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A hydrological drought index for the Clutha catchment, New Zealand

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Abstract

The Clutha River is New Zealand's largest river, both in terms of discharge and catchment size. It has a large seasonal flow variability with large spring and summer flows and very low flows in winter. The river is important for its contribution to energy production from two large hydro dams, irrigation for agriculture and horticulture, and tourist activities. The Clutha River flows are modified by discretionary releases of water from the only storage lake in the catchment, at Hawea. The mountainous South Island topography to the west means that a large part of the catchment is in a rain shadow and is regularly subject to long periods without any significant precipitation, similar to many other rain shadow catchments globally.

While floods can be mitigated against, droughts are insidious and generally well established before being identified. A hydrological drought is defined as a lack of water in the hydrological system, identified by abnormally low streamflow in rivers and abnormally low levels in lakes and reservoirs. A drought index is proposed for the upper and mid-Clutha catchment that identifies the onset of hydrological drought conditions, measures the severity of the drought, and signals the end of the drought. This index has the advantage over other hydrological indices in that it uses a daily threshold rather than a monthly or seasonal one and indicates the start of a drought as soon as it occurs.

Keywords

Clutha, rain shadow, drought, drought index, low flow.

Introduction

The Clutha catchment, with an area of 21,400 km^2, is the largest river catchment in New Zealand and is also one of the most volatile in terms of rates of discharge, with a large monthly flow variability (Murray, 1975). The headwaters of the Clutha River are in the Southern Alps where precipitation, mainly from the west and north west, is as high as 8000 mm per annum. Outflow from three large lakes (Wakatipu, Wanaka and Hawea) feeds the Clutha River and its major tributaries, while smaller tributaries (the Shotover, Nevis, Lindis, Arrow, Manuherikia, Teviot, Talla Burn, Beaumont and Pomahaka rivers) all add to the river flow as it progresses (Figs. 1 and 2). The main part of the catchment, from the outflow of the lakes to Roxburgh, is in a rain shadow with rainfall as low as 325 mm per annum in the Springvale area near Alexandra (Cossens, 1975; Fitzharris, 1992; Poyck et al., 2011) resulting in a high demand for irrigation water from the main river and its tributaries. As the annual actual evaporation and transpiration is around 700 mm per annum, close to double the mean rainfall in the rain shadow, this area has a significant soil moisture deficit. In the main area of the rain shadow almost

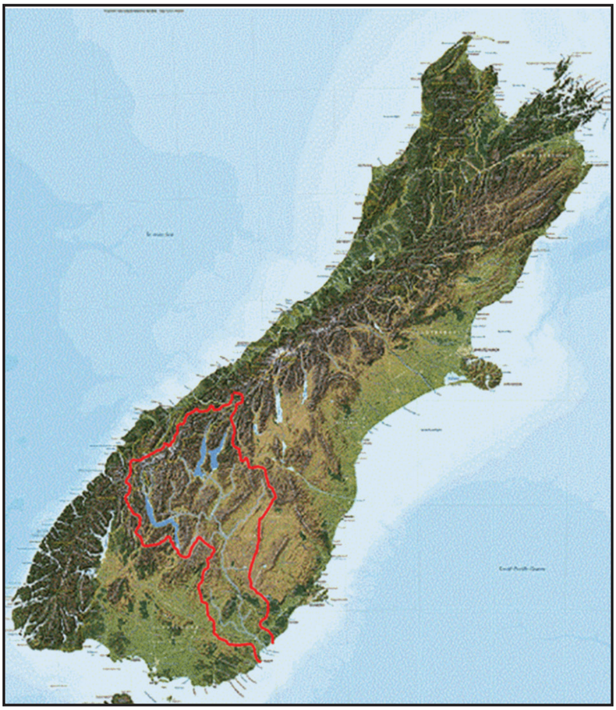

Figure 1 – Location of the Clutha Catchment in New Zealand's South Island.

Figure 2 – Major lakes and rivers of the Clutha catchment.

all irrigation water is taken from the river or from its tributaries. The water of the Clutha is also used for hydro-electric generation and supplies almost 10% of New Zealand's electricity requirements (Taylor and Bardsley, 2015).

