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Monitoring and Assessment of Surface Water Abstractions for Pasture Irrigation from Landsat Imagery: Bega–Bemboka River, NSW, Australia

Ivars Reinfelds

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Abstract Irrigation of pasture forms the greatest single use of irrigation water in Australia yet there has been little monitoring of its spatial extent and water demands across southeast Australian coastal catchments where irrigated dairy farming forms an important rural livelihood. This paper provides an analysis of spatio-temporal patterns in the extent of irrigated pasture in the Bega–Bemboka catchment on the south coast of New South Wales from Landsat imagery, and establishes quantile regression relationships between metered monthly irrigation abstraction volumes, evaporation and rainfall. Over the metering period (2000–2007), annual water usage averages 4.8 ML ha^{-1} year^{-1}, with January being the month of highest demand with an annualised usage of 10.4 ML ha^{-1} year^{-1}. Analysis of Landsat imagery indicates that the spatial extent of irrigated pasture across the catchment has increased from 1266 ha in 1983 to 1842 ha by 2002, together with amalgamation of smaller holdings along less reliable streams into larger parcels along the trunk stream. Quantile regressions to estimate monthly mean and maximum abstraction volumes from monthly evaporation and rainfall data indicate that abstraction volumes are more closely correlated with evaporation. When combined with Landsat analyses of the spatial extent of irrigated areas, such relationships enable estimation of catchment-scale hydrological effects of irrigation abstractions that in turn can help guide regional-scale assessments of the ecological effects and sustainability of spatially and temporally changing irrigation abstraction volumes.

Keywords Irrigation · Water abstraction · Water extraction · Landsat · Environmental flow

I. Reinfelds (✉)
New South Wales Office of Water, PO Box 53, Wollongong, NSW, 2520, Australia
e-mail: ivars.reinfelds@water.nsw.gov.au

1 Introduction

Irrigated agriculture accounts for approximately 70% of total water consumption across Australia (Australian Bureau of Statistics 2000). According to the 2005–06 Agricultural Census, pasture irrigation for grazing livestock forms the greatest single use of irrigation water across Australia, accounting for 26.9% of all irrigation water used nationally and 64.5% of all irrigation water used in the state of Victoria (Australian Bureau of Statistics 2008). Despite the dominance of pasture irrigation in agricultural water consumption across south-eastern Australia (Australian Bureau of Statistics 2008), there have been few studies of spatio-temporal changes in patterns of water usage for pasture irrigation in the coastal plains east of the Australian Great Dividing Range where dairying forms an important rural landuse. This dearth of information stems from both a lack of metered data on actual water usage by licensed irrigators (Reinfelds et al. 2006) and a lack of reliable and accurate spatial analyses on the extent of irrigated agriculture within east Australian coastal catchments. Such data are essential for informed and effective management of water resources, particularly where climate change, agricultural expansion, water trading and population growth place increasing pressure on limited, and potentially diminishing, water resources.

Satellite imagery, and Landsat in particular, have received widespread application for monitoring of agricultural irrigation. Estimation of the spatial extent of irrigated lands and identification of different agricultural crop types forms one of the more common applications of remote sensing (e.g. Kolm and Case 1984; Barbosa 1998; Abuzar et al. 2001; Martinez et al. 2001; Akbari et al. 2006; Ozdogan et al. 2006; Serra and Pons 2008). Such estimates are increasingly being used to assess regional irrigation water demands through relationships between the spatial extent of irrigated areas, crop water requirements and agrometeorological data (Casterad and Herrero 1998; Herrero and Casterad 1999; Heinemann et al. 2002; Casa et al. 2009). Costs for satellite image based assessments of regional irrigation water abstraction can be sixty time lower than for traditional metering methods based on volumetric monitoring or electricity consumption, with accuracies of 95% being reported by some studies (e.g. Castano et al. 2010). A further advantage of satellite based methods is that access to archived imagery enables assessment of changes in water abstraction pressures over the past 30–40 years, thereby providing historical 'reference points' for communities dependent on, or affected by, irrigation abstraction of water resources.

The Bega–Bemboka River in southeastern Australia is unique among catchments east of the Australian Great Dividing Range in that surface water abstractions for pasture irrigation that support a regionally important dairy industry have been the subject of a comprehensive metering program since February 2000. Reinfelds et al. (2006) presented an analysis of three years of daily metering data (2000–03) and discussed the effects of surface water abstractions on hydrology and aquatic habitats. In this paper, the analysis of surface water abstractions is extended to include 2004–07, a period spanning an enduring drought across eastern Australia that was described in the popular media as a 1 in 1000 year event (Australian Broadcasting Corporation November 7, 2006). Nicholls (2004) found that rainfall deficits in eastern Australia during this recent drought were similar in magnitude to several other historical droughts, but the effects of the deficits were exacerbated by higher than average minimum and maximum temperatures, leading to increased evaporation, decreased soil moisture and decreased runoff.

