# A HYDROLOGICAL DROUGHT INDEX FOR THE CLUTHA CATCHMENT

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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 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 mountainous South Island topography to the west of the catchment area means that a large part of the catchment is in a rain shadow, and is regularly subject to long periods of time without any significant precipitation. The actual river flows are modified by discretionary releases of water for the only storage lake in the catchment at Hawea.

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, reservoirs. A drought index is proposed for the upper and mid Clutha Catchment that identifies the onset of hydrological drought conditions, measure 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 actual start of a drought as soon as it occurs.

## Key Words

Clutha, Drought, Index, Rain-shadow, Storage-lake,

## Introduction

The Clutha River is used for hydro electricity production, irrigation for agriculture and for recreational activities, all of which depend on river users knowing how much water is available and whether conservation measures may be necessary during dry periods.

While flood events usually are accompanied by some warning, either of high rainfall expected, or from river flows in the higher parts of the catchment increasing rapidly which allows time for downstream communities to react and mitigate the worst effects, 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 ground water; and Socioeconomic drought which is associated with the impacts of any or all of three fore-mentioned types (Van Loon, 2015). There is a difference between low flow hydrology 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. 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 Jr, 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 a large time steps that can be months long (Byun and Wilhite, 1999). Past droughts have tended to catch many river users by surprise as what was initially thought to be just a normal seasonal dry spell, just continued to deteriorate to the stage of drought.

The Clutha Catchment, with an area of 21,400 km2 (Murray, 1975), is the largest river catchment in New Zealand and is also one of the most volatile in terms of rates of discharge. The headwaters of the Clutha River are in the Southern Alps where westerly and north westerly precipitation is collected, and flows into three large lakes Wakatipu, Wanaka and Hawea, while smaller tributaries; the Shotover, Nevis, Lindis, Arrow, Manuherikia, Teviot, Tullaburn, Beaumont and Pomahaka all add to the river flow as it progresses. The main part of the catchment, from the outflow of the lakes to below Roxburgh, is in a rain shadow with rainfall as low as 325 mm per annum (Cossens, 1975; Fitzharris, 1992) which means that there is a high demand for irrigation water from the main river and its tributaries. As the annual evaporation is around 700 mm per annum, close to double the mean rainfall in the rain shadow, this area is always dry with a high soil moisture deficit. In the main area of the rain shadow almost 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).

The high variability of river flows within the 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 go 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 water takes may be restricted even when there is normal to above normal precipitation in the rain shadow area.  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 an actual drought.  Further complicating factors in determining whether Clutha River flows and headwater rainfalls are abnormal include the seasonal variation of the flow (Taylor and Bardsley, 2015), and the artificial discharge of water from the Hawea dam.  Prior to damming and raising Lake Hawea in 1955 – 1959 the flow of the river at Roxburgh was completely natural.  But once Lake Hawea was dammed, water was held back in spring and summer when natural flows were high and released during winter when natural flows were low resulting in a modified flow pattern that would tend to hide most hydrological droughts during winter, or make them appear worse during summer. (Figs 1 and 2).

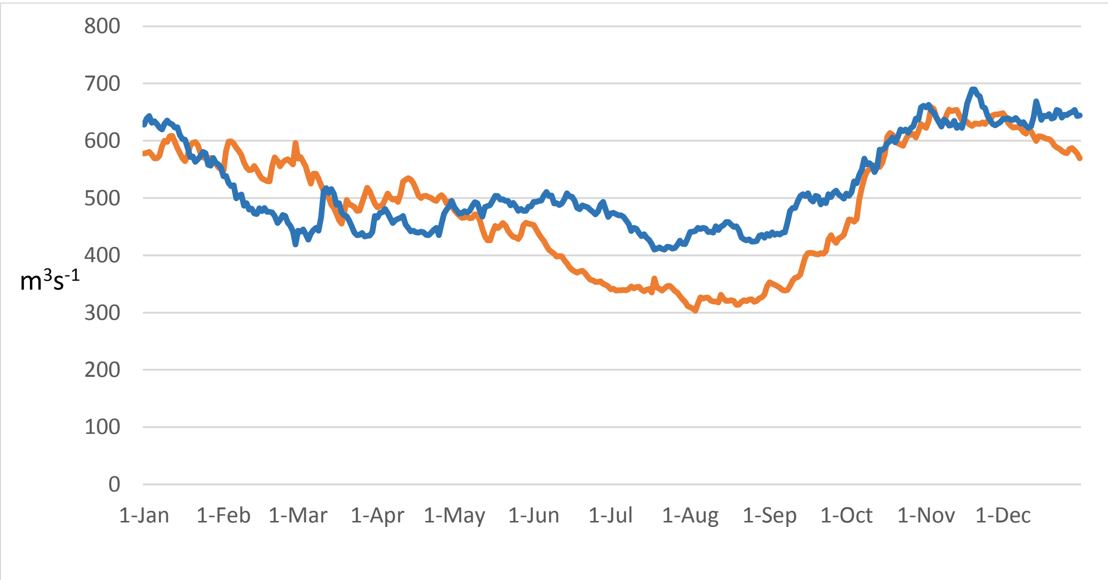


Fig 1:   Mean annual Clutha River flow at Roxburgh prior (brown line) and post (blue line) Hawea Dam