Despite the reliance on the Clutha River and its tributaries for the main economy of the region there is currently no suitable drought index that gives warning of dry conditions until the situation is already well developed. Having a suitable method of measuring dry periods and determining if or when a drought is established will assist irrigators in deciding to whether to reduce water releases from storage dams in order to maintain some irrigation water over a longer timeframe. At present it is quite common to have long dry periods with no water restrictions in the hope that it may rain soon, then to suddenly be at 50% or even 75% restriction on abstraction with resulting loss of pasture growth. In addition, with a suitable drought index, electricity generators would be in a better position to regulate water released from storage in order to ensure that a reasonable level of generation can be maintained over the traditionally dry winter period.

Flood events usually are accompanied by some warning, either from high expected rainfall or from river flows rising in the higher parts of the catchment. Such warnings allow time for downstream communities to react and mitigate the worst flood effects. However, droughts, sometimes called the creeping disaster, give no warning, and drought conditions are usually well established before they are recognised (Fitzharris, 1992; Mishra and Singh, 2010; Van Loon, 2015; Wilhite and Buchanan-Smith, 2005). It is not practical to have a single definition of drought as it can be defined in many different ways (Lloyd-Hughes, 2014), and the simplest definition of drought is: a deficit of water compared with normal conditions.

Droughts can be generally classified into four categories: meteorological drought, which is a deficiency in precipitation; soil moisture drought (sometimes called an agricultural drought), which is a deficit in soil moisture; hydrological drought, which refers to a deficit in river flows, lake levels, reduced wetlands and even reduced groundwater; and socioeconomic drought, which is associated with the impacts of any or all of the three fore-mentioned types (Van Loon, 2015). There is a difference between low flow conditions and meteorological drought. The International Glossary of Hydrology (WMO, 2012) defines low flow as 'a reduced flow of water in a stream during prolonged dry weather'. This definition does not make a clear distinction between low flows and droughts. Low flow may be a seasonal or even an anthropogenic phenomenon and is an integral part of any river flow regime, whereas drought is a natural occurrence resulting from lower than normal precipitation for an extended period of time (Smakhtin, 2001).

A number of methods have been suggested in the past for measuring droughts and many indices have been suggested. The most commonly-used indices include the Standardized Precipitation Index (McKee *et al.*, 1993), the Standardized Streamflow Index (Vicente-Serrano *et al.*, 2011) and the Standardized Snow Melt and Rain Index (Staudinger *et al.*, 2014). A review of twentieth-century drought indices used in the United States showed that there was a different index used for most main catchments (Heim, 2002). Issues that affect many of the common drought indices include: difficulties in identifying the onset, end, and accumulated stress of drought; failing to recognise the cumulative effects of runoff and evapotranspiration, which build up with time; and limited ability to monitor ongoing drought conditions because they are based on large time steps that can be months long (Byun and Wilhite, 1999). New Zealand's National Institute of Water and Atmospheric Research (NIWA, 2018) do have a nation-wide drought monitor which indicates the extent of dryness in various regions; however, it uses precipitation and soil moisture to determine any drought and so fails to address the specific issue of rain shadow catchments. Past droughts have tended to catch many river users by surprise, as what was initially thought to be just a normal seasonal dry spell continued to deteriorate to the stage of severe drought.

The high variability of river flows within the Clutha catchment provides many challenges for water users. Being in the rain shadow of the Southern Alps, it is not uncommon for the mid-part of the Clutha catchment, where irrigation is needed the most, to have weeks or even months without any precipitation while the western parts receive almost normal rain and river flows remain close to normal. Under these circumstances water may be extracted by river users without any abnormal restrictions. Conversely, when there is a lack of precipitation in the alpine regions irrigation, and other, water takes may be restricted as even normal to above normal precipitation in the rain shadow area is insufficient to maintain soil moisture. The meteorological disconnect between the alpine region and the rain shadow area makes it even more difficult to determine whether the region is in a dry period or a drought; this indicates that a hydrological drought index would be the most appropriate for this catchment.