In addition to the data on metered water usage, spatial boundaries of irrigated pastures were surveyed with a differential Global Positioning System (GPS) by New South Wales Government surveyors in August–September 2001. This field-based data set provides an excellent opportunity to assess the utility of Landsat imagery to provide information on the spatial extent of irrigated pasture. Such spatial information, combined with knowledge of irrigation water requirements, can provide water management authorities with estimates of water abstractions from surface and ground water resources at a catchment scale. Accurate spatial information hence provides a means of monitoring changes in water usage between catchments, thus

Fig. 1 Map of the Bega–Bemboka catchment showing distribution of licensed surface water pumps, rivers and streams, forested areas, gauging and rainfall stations

facilitating assessments of the sustainability of spatially and temporally changing water usage patterns, related for example, to trading of farmers' water rights. The aims of this paper are thus:

1. to assess temporal patterns and climatic controls on surface water abstractions for pasture irrigation in the Bega–Bemboka catchment;
2. to assess spatio-temporal changes in the extent of irrigated pasture in the Bega–Bemboka catchment from a time-series of Landsat imagery; and
3. to discuss the utility and limitations of catchment-scale assessments of the spatial extent of irrigated pasture from Landsat imagery.

1.1 Study Area

The Bega–Bemboka River is located on the south coast of NSW and has a catchment area of 825 km^2 at the Kanoona Rocks gauging station (Fig. 1). Long term median annual rainfall totals of about 1000 mm occur in the headwaters near Nimmitabel and 650–775 mm across the middle to lower catchment around Bemboka and Kameruka

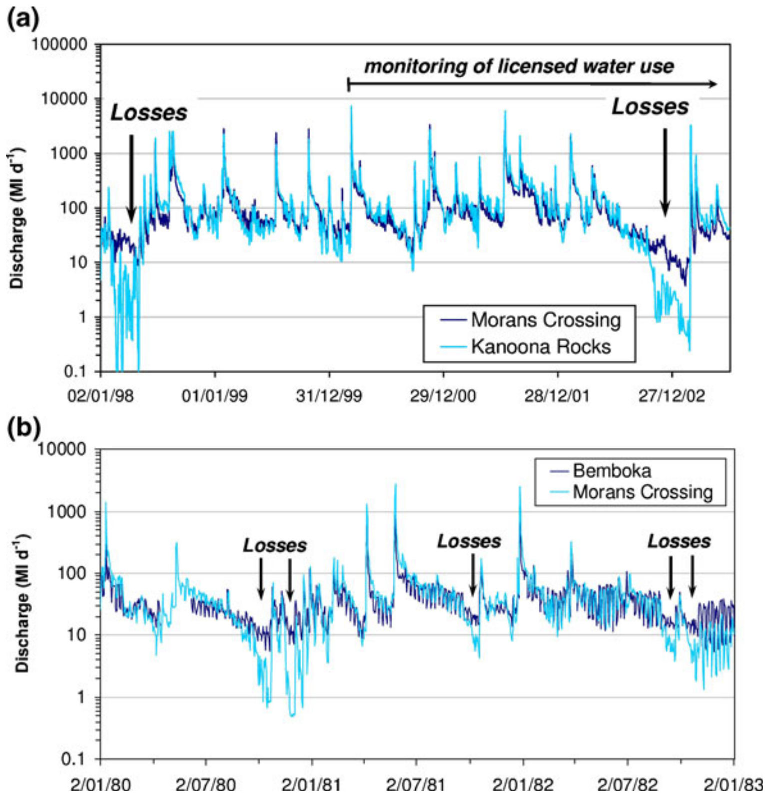

Fig. 2 Daily flow hydrographs showing downstream flow losses for the Bega–Bemboka River comparing: **a** Morans Crossing and Kanoona 1998–2002; and **b** Bemboka and Morans Crossing 1980–1983

(Fig. 1). Devonian granites and granodiorites of the Bega batholith form the dominant geology across the catchment. Cochrane Dam is located in the headwaters of the Bega–Bemboka River at a catchment area of 35 km^2 (Fig. 1) The dam has a capacity of 2800 ML and can release water at a maximum rate of 70–80 MLd^{-1} for hydro-power generation and downstream irrigation consumption (Reinfelds et al. 2006). During drought years, water releases for irrigators are insufficient to fully offset volumes extracted by downstream irrigators (Reinfelds et al. 2006).

The Bega–Bemboka River upstream of the Kanoona Rocks gauging station is subject to regulation effects from Cochrane Dam as well as irrigation and water supply abstractions from the trunk stream and main tributaries (Reinfelds et al. 2006). The system is characterised by periods of downstream flow losses between the Morans Crossing and Kanoona Rocks gauging stations (Fig. 2a), and historically, between Bemboka and Morans Crossing (Fig. 2b). Reinfelds et al. (2006) noted that these losses are apparent in daily flow hydrographs as short-duration, low-flow spikes, and over drought-affected months, as extended duration low-flow troughs (Fig. 2). The downstream losses in flow are attributable both to the effects of surface-water abstractions and natural transmission losses (Healthy Rivers Commission 2000; Reinfelds et al. 2006). While surface water abstractions for irrigation form the dominant source of downstream flow losses, transmission losses dominate during drought periods with irrigation restrictions. Under such conditions, the piedmont zone of the Bega–Bemboka River switches from a naturally 'gaining' to a naturally 'losing' stream (Reinfelds et al. 2006).

2 Methods

2.1 Irrigation Abstraction, Rainfall, Evaporation and River Flow Data

Metering of licensed surface-water abstractions through measurement of electricity consumption commenced in January 2000 and remains ongoing. Monthly data for 17 licences irrigating 924 ha of dairy pasture, with water drawn from the trunk stream between Cochrane Dam and Kanoona Rocks gauging stations, were analysed for the period 06/02/2000 to 30/06/2007. Abstraction restrictions due to low river flows affect 16.9% (15/89 months) of available data. These data were excluded from analysis so that results presented here reflect monthly abstraction volumes under unrestricted conditions. Rainfall and evaporation data from the Bureau of Meteorology for Bemboka Post Office (69003) and Kameruka (69017; Fig. 1) were used for statistical analysis of relationships between irrigation abstractions and these variables. Rainfall and evaporation were averaged for these stations to account for spatial climatic variability across the central and lower portions of the catchment where irrigation is greatest. While additional variables (temperature, solar radiation) are also available, linear regressions show these are highly correlated to evaporation (r^2 greater than 0.8). To minimise redundancy, relationships between these variables and irrigation abstractions were not assessed.

