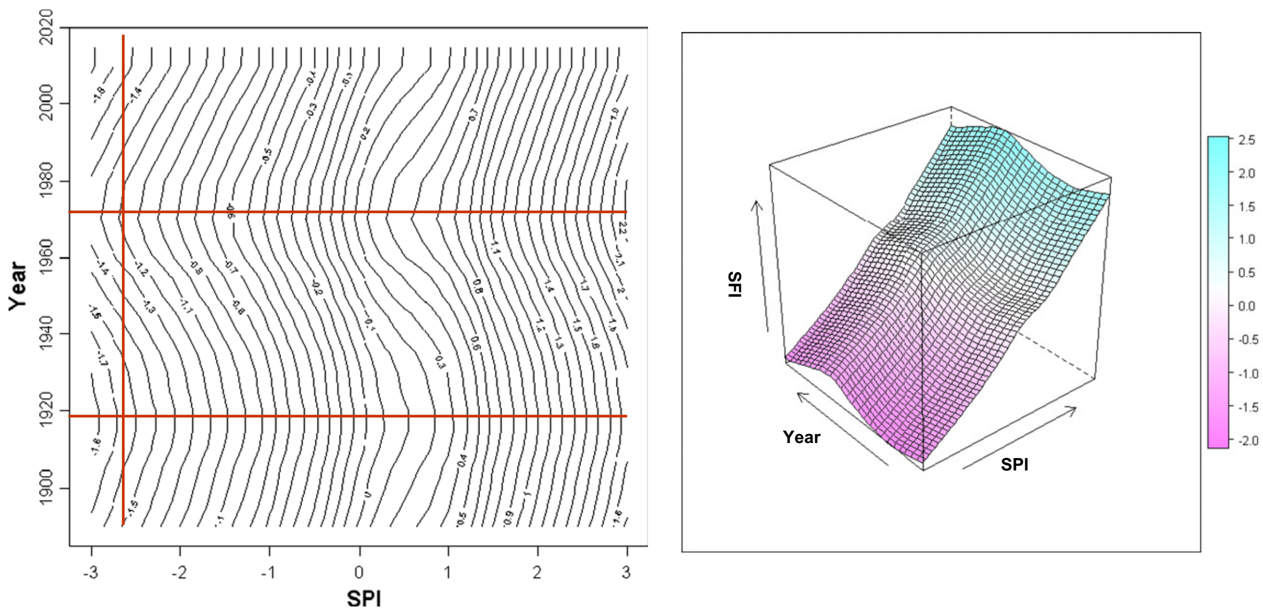

Fig. 4. Contour plot (left) and surface plot (right) of the fitted GAM (Model 4) for SFI at Wagga responding to SPI and year. Horizontal lines showed that there were two shifts in the relationship between SFI and SPI: during the period of around 1917 and about 1975, the hydrologic drought severity was progressively reduced. For example, a severe hydrologic drought in late 1910s (SFI > −1.6) could be only moderate (SFI > −1.2) in the middle 1970s (the vertical line). The reduction in drought severity most likely resulted from water resource development.

Table 5
Summary of the LOESS models for Balranald in the order of accuracy (from high to low).

	Df	GD	AIC	Model parameters			
				Intercept[a]	LOESS (SFIu)	LOESS (SPI)	LOESS (Year)
Model 7	16.99	−373.72	−339.74	−0.00	30.52***	n.i	−22.77***
Model 6	14.63	212.06	241.31	−0.00	−3.86***	28.02***	−22.67***
Model 5	10.01	365.97	385.69	−0.00	30.30***	n.i	−22.72***
Model 4	16.91	2777.69	2811.51	−0.00		19.96	−20.55
Model 1	9.94	2805.19	2825.08	−0.00	n.i	19.71***	−20.56***
Model 3	27.91	2777.63	2833.45	−0.00	n.i	19.96***	−20.55***
Model 2	20.95	2805.18	2847.07	−0.00	n.i	19.71***	−20.56***

GD = Global Deviance; Df = degree of freedom; AIC = generalised Akaike Information Criterion index.n.i. = variable not included in the model.
n.i. = variable not included in the model.
Refer to the method section for model formula (Eqs. (6)-(8)).
*** Significant level: 99.9%.
[a] Log transformed.

of Lowbidgee Irrigation Scheme (Table 1). The hydrological benefits of river regulation upstream of Wagga Wagga vanished when the Murrumbidgee reaches Balranald.

Unlike at Wagga Wagga, the impact of diverting water from the River was consistent for the whole modelling period as there were no obvious switches or "turn-points" identified in the contour plot of Balranald model (left panel, Fig. 5). Furthermore, the impact of water diversion was similar across all weather conditions (this was also opposite to what happened at Wagga Wagga). As showed in the contour plot (left panel, Fig. 5), severe hydrologic drought could occur under normal climatic conditions. The identical impacts suggested that the water demand in this region was far above the water supply.