There are further complicating factors in determining whether Clutha River flows and headwater rainfalls are abnormal. These include the monthly variation of the flow (Fig. 3) and the artificial discharge of water from the Hawea dam. Prior to damming

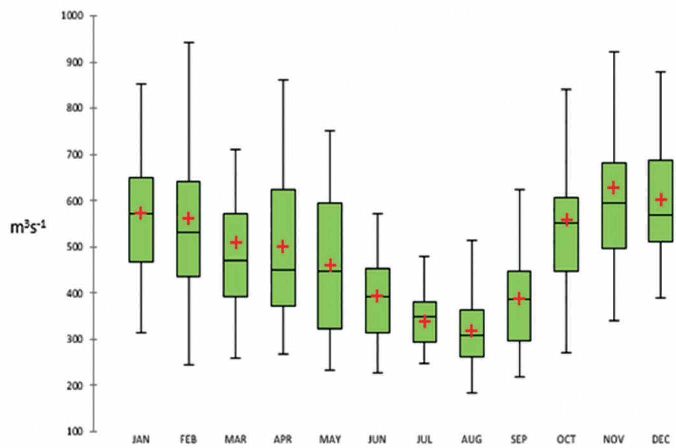

Figure 3 – Clutha River monthly flow variability at Roxburgh showing mean discharge (red plus), median, 25th and 75th percentiles (green box) and range.

and raising Lake Hawea in 1955–1959 the flow of the river at Roxburgh was completely natural. Following the damming of Lake Hawea, water has been held back in spring and summer when natural flows are high and released during winter when natural flows are low, resulting in a modified flow pattern that tends to 'hide' most hydrological droughts during winter, or make them appear worse during summer (Figs. 4 and 5).

The possibility of using just the outflows from Lakes Wanaka and Wakatipu to measure a hydrological drought would restrict the index assessment to conditions in the alpine regions only. There are times when heavy rainfall in the mid-catchment does occur, which alleviates the need for irrigation and results in increased flow in the Manuherikia tributary. This increase in flow is matched by a similar flow increase in the Clutha River

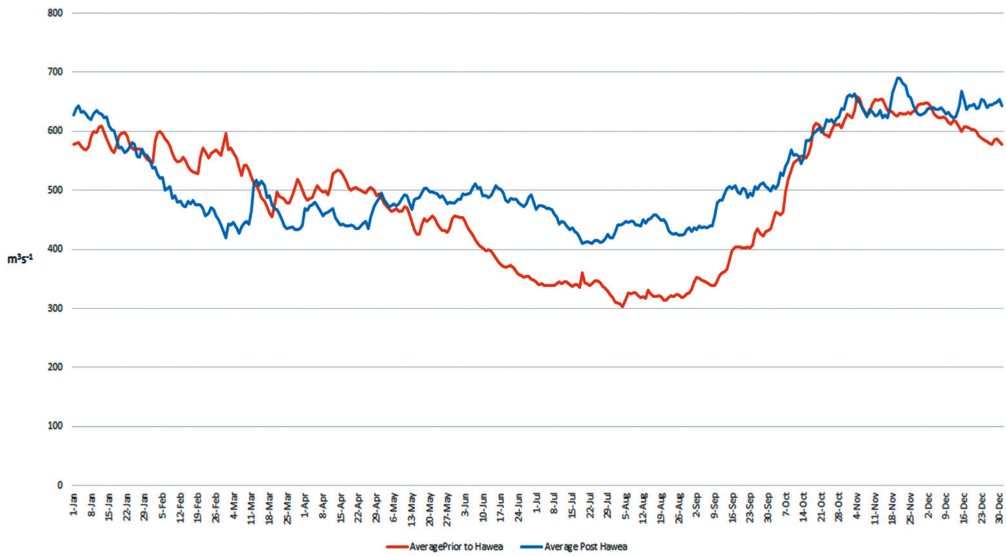

Figure 4 – Mean annual Clutha River flow at Roxburgh prior 1930–1955 (red line) and post1956–2014 (blue line) Hawea Dam.