2.2 Statistical Analysis

Quantile regression analysis in R Project software was used to determine upper limiting and central response models between monthly irrigation volumes, rainfall and evaporation. For specified quantiles (a proportion ranging between 0 and 1), the quantile regression algorithm determines a function for which the specified proportion of data points fall at or below the value predicted (Lancaster and Belyea 2006). For high quantile values (e.g. 0.9), the regression thus estimates an upper limit to the scatter of data points. Quantile regression hence extends ordinary least squares regression analyses (where a single model for central tendency is calculated), by enabling calculation of the full range of functions for the median (50th quantile) or any other quantile of interest (Lancaster and Belyea 2006). Such analyses are becoming increasingly common in aquatic ecology to assess ecological responses to hydrologic and hydraulic variables (e.g. Cade and Noon 2003; Lancaster and Belyea 2006), and are gaining popularity in a range of environmental modelling applications (Yu et al. 2003). Quantile specific coefficients of determination (R^1) "are similar to, but not directly comparable with, the R^2 coefficients of determination in ordinary least squares regression" (Lancaster and Belyea 2006, p. 788).

2.3 Landsat Image Selection and Analysis

Time series of daily river flow and rainfall data extending back to the early 1980s were assessed graphically to identify drought periods for image selection in order to maximise spectral contrasts between areas of irrigated and non-irrigated pasture. Radiometrically corrected, orthorectified Landsat scenes covering the Bega–Bemboka catchment were purchased for three drought periods: 6 November 2002 (Landsat 7 Enhanced Thematic Mapper); 4 February 1998 (Landsat 5 Thematic Mapper); and, 18 January 1983 (Landsat 4 Multi Spectral Scanner). Images were re-sampled (cubic convolution) by the data provider into 25 m (2002 and 1998 imagery) and 50 m (1983 imagery) pixels during radiometric correction and ortho-rectification procedures. All images were masked to exclude from analysis areas outside the catchment boundary, as well as National Parks and State Forests (the majority of forested areas) occurring within the catchment (Fig. 1). The masked images were classified into 25 classes using an ISODATA unsupervised classification algorithm with 12 iterations and a 95% convergence threshold in Arcview Image Analyst. Standard Normalised Difference Vegetative Index (NDVI) images were also generated. Classified and NDVI images were converted into ESRI grids, with classified images also converted to shapefiles to facilitate post-classification interrogation and analysis of irrigated areas in Arcview 3.3.

Arcview 3.3 with Image Analyst and Spatial Analyst was used to overlay differential GPS surveyed polygons covering 830 ha of known irrigated areas (surveyed in August–September 2001) onto the 2002 classified and NDVI images, to determine class correspondence with areas of known irrigation and their spectral characteristics (Fig. 3a). For the November 2002 image, four classes covered 92% of the total 830 ha of field surveyed irrigated areas (Fig. 3b). The primary characteristics distinguishing approximately 90% of known areas of irrigated pasture from non-irrigated areas were high mean class values in the near infra-red wavelengths of band 4 (Fig. 3c), and correspondingly, NDVI values greater than about 0.08 (Fig. 3d). For the 1998 and 1983 images, four and three ISODATA classes, respectively, exhibited the high near infra-red reflectance values associated with irrigated pasture, and a spatial context (proximity to water sources, water licenses, suitable topography) amenable to interpretation as irrigated areas.