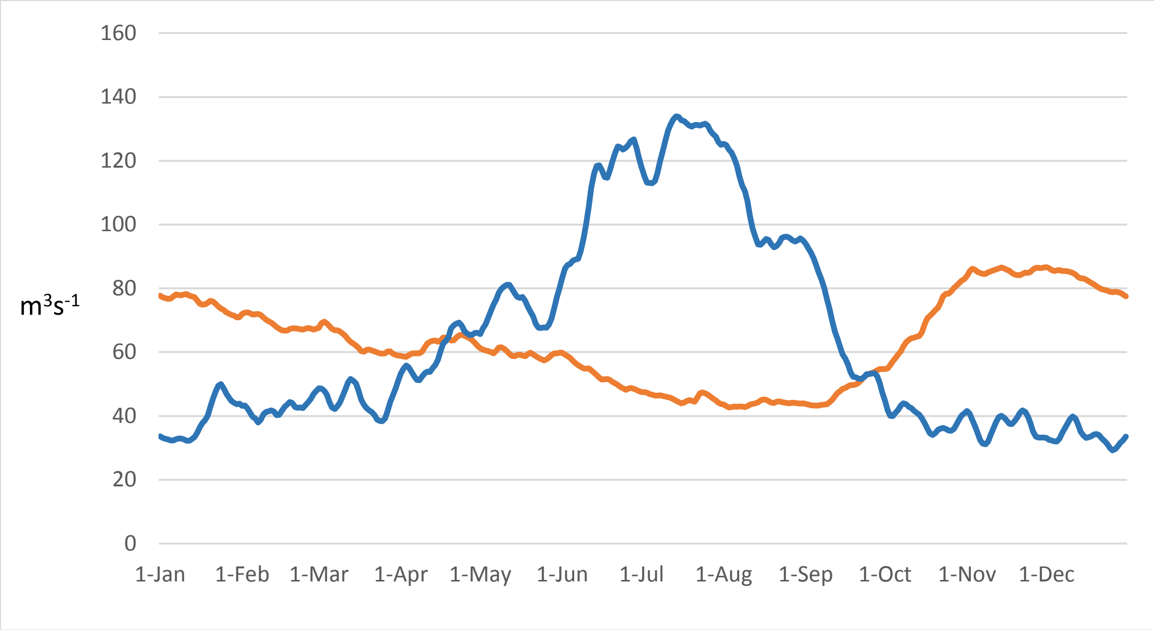


Fig 2: Mean annual Hawea River flow prior (brown line) and post (blue line) Hawea Dam

The possibility of using just the outflows from Lakes Wanaka and Wakatipu to measure a hydrological drought would restrict the measuring the conditions in just the alpine regions. There are times when heavy rainfall in the mid part of the catchment does occur which alleviates the need for irrigation offtakes and results in increased flow in the Manuherikia tributary, This increase in flow is measured by a similar flow increase 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 affected 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, and similarly as the soil is naturally almost always dry a soil moisture drought index would show perpetual drought, which leaves a hydrological drought index as the preferred method of measurement.

However 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 already be occurring for up to 3 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.

There appear to have been no previous attempts at actually measuring 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, local district and regional councils, irrigation companies, farmers and orchardists, and tourist operators, such method must use data that is readily and publicly available, and be able to be used by anyone with access to that data using commonly available applications. While it is based on the Clutha catchment, the methods used could potentially be applied to other rain shadow catchments.

indicates that a method of identifying the start of a drought, the severity of the drought, and showing when the drought was actually over is urgently needed.

## Discussion

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 would have been without the influence of the Hawea water.

Daily flow data for the Clutha River measured at the Roxburgh Dam and for the Hawea River was obtained from Contact Energy from 1930 to 2014. Unfortunately, for the period of august 1955 to the end of 1967 only weekly average data was available for Hawea. The average daily data for this period was assumed to be the same as the weekly data. 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 still upstream of the coastal rainfall area. Current and recent data for both the total flow at Roxburgh and the Hawea River discharge are also publicly available from the Otago Regional Council.  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, but the 29th February is ignored at this stage on leap years to allow for a standard 365 day year.  For unmodified rivers this part of the calculation would not be needed.  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 because of the large rain shadow is very indicative of the precipitation in the alpine region.