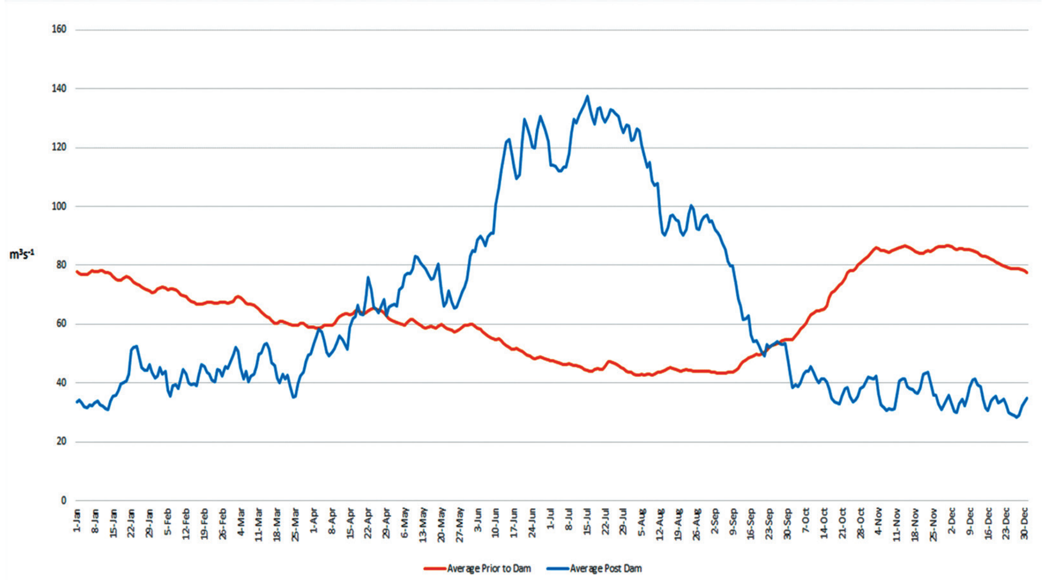

Figure 5 – Mean daily Hawea River flow prior1930–1955 (red line) and post 1956–2014 (blue line) Hawea Dam

at Roxburgh, but not at Lakes Wanaka or Wakatipu.

One explanation of the Clutha's flow variability has been given as changes in temperature, which in turn affect the freezing level and the amount of snow melt and accumulation (Jowett and Thompson, 1977), but there is no similar large disparity in alpine precipitation. The disconnect between high precipitation in the alpine region and the demand for water in the dry rain shadow region make it impractical to use a meteorological drought index. Also, as the soil is naturally almost always dry, a soil moisture drought index would show perpetual drought. This leaves a hydrological drought index as the preferred method of measurement.

Because of the high variability of seasonal flow in the Clutha catchment, measuring a hydrological drought using an index such as the Streamflow Drought Index (Nalbantis, 2008) would not be suitable as a drought could occur for up to three months before it is identified. Many of the irrigation dams in the region only hold a few weeks' supply of water, and the hydro power stations operate as run-of-river with less than a single day of hydro storage in their headponds and an average of 45 days' supply of water in Lake Hawea if the maximum daily permitted discharge is released. Therefore, a new version of a hydrological drought index is required.

There appears to have been no previous attempts at defining Clutha catchment drought conditions. Cossens (1975) compared crop yields with the number of drought days, but did not define what a drought day was. This paper proposes a hydrological drought index that is suitable for a catchment in a rain shadow and can be used over both short and long time periods. As it is likely that this index would be used by electricity generators, district and regional councils, irrigation companies, farmers, orchardists, and tourist operators, a practical index must use data that are readily and publicly available and be able to be used by anyone with access to that data using commonly-available applications. While the drought index defined here is based on the Clutha catchment, the methods used could potentially be applied to other modified rain shadow catchments such as the Des Chutes in north-western USA or the Rio Senguer in Argentine Patagonia. Both of these catchments are similar in size to the Clutha, lie on the 45th parallel and have high intercepting mountains to the west and a dry interior through which the river flows. There are many catchments globally that also have similar issues with calculating a drought index.