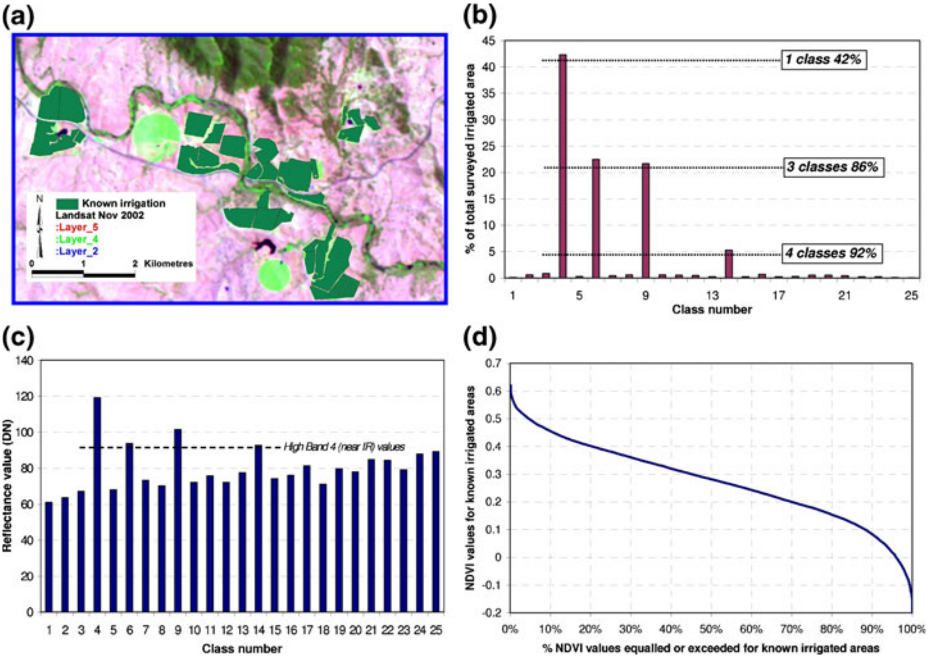

Fig. 3 **a** Shows overlay of field surveyed polygons of irrigated pasture over 2002 Landsat image; **b** shows cumulative percentage of field surveyed irrigated area explained by individual ISODATA classes for 2002 imagery; **c** shows Landsat ETM band 4 reflectance values associated with surveyed irrigated areas for 2002 imagery; **d** shows cumulative frequency distribution of NDVI values associated with surveyed irrigated areas for 2002 imagery

Although NDVI thresholding is a commonly used method for delineating irrigated from non-irrigated areas (e.g. Ozdogan et al. 2006), this simple technique could not be easily applied to mapping spatio-temporal changes in the extent of irrigated pasture in the Bega–Bemboka catchment. Here, forested areas outside of the masked areas of National Park and State Forest commonly returned NDVI values within the range of values representative of irrigated pasture, leading to the possibility of errors of commission from simple application of an NDVI threshold. A second and more problematic area of concern lies in the substantial variation in NDVI values between the masked images from different years (Table 1), reflecting regional differences in soil moisture availability between the different years. In this situation, application

Table 1 Normalised Difference Vegetative Index (NDVI) descriptive statistics for 1983, 1998 and 2002 Landsat imagery

Statistics	1983	1998	2002
Minimum	−0.026	−0.116	−0.41
Maximum	0.673	0.692	0.53
Mean	0.165	0.33	−0.051
Median	0.113	0.31	−0.109
Mode	0.064	0.228	−0.156
Std. dev.	0.132	0.128	0.139

of a single NDVI threshold from one year, such as 0.08 for the November 2002 image (Fig. 3d), that provided an accurate distinction between areas of irrigated and non-irrigated pasture, could not be applied to other years without the potential for introducing substantial errors of commission or omission in the analysis.

In order to accommodate these concerns, the multi-criteria decision rules illustrated in Fig. 4 were developed to minimise operator subjectivity in the assessment of spatio-temporal changes in pasture irrigation from the 2002, 1998 and 1983 Landsat

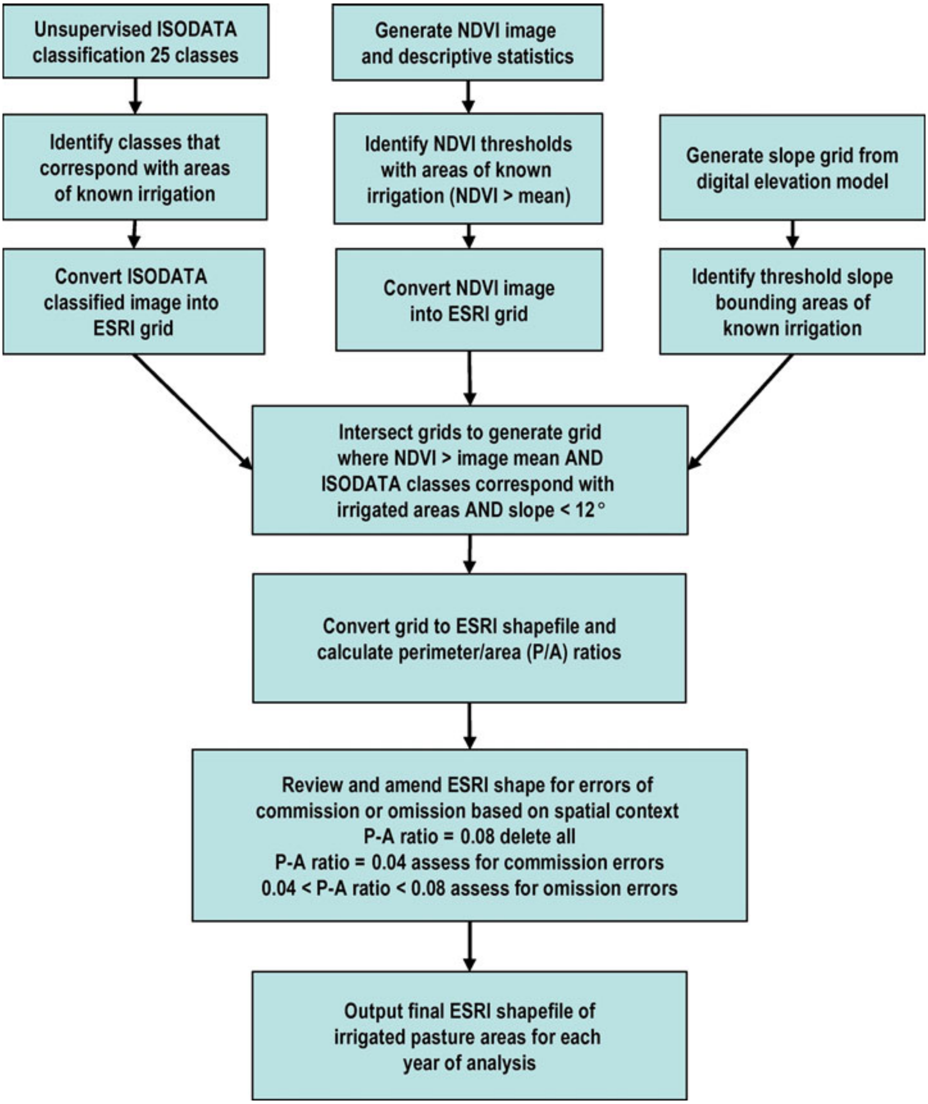

Fig. 4 Flow chart of multi-criteria decision rules used to delineate irrigated areas for 1983, 1998 and 2002 Landsat imagery