4.3.3. Modelling the relationship between upstream and downstream SFI

In the natural states (i.e. free of dams and water diversion), the curves of SFI for upstream and downstream are identical in shape with a lag representing the water travel time, because the index was normalised (see method section). By contrast, in the regulated system such as the Murrumbidgee, dissimilarity is expected and observed (Figs. 4 and 5). Additional GAM models which include upstream SFI as an explanatory variable (Eqs. (6)-(8)) were fitted to investigate the divergence imposed by water diversion.

The models which included upstream SFI fitted the data better, and were summarised in Table 5. Of the three models, Model 7, which take account of upstream flow, Year and their interactions ranked first with a low global deviance of −373.72 (Table 5). As expected, the downstream SFI was significantly positively related to upstream SFI. However, the time variable (Year) had a significantly negative effect, indicating water diversion in this river reach had increased the magnitude of hydrologic drought.

The upstream and downstream relationship varied with river flow with greater impacts during low flow periods. During high flow periods (i.e. upstream SFI > 1), the surface was relatively flat. On the other hand, during low flow, a steeper downhill slope was noticeable (right panel, Fig. 6). The impacts of water resource development on the upstream–downstream relationship were illustrated well in the contour plot (left panel, Fig. 6). The vertical line in the contour plot demonstrated the progressive augment in drought magnitude with time: a moderated drought (SFI = −1) at Wagga Wagga, the hydrological condition at Balranald would be normal (SFI > −0.8) till 1940s, remain mild (SPI < −1.5) until early 1960s, but become severer and severer till the end of modelling period. In 2007, the hydrologic drought would evolve into an

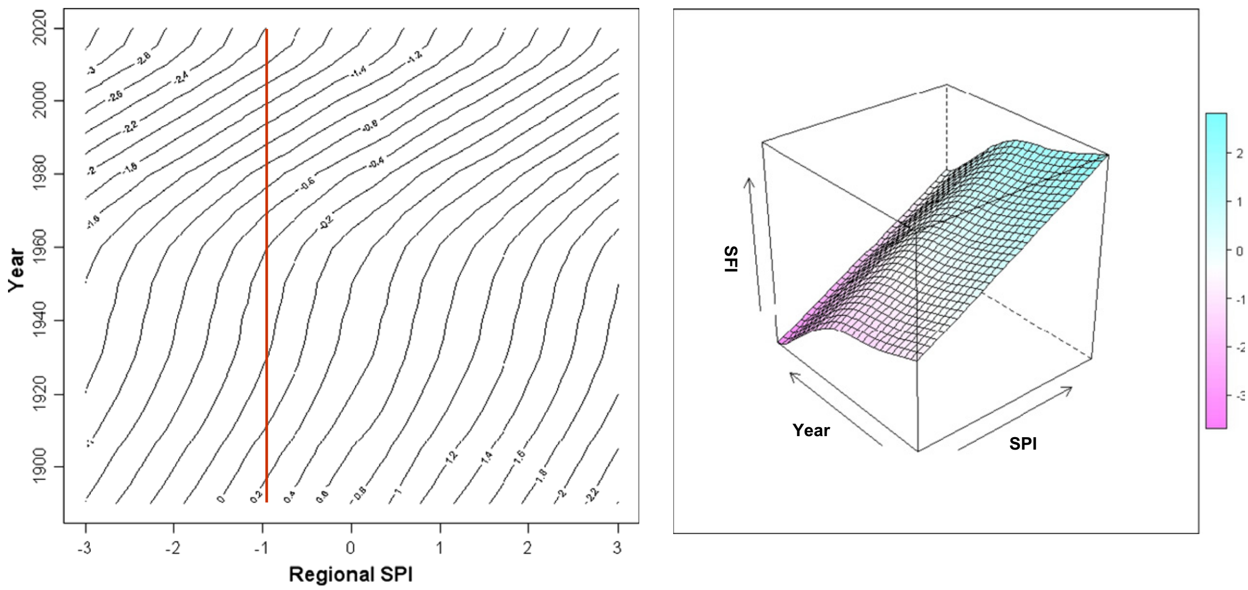

Fig. 5. Contour plot (left) and surface plot (right) of the fitted GAM (Model 4) shows the relationship between SFI at Balranald responding to regional SPI and year. The hydrologic drought gradually became more and more severe, and contrast to Wagga Wagga station, no switches or "turning-points" was identified during the modelling period. The vertical line shows that a normal hydrological condition (0.2) at the early 1900 would be a severe hydrological drought (−1.6) from 2000.