Method

The Clutha River at Roxburgh Dam was chosen as the site for determining the Clutha drought index as it has a long flow record and is downstream of the mid-catchment that is in the rain shadow, but upstream of the coastal rainfall area. The choice of Roxburgh as a reference point results in a measure of total flow from the 16,000 km^2 upper and middle parts of the catchment, and is very indicative of the precipitation in the alpine region. However, because the Clutha River flow is modified by releases from the Hawea dam it is necessary to determine what the natural portion of the river flow is without the influence of the Hawea water. Without doing so any analysis of river flows would be distorted by the demands of the electricity market.

Daily flow data for the Clutha River at the Roxburgh Dam and for the Hawea River were obtained from Contact Energy for the period 1930 to 2014. Recent data for both sites are also publicly available from the Otago Regional Council (2018). Unfortunately, for the period August 1955 to the end of 1967 only weekly average data were available for Hawea and so the average daily data for this period was assumed to be the same as the weekly data.

The natural river flow at Roxburgh Dam is calculated by subtracting the controlled water released from Hawea from the total flow at Roxburgh for each date (Eq. 1). Note that 29 February (during leap years) is ignored at this stage to allow for a standard 365 day year.

$$Q = R - H \tag{1}$$

Where Q is the natural river flow at Roxburgh, R is the total river flow at Roxburgh, and H is the outflow from Lake Hawea. For unmodified rivers this part of the calculation would not be needed.

An array of natural flow data is constructed with dates in the rows and years in columns, i.e., row 1 is for 1 January from 1930 to 2013 and row 365 is 31 December 1930 to 2013. For each individual date the 20th percentile flow value is calculated, i.e., the flow is below this level on 20% of occasions. The 20th percentile flow was selected as being within, but still close to, one standard deviation below the mean flow for that day. It would thus be an indicator that conditions are tending towards dry.

The 20th percentile flow value is smoothed by using a 7-day running mean to compensate for the assumed daily Hawea flow during the period that only weekly data are available, to allow for the travel time of around twelve hours for water to flow from Lake Hawea to Roxburgh and to reduce noise. This becomes the threshold, or trigger flow (Qt), for the start point of measuring low flow sequences (Fig. 6).

A deficit value for each low flow day is calculated as being the difference between the actual flow and the trigger flow for that day. On days that have both a flow above the trigger flow and no cumulative deficit carried over from the previous day, no deficit is recorded. Once the actual flow drops below the trigger value the deficit value is calculated and added to the previous day's deficit to obtain a cumulative deficit. Thus, the peak cumulative deficit will continue to increase until such time as an increase in actual flow takes the river to above the trigger flow. To prevent a low flow sequence being interrupted by a single small event and a