imagery (Fig. 4). The conversion of classified and NDVI images to Arcview Spatial Analyst grids simplified the application of an initial triple criteria decision rule based on the results of an unsupervised ISODATA image classification, NDVI indices and landform (slope) constraints (Fig. 4). Conversion of the resultant multi-criteria grid into vector polygons and calculation of perimeter–area ratios (P/A) enabled rapid clean-up of very small and elongate polygons with high P/A ratios (Fig. 4), many of which are probably not irrigated but represent better pasture growth in swampy valley fills (Brierley and Fryirs 1998). Errors of commission and omission for the P/A ratio classes identified in Fig. 4 were individually assessed for each polygon on the basis of: proximity to rivers, streams and locations of licensed irrigation pumps; surrounding topography; and, woody vegetation cover.

3 Results

3.1 Monthly Surface Water Abstractions for Pasture Irrigation

Temporal variations in monthly irrigation abstractions show some dependency on variations in monthly rainfall patterns (Fig. 5). Irrigation abstractions are generally lowest during high rainfall months, and are highest during prolonged periods of low rainfall, such as occurred over winter–spring 2002 and summer–autumn 2006 (Fig. 5). Under low rainfall conditions, high levels of irrigation abstraction are sustained over periods of up to 6 months duration until abstraction restrictions are commenced or significant rainfall occurs (Fig. 5).

Monthly statistics for irrigation abstractions show that January is the month of highest water use with a mean water demand of 0.87 ML ha^{-1} $month^{-1}$, a

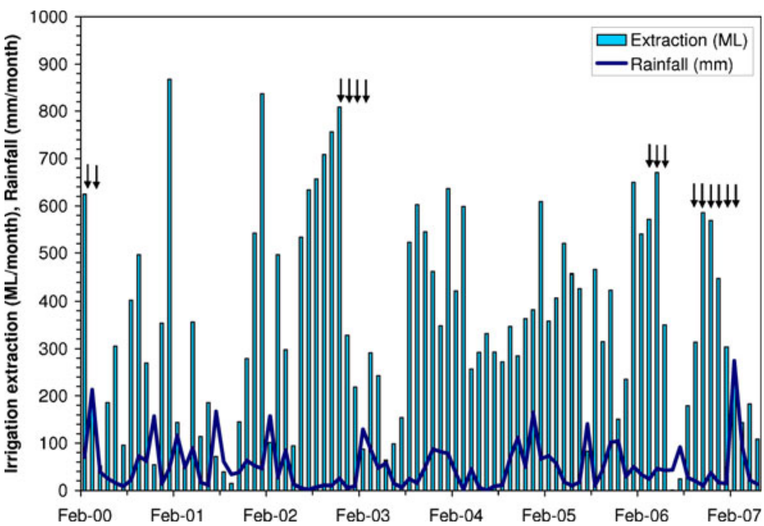

Fig. 5 Monthly surface water abstractions and monthly rainfall from February 2000 to June 2007. *Arrows* indicate months of abstraction restrictions

Table 2 Monthly surface water abstraction statistics for unrestricted months expressed as ML ha^{-1} month^{-1}

Diversion	Jan	Feb	Mar	Apr	May	Jun	Jly	Aug	Sep	Oct	Nov	Dec	Annual
Mean	0.87	0.38	0.40	0.33	0.23	0.30	0.23	0.44	0.50	0.49	0.32	0.45	0.40
Max	1.05	0.65	0.72	0.63	0.55	0.64	0.76	0.79	0.85	0.91	0.56	0.65	1.05
Min	0.73	0.12	0.07	0.06	0.08	0.00	0.03	0.05	0.02	0.18	0.07	0.28	0.00
Std. dev.	0.15	0.22	0.25	0.18	0.17	0.21	0.26	0.26	0.30	0.27	0.20	0.13	0.26
Count	5	5	6	7	7	8	7	7	6	6	5	5	74

figure approximately 2.2 times greater than the mean annual demand of 0.40 ML ha^{-1} month^{-1} (Table 2). The months of August to October and December all have average water demands greater than the annual mean indicating that the greatest average irrigation demands occur in spring and summer (Table 2). The lowest irrigation demands occur in autumn and early–mid winter (Table 2). Maximum water demands for all months, however, exceed the annual average monthly demand (Table 2), ranging from 1.4 times the annual average in May to 2.6 times in January, indicating that significant irrigation of pasture occurs year-round, including winter. The mean annual water application rate for irrigated pasture in the Bega–Bemboka catchment equates to 4.8 ML ha^{-1} year^{-1} (Table 2).