An array of natural flow is constructed of date by year, so that all dates are in the rows and all years in columns. I.e. row 1 is for the 1st of January from 1930 to 2014 and row 365 is 31st December 1930 to 2014.  For each individual date the 20% flow value is calculated, i.e. the flow is below this level on 20% of occasions.  The 20% flow was selected as being within, but still close to 1 standard deviation below the mean flow for that day.  It would thus be an indicator that conditions are tending towards dry, even if not quite there yet.

The 20% 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 was available and to reduce noise.  This becomes the threshold or trigger value for the start point of measuring low flow sequences.

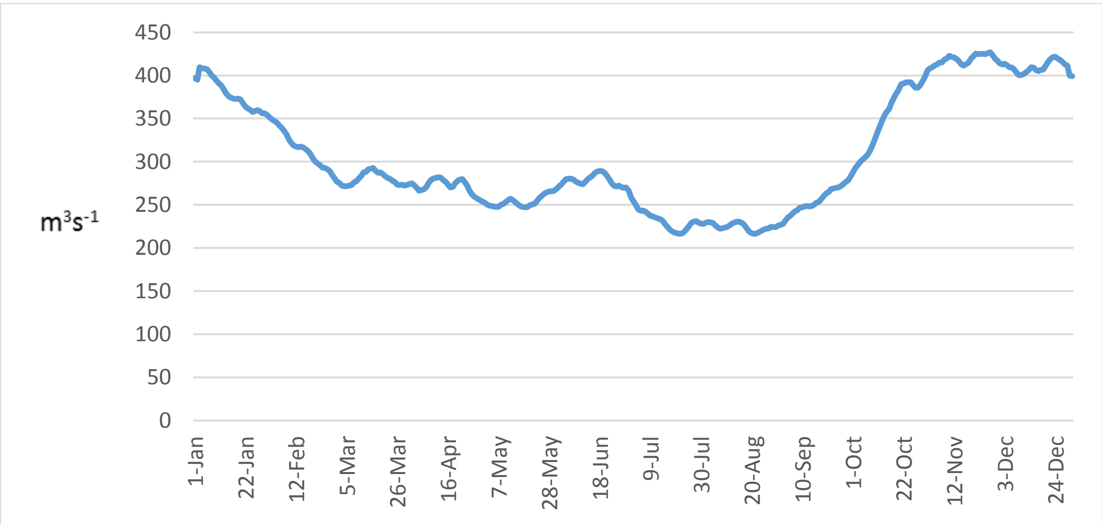


Fig 3:    Trigger values to begin deficit measurements

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 a flow above the trigger flow 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 new sequence starting within a few days, the deficit is reduced by the actual flow until there is no remainder, at which point the drought can be considered over. This increases the number of low flow days to an average of 80 per year; the extra days being the flow required to confirm the drought has ended.

For all of the years 1930 to 2014 the mean of the annual peak deficits is calculated and this deficit is standardised by dividing the cumulative deficit on any day by the mean annual deficit to give a drought index for that day. The resulting index is a measure of both duration and severity of the flow deficit. For the 20% flow the mean annual deficit is calculated as -2362 cumec-days.

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.

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 does assist in removing some of this subjectivity. Over the 84 years examined, the index identifies extreme droughts in 1930, 1932, 1937, 1941, 1953 and 1976. The severe drought that caused the nationwide electricity crisis in 1992 followed a moderate drought on 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 minor restriction on irrigation offtakes, the amount of restriction would likely to be increased during moderate and severe droughts, and possibly curtailed completely in extreme droughts. In the 2012 severe drought the Manuherikia Irrigation Company imposed 75% restrictions on irrigation water.

The full list of years, and the index value experienced is shown in table 1.

| **Wet** | **Low Flow** | | **Mild** | **Moderate** | **Severe** | **Extreme** |
|---|---|---|---|---|---|---|
| < 0 | 0 – 0.5 | | 0.5 - 1 | 1 - 2 | 2 - 3 | > 3 |
| 3 years | 34 years | | 18 years | 17 years | 7 years | 5 years |
| 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 | | |

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|---|---|---|---|---|---|---|
| | 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 | | | |

Table 1: Years showing severity of drought as defined by the index.

Of the 260 times that the actual flow dipped below the threshold 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 threshold with no significant precipitation showing in the long range weather forecasts.

## 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 actually is and also when it is actually over. A precipitation based index is not suitable for a rain shadow catchment due the natural long periods without any sustained rainfall, whereas a hydrological index which integrates the total effects of alpine precipitation, snow melt and lake discharge does give the information desired. The proposed index meets these requirements and correctly identified known dry periods when applied to the Clutha catchment. It is likely that the same methodology could be applied to other similar catchments once an appropriate threshold for measuring the deficit flows has been established.

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