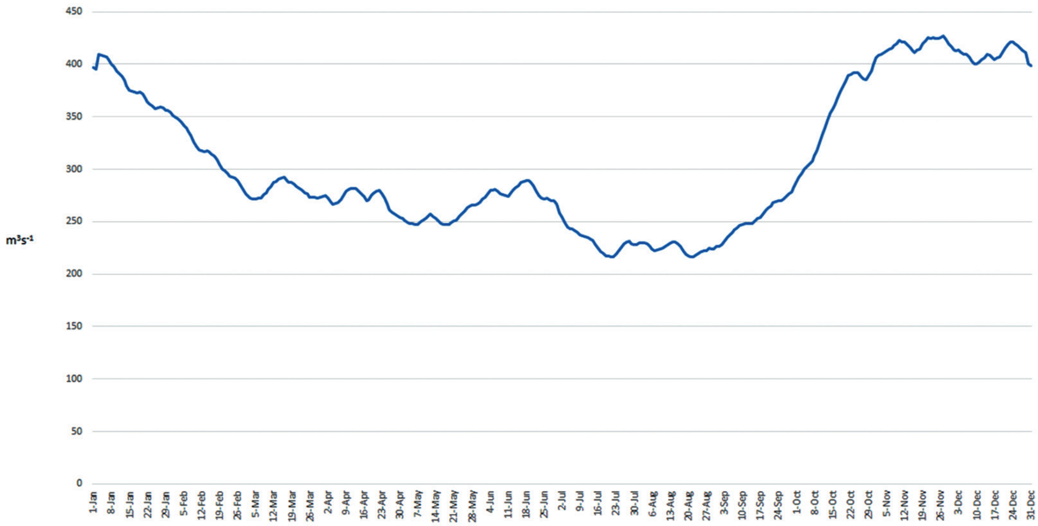

Figure 6 – Threshold flow series to begin deficit measurements for the Clutha River at Roxburgh.

new sequence starting within a few days, the accumulated deficit is reduced by the actual flow until there is no remainder, at which point the drought can be considered over. For the Clutha River, this increases the number of low flow days to an average of 80 per year; the extra days, above the expected 72 that would occur for the 20^{th} percentile, being the flow required to confirm the dry period or drought has ended.

The cumulative deficit (D) on any date (d) is given by:

$$D = \sum_{n=1}^{n=d} (Qt - Q) \quad (2)$$

Where n=1 is the first day a deficit is measured in the current sequence.

For each year the annual peak deficit is obtained and the mean annual peak deficit over all years is calculated. For the 20th percentile flow for the Clutha River (1930–2014) this is -2362 cumec-days. The deficit is then standardised by dividing the cumulative deficit on any day by the mean annual peak deficit to give a drought index for that day. The resulting Clutha Drought Index (CDI) (Eq. 3) is a measure of both duration and severity of the flow deficit on any day.

$$CDI = \frac{D}{-2362} \quad (3)$$

The level of drought for the Clutha catchment, as measured by the river flow at Roxburgh, is defined by the index as:

0–0.5	Low flows, but not truly a drought as this condition is experienced almost every year.
0.5–1	Mild drought.
1–2	Moderate drought.
2–3	Severe drought.
>3	Extreme drought.

Discussion

The actual point at which a low flow becomes a drought can be an arbitrary, subjective, decision by a policy maker, and having an index that gives consistent results assists in removing some of this subjectivity. Over the 84 years examined, the index identifies

Table 1 – Clutha catchment drought index results by year, 1930 to 2014

Description	Wet	Low Flow		Mild	Moderate	Severe	Extreme
Index	**< 0**	**0–0.5**		**0.5–1**	**1–2**	**2–3**	**> 3**
Frequency	**3 years**	**34 years**		**18 years**	**17 years**	**7 years**	**5 years**
Years occurred	1979	1931	1967	1936	1930	1970	1932
	1980	1933	1968	1946	1935	1974	1937
	1983	1934	1981	1950	1947	1977	1941
		1938	1984	1954	1951	1992	1953
		1939	1986	1960	1952	2005	1976
		1940	1987	1961	1956	2006	
		1942	1994	1963	1959	2012	
		1943	1995	1969	1964		
		1944	1996	1972	1966		
		1945	1997	1973	1971		
		1948	1998	1978	1975		
		1949	2000	1982	1985		
		1955	2002	1988	1989		
		1957	2004	1990	1991		
		1958	2007	1993	2003		
		1962	2010	1999	2008		
		1965	2011	2001	2013		
				2009			

extreme droughts in 1932, 1937, 1941, 1953 and 1976 (Table 1). The severe nation-wide drought that caused the New Zealand electricity crisis in 1992 followed a moderate drought in 1991 with dry conditions prevailing between the two; both situations were identified by this index. Drought severity is recognised by the index as mild, moderate, severe and extreme according to both the duration and degree of deficit. While mild droughts in the above definition may only require a watch or minor restriction on irrigation abstractions, restrictions would likely be increased during moderate and severe droughts, and abstraction possibly curtailed completely in extreme droughts. In the 2012 severe drought the Manuherikia Irrigation Company imposed 75% restrictions on irrigation abstractions.