3.2 Climatic Controls on Irrigation Abstractions

Quantile regression analysis of monthly irrigation abstractions against monthly rainfall and monthly evaporation indicates that evaporation has a stronger influence on irrigation abstractions than rainfall (Fig. 6, Table 3). Evaporation in particular shows a clear upper limiting relationship with irrigation abstractions that can be effectively modelled by quantile regressions (Fig. 6b). The relatively small number of available data points (74 months of unrestricted abstraction data) limits the

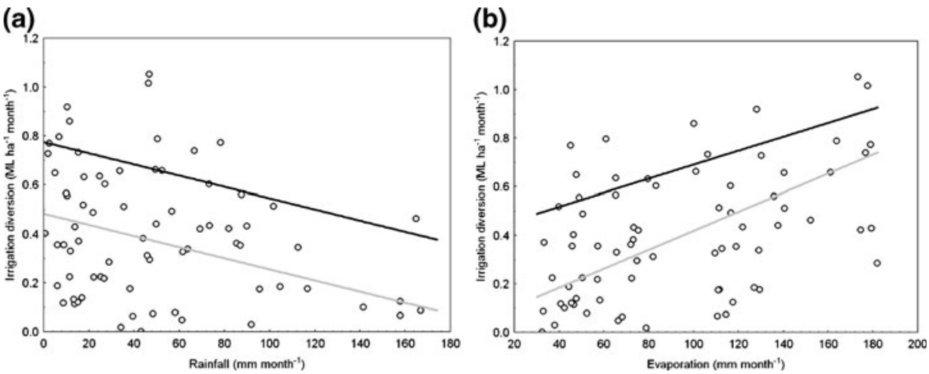

Fig. 6 Scatterplots of **a** monthly abstraction volumes and monthly rainfall; and, **b** monthly abstraction volumes and monthly evaporation. Upper trend lines represent the 85th quantile where 85% of data points lie on or below the trendline, lower trend lines represent the 50th or median quantile regression

Table 3 Quantile regressions for 50th (median) and 85th percentiles (upper estimate) between monthly irrigation abstraction volumes, evaporation and rainfall

Regression quantile (τ)	Equation	P	R^1
0.5	Abstraction = −0.0023Rain + 0.4834	<0.01	0.03
0.5	Abstraction = 0.0039Evap + 0.0283	<0.01	0.11
0.85	Abstraction = −0.0023Rain + 0.7743	0.11	0.08
0.85	Abstraction = 0.0029Evap + 0.4036	<0.05	0.12
0.5	Abstraction = 0.0046Evap − 0.0028Rain + 0.1114	<0.01	0.20
0.85	Abstraction = 0.0037Evap − 0.0035Rain + 0.4753	<0.01	0.31

P denotes the significance level, R^1 is the quantile specific co-efficient of determination

analysis to the 85th quantile (Scharf et al. 1998; Lancaster and Belyea 2006), where 85% of data points lie on or below the upper trend line (Fig. 6). Although the 85th quantile regression between evaporation and irrigation abstractions provides a conservative (low) estimate for maximum monthly irrigation demands (Fig. 6), it nonetheless provides a simple and rapid means of estimating maximum water demands for pasture irrigation from monthly evaporation data. The 50th quantile (median) regression between monthly irrigation abstractions and evaporation provides an alternative central tendency estimate to ordinary least squares regression for estimating 'average' monthly irrigation abstractions from evaporation data alone (Fig. 6, Table 3).

Multiple quantile regression equations incorporating both monthly evaporation and monthly rainfall show improvement over single parameter quantile regressions for estimation of irrigation abstractions from climatic variables (Table 3). R^1 coefficients of determination increase to 0.20 and 0.31 for the 50th and 85th multiple regression quantiles, respectively (Table 3). While the upper limit to monthly irrigation abstractions can be estimated from evaporation data alone (Fig. 6b; Table 3), or preferably by multiple regression incorporating both evaporation and rainfall (Table 3), the coefficients of determination for the regressions indicate that irrigation abstractions are influenced by additional factors that are not accounted for in the climatic variables.

3.3 Spatio-Temporal Changes in Extent of Irrigated Pasture

The analysis of Landsat imagery from drought periods in January 1983, February 1998 and November 2002 provides a clear picture of spatio-temporal changes in the patterns and extent of irrigated pasture in the Bega–Bemboka River catchment upstream of the Kanoona Rocks gauging station (Fig. 7). The total area of irrigated pasture has increased by 45% from 1266 ha in 1983 to 1842 ha by 2002, with the large majority of this increase occurring between 1983 and 1998 (Fig. 7; Table 4).

At a sub-catchment scale, since 1983 the extent of irrigated pasture has remained constant at about 690 ha in the Upper Bega–Bemboka sub-catchment upstream of the Morans Crossing gauging station (Table 4). The Middle Bega–Bemboka sub-catchment between the Morans Crossing and Kanoona gauging stations shows the largest increase in irrigated pasture, increasing by 403 ha since 1983 (Table 4). Tantawangalo Creek and Sandy Creek sub-catchments also show increases in the extent of irrigated areas of 149 and 71 ha, respectively, with Candelo Creek showing