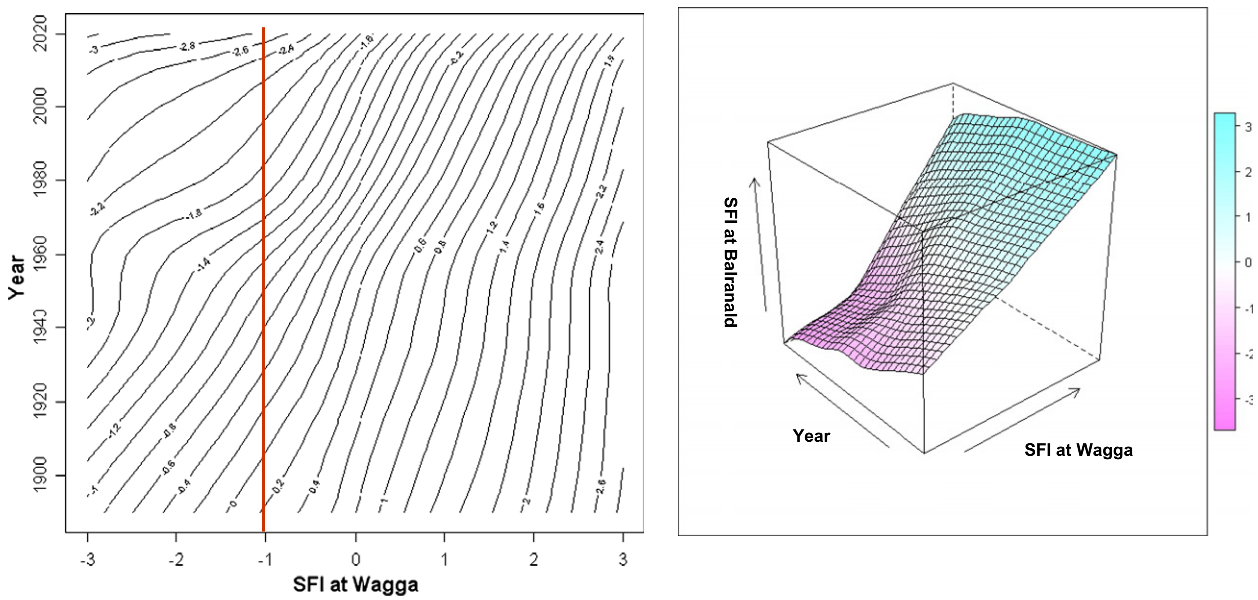

Fig. 6. Contour plot (left) and surface plot (right) of the fitted GAM (Model 7) shows the relationship between upstream and downstream SFI. The vertical line illustrates that a moderate drought ($-1 < SFI < 0$) at Wagga Wagga remained mild at Balranald until early 1960, but would develop into a severe drought ($SFI < -1.5$) in late 1980s and an extreme drought ($SFI < -2.0$) in the 1990s and 2000s.

extreme drought (SPI = -2.8 at 2007). The modelled downstream-upstream relationship and its evolving path matched well with the patterns observed in Fig. 2.

5. Conclusions

The study demonstrated that the Gamma probability distribution function was adequate to describe the probability density function of the monthly river discharge, thus validating the application of the Standardised Precipitation Index concept to the investigation of hydrologic droughts using monthly flow time series. More importantly, the case study for the lower reach of Murrumbidgee River suggested that the Standardised Flow Index integrates both meteorological and water resource development information, thereby providing a useful tool for researching, monitoring and managing hydrological drought in regulated river systems.

While meteorologic droughts at Wagga Wagga increased slightly in terms of magnitude and duration i.e. becomes drier, the hydrologic drought was substantially reduced. On the contrast, the meteorologic conditions at Balranald was wetter in the recent 40 years compared to early 1900s, yet the magnitude, frequency and duration of hydrologic drought has increased dramatically. The comparison between upstream and downstream SFI indicated that river regulation and water diversion had totally different influences on hydrologic drought indices: while river regulation was positively related the SFI, the impacts of water diversion was negative.

The impacts of river regulation upstream of Wagga Wagga on hydrologic droughts were further investigated by applying GAM models with LOESS smoothing term to the computed SPI and SFI. The results showed that the regulation had successful mitigated the magnitude of hydrologic droughts, thus ensuring a more reliable water supply for water users downstream of Wagga Wagga. However, the hydrologic benefits of regulation progressively disappeared along the rive course. The Balranald GAM models revealed that the hydrological benefits realised upstream were totally reversed at Balranald by the diversion of water at the river reach of Wagga Wagga-Balranald. In fact, the magnitude and duration of hydrologic droughts at Balranald were augmented progressively during the modelling period, reflecting the increasing water demands in the region. The results of the study highlighted the importance of balancing the water needs between upstream and downstream users in river management.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jhydrol.2011.05.037.

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