The actual timing of droughts is more obvious when presented graphically. Figure 7 shows the duration of past droughts as well as the years in which they occurred, as measured by the Clutha Drought Index. Many quite long droughts were only mild to moderate, but severe and extreme droughts often developed quite quickly. Of the 260 times that the river flow dipped below the trigger flow and started the deficit count, droughts developed on 47 occasions, or 18% of the time. So, while the threshold is not a prime indicator of a drought developing, it does give an early indication of the possibility, particularly if the flow drops below the

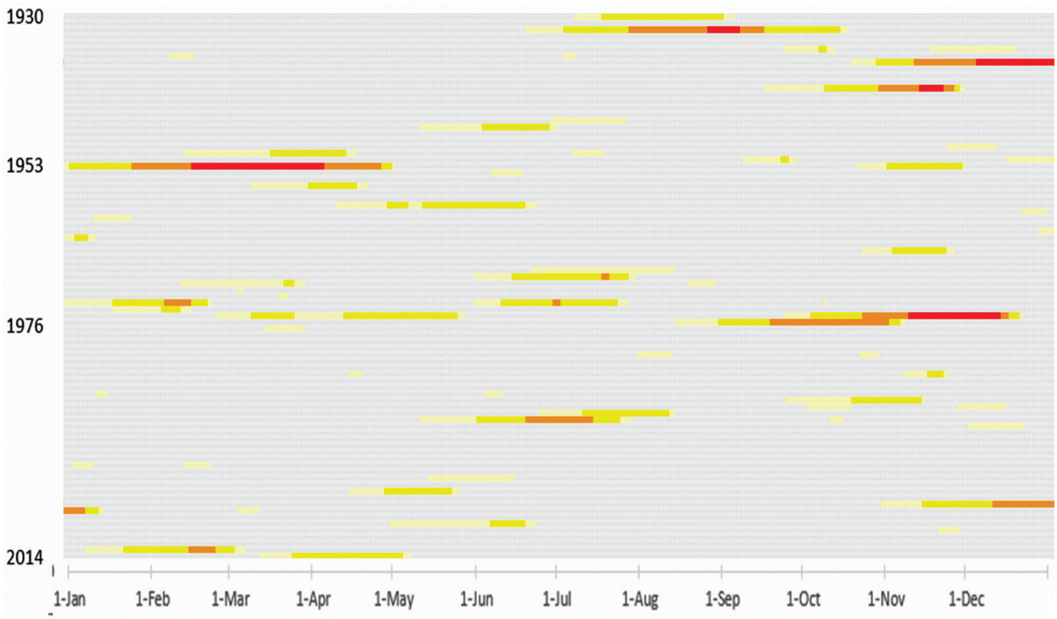

Figure 7 – Drought severity results for the Clutha catchment, 1930 to 2014: Grey – no drought, pale yellow – mild drought, dark yellow – moderate drought, orange – severe drought, red – extreme drought

threshold with no significant precipitation in the long-range weather forecasts.

The Clutha Drought Index did not appear to produce any obvious false positives, i.e., dry periods being indicated when one did not occur. Less certain is whether there were any dry periods that were not identified, or any where the degree of severity was incorrectly calculated, as historical drought records are often anecdotal. Of note is that many of the historic droughts in the north and east of New Zealand mentioned in Mosley and Pearson (1997) do not show up as severe in this analysis, but often followed a drought in the Clutha catchment the previous year.

Conclusion

A hydrological drought index, based on readily available data, is desirable to enable stream and river users to determine the point at which a drought actually starts, how severe it becomes and when it finishes. A precipitation-based index is not suitable for a rain shadow catchment due long periods without any sustained rainfall, whereas a hydrological index that integrates the total effects of alpine precipitation, snow melt and lake discharge does give the information desired. The proposed index uses readily-available data and clearly indicates the onset of dry conditions along with the increasing severity as a drought develops and intensifies. It also correctly identified known historic dry periods when applied to the Clutha catchment. It is likely that the same methodology could be applied to similar catchments once an appropriate threshold for measuring the deficit flows has been established.

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