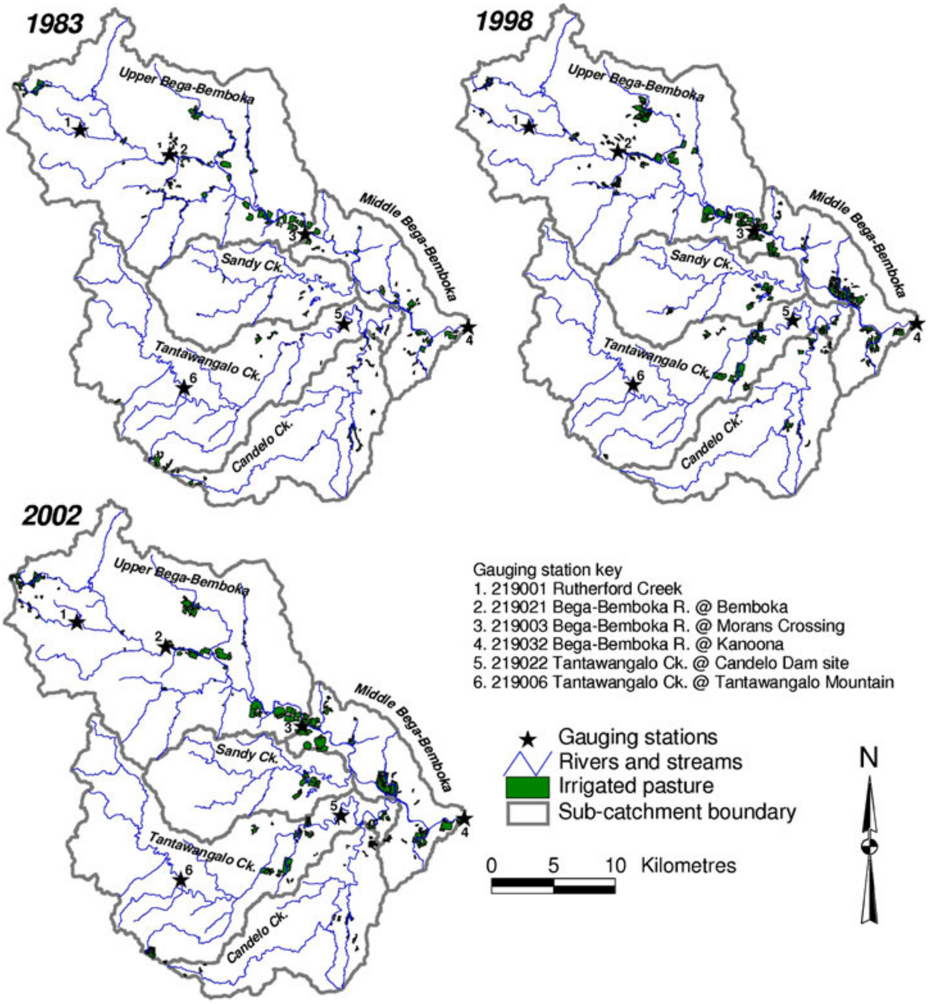

Fig. 7 Spatial extent of pasture irrigation in the Bega–Bemboka catchment from analysis of 1983, 1998 and 2002 Landsat imagery

a minor decline (Table 4). Also apparent since 1983 is the amalgamation of smaller irrigated areas into larger parcels, particularly along smaller tributaries with less reliable streamflow such as Pollock's Flat and Colombo Creeks (Figs. 1 and 7).

Table 4 Total and sub-catchment areas of irrigated pasture (ha) assessed from Landsat imagery for January 1983, February 1998 and November 2002

Year	Upper Bega–Bemboka	Middle Bega–Bemboka	Tantawangalo Creek	Sandy Creek	Candelo Creek	Total
1983	689	262	146	35	134	1266
1998	696	531	324	100	98	1749
2002	698	665	295	106	78	1842

4 Discussion

Temporal patterns in surface water abstractions for irrigation of perennial pasture in the Bega–Bemboka catchment indicate that significant irrigation occurs year-round. Maximum irrigation abstractions for all unrestricted calendar months, including the winter months, substantially exceed the annual average of 4.8 ML ha^{-1} $year^{-1}$ (Table 2). Assumptions that perennial pasture in south-eastern Australia is irrigated only over summer and autumn (e.g. Abuzar et al. 2001) are clearly not supported by these data. Indeed, the annualised mean winter-season (June, July, August) water abstractions for pasture irrigation in the Bega–Bemboka catchment of 3.9 ML ha^{-1} $year^{-1}$ (Table 2) are equivalent to the Australian Bureau of Statistics (2008) 2005–06 Agricultural Census annual estimates for pasture irrigation in Victoria.

The metered mean annual abstractions of 4.8 ML ha^{-1} $year^{-1}$ in the Bega–Bemboka catchment for 74 unrestricted months between February 2000 and June 2007, are considerably higher than the National, NSW and Victorian Agricultural Census annual averages for pasture irrigation of 3.5, 2.7, and 3.9 ML ha^{-1} $year^{-1}$, respectively, for 2005–06, and higher than like application rates reported for 2002–03, 2003–04 and 2004–05 (Australian Bureau of Statistics 2008). While the exclusion of 15 months with irrigation restrictions from the analyses presented here is likely to have slightly elevated monthly and annual average water use figures for the Bega–Bemboka catchment, it is also possible that the Agricultural Census data (Australian Bureau of Statistics 2008) are affected by the lack of reliable metered data on irrigation abstractions for catchments outside of the more closely monitored and intensively regulated inland Murray–Darling Basin. Implementation of additional water use metering by management authorities along high irrigation unregulated rivers, where abstractions are typically not monitored, would enable more accurate assessments of actual abstraction volumes.

While high winter irrigation abstractions are related to low winter rainfall such as occurred in 2002–03 (Fig. 5), quantile regression analysis of relationships between monthly irrigation abstractions, rainfall and evaporation indicate that evaporation exerts a stronger control over abstraction volumes than rainfall (Fig. 6, Table 3). The relatively low coefficients of determination for the quantile regressions indicate that irrigation abstractions are influenced by additional factors that are not accounted for by the climatic variables, such as soil moisture, soil type and pasture species, as well as less deterministic factors such as irrigator behaviour and choices (Poussin et al. 2008). The ease with which basic climatic variables such as evaporation and rainfall can be obtained for the agricultural areas of Australia, however, suggests that simple quantile regression-based techniques such as those presented here may be of considerable value in estimating mean and maximum monthly water usage for pasture irrigation in an otherwise data poor situation. Such analyses can help quantify the hydrological impacts of irrigation abstractions at catchment and sub-catchment scales as a first step to guide further investigations of the ecological effects of water abstractions (Richter et al. 2003; Arthington et al. 2006), and assessments of the sustainability of catchment abstraction volumes (e.g. Nathan et al. 2001; Reinfelds et al. 2006).

Similar to many other remote sensing investigations of irrigated crop areas (e.g. Abuzar et al. 2001; Martinez et al. 2001; Akbari et al. 2006; Ozdogan et al. 2006; Serra and Pons 2008), Landsat imagery was found to provide an effective means of assessing the extent of irrigated pasture in the Bega–Bemboka catchment. Careful selection of imagery from drought periods identified from river flow and rainfall data maximised spectral contrasts between areas of irrigated and non-irrigated pasture that may be less apparent during wetter years, or in areas with median annual rainfall greater than the 650–775 mm characteristic of the irrigated areas in the Bega–Bemboka catchment. One of the main challenges encountered in the spatio-temporal analysis of changes in the extent of irrigated pasture in this study lay in the development of an objective method for delineating irrigated areas from historical imagery where ground-truthing data was unavailable. In this regard, the multi-criteria decision rules illustrated in Fig. 4 enabled objective analysis of the historical imagery, with the primary subjective element being the analyst's choice of the number of classes representing irrigated pasture from the ISODATA unsupervised image classification. Subjectivity in this element, however, was reduced by analysis of image reflectance characteristics associated with known irrigated pasture (high band 4 values). This analysis helped guide the selection of classes representing irrigated areas, together with GIS-based interpretation of their spatial context with regard to proximity to water sources, water licenses and suitable topography.

The areas under irrigation between Bemboka and Morans Crossing gauging stations (Figs. 1 and 7) that drew water from the main river in 1983, and between Morans Crossing and Kanoona in 1998 (Figs. 1 and 7), are consistent with the magnitude of monthly flow losses between these gauging stations in spring 1980 (Fig. 2b), summer–autumn 1998 (Fig. 2a), and quantile regression estimates of monthly irrigation withdrawals based on climatic data (Table 5). These data clearly indicate that historical flow losses observed in the Bega–Bemboka River gauging record are attributable to surface water abstractions for irrigation. A further interesting element in this regard is the similarity in hydrological effects of irrigation abstractions in summer 1998 with those of spring–summer 2002–03 (Fig. 2a). This is despite the fact that the area under irrigation between Morans Crossing and Kanoona gauging station (Table 5), and regional drought stress as indicated by image mean NDVI values (Table 1), was greater in 2002–03 than in 1998. The implementation of a flow management plan in 1999 by irrigators and regulatory authorities (Bega Valley Water Management Committee 1999) to improve rostering, sharing and monitoring of water allocations, is the most likely reason for this improvement in the efficiency of water use after 1998.

Table 5 Irrigated areas estimated from 1983 and 1998 Landsat imagery drawing from the Bega–Bemboka trunk stream between Bemboka and Morans Crossing gauging stations (1980 Sep–Nov), and between Morans Crossing and Kanoona gauging stations (1998 Feb–Apr), monthly downstream flow losses between these gauging stations (corrected for tributary inflows), quantile regression estimates of median (50%) and maximum (85%) monthly abstraction volumes, rainfall and evaporation

Year-Month	Irrigated area (HA)	Flow loss (ML)	Diversion estimate 50%	Diversion estimate 85%	Rainfall (MM)	Evaporation (MM)
1980 Sep	320	201	220	293	16.2	135.0
1980 Oct	320	225	202	266	51.5	144.6
1980 Nov	320	320	268	327	30.6	176.6
1998 Feb	497	508	424	527	9.0	166.8
1998 Mar	497	738	385	563	6.8	148.2
1998 Apr	497	392	229	367	13.4	84.0

5 Conclusion

Metering of water use for pasture irrigation in the Bega–Bemboka catchment since 2000 provides a valuable insight into temporal patterns of water usage and climatic controls on the single greatest use of irrigation water in Australia. Pasture irrigation in the Bega–Bemboka catchment occurs year-round, with monthly maximum water usage for all seasons exceeding the metered average annual water use of 4.8 ML ha^{-1} $year^{-1}$. Average and maximum monthly irrigation volumes at a catchment scale can be reasonably estimated by multiple quantile regressions relating irrigation volumes to monthly evaporation and rainfall data. Despite the fact that the majority of irrigation water used in Australia goes to irrigation of pasture, there is surprisingly little analysis of spatio-temporal patterns in irrigated pasture from remotely sensed imagery. For the coastal regions of southeastern Australia where water use for irrigation is typically not metered and pasture irrigation for dairy farming forms the major agricultural water use, selection of Landsat imagery from drought periods enhances spectral contrasts and facilitates mapping of irrigated areas. Spatial analyses of irrigation extent at a catchment scale from Landsat imagery combined with knowledge of crop water requirements enables estimation of monthly mean and maximum irrigation water usage. This information can in turn be used to guide further investigations of the ecological effects of water abstractions and assessments of the sustainability of spatially and temporally changing catchment abstraction volumes.

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