Nordic Hydrology, 28 (4/5), 1997, 297-306

How Extreme was the Drought?

Paper presented at the Nordic Hydrological Conference
(Akureyri, Iceland – August 1996)

Bente Clausen*
Dept. of Civ. Eng., Univ. of Canterbury, Christchurch, NZ

Charles P. Pearson
Nat. Inst. of Water and Atm. Res. Ltd. (NIWA),
Christchurch, New Zealand

In 1993/94 a severe drought on the North Island of New Zealand caused water shortage in the Auckland metropolis. How extreme was the drought? This paper presents comparisons of frequencies of the 1993/94 drought in four North Island regions using different indicators of drought and including both streamflow and rainfall data. With regard to streamflow deficit volume and duration the exceedance probabilities ranged from 1 to 25%; however, the 7-day annual minimum flows in 1993/94 were less extreme with non-exceedance probabilities from 10 to 34%. With regard to rainfall the drought in the Auckland region was most extreme (on average 2% exceedance probability) when annual rainfall totals were analysed, compared to seasonal totals (on average 6% exceedance probability for half-annual totals and 13-38% for three-month totals). Thus, the conclusion was that the 1993/94 drought was extreme because of its duration rather than its magnitude.

Introduction

Drought is a major constraint on economic activity and occurs more or less frequently in any one location. In Denmark and the UK large droughts occurred in the mid 1970's and again in the early 1990's. In the North Island of New Zealand a prolonged drought in 1993/94 caused water shortage in the Auckland metropolis (McPike 1995) and increased water demand in the drought-prone northern and east-

* Formerly: Dept. of Earth Sciences, Aarhus Univ., Denmark

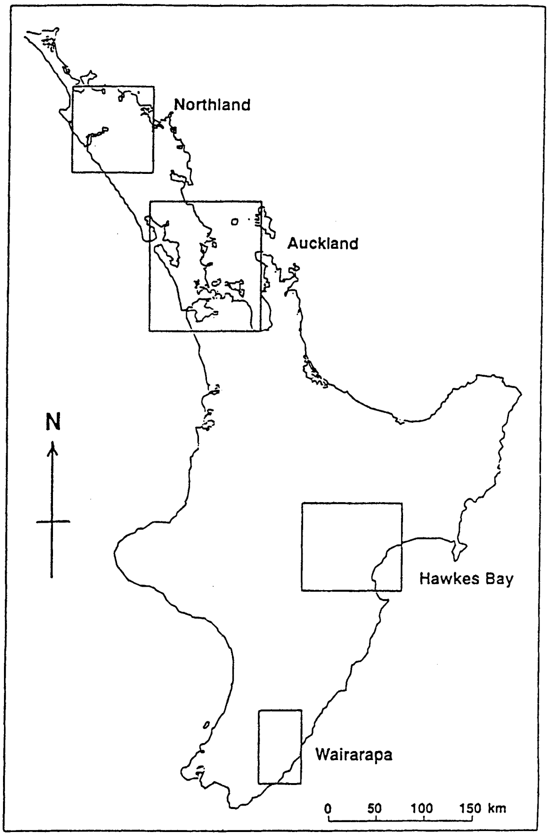

Fig. 1. The four study regions on the North Island of New Zealand.

ern regions of the island. The drought was associated with a long lasting El Nino event (the longest since the mid 1910's), where persistent anticyclonic conditions over eastern Australia brought westerlies and south-westerlies winds and dry conditions over the North Island (Salinger 1995).

To quantify drought there is a variety of indicators based on measurements of rainfall, soil moisture or streamflow (Dracup *et al.* 1980; Beran and Rodier 1985). For low streamflows the two most widely used analysis methods are the 'truncation level' (Yevjevich 1967) and the 'low flow frequency' analysis. The truncation level approach identifies periods during which the flow is lower than a certain threshold. The parameters are the deficit volume and the duration, which are highly important when a certain river flow is required, *e.g.* for designing reservoirs for water supply and for river ecology (Poff 1992). Both deficit volume and duration can be taken as drought indicators in that low exceedance probabilities of a particular year's deficit volume and duration indicate drought conditions. This approach was applied among others by Yevjevich (1967), Zelenhasic and Salvai (1987), Chang and Stenson (1990), Clausen and Pearson (1995) and Tallaksen *et al.* (1997).

The other approach is the more traditional method of using the frequency of low flows of fixed duration, as for example the annual minimum flow averaged over a given number (for example 1, 7 or 30) of consecutive days, which is widely used in for example the USA (Riggs *et al.* 1980), the UK (Gustard *et al.* 1992) and New Zealand (Pearson 1995). The annual minimum flow can also be used as a drought indicator in that a low non-exceedance probability of the annual minimum flow indicates extremely low streamflows over a given number of days which usually occur during droughts.

In this study both approaches were applied to four regions of the North Island of New Zealand (Fig. 1). The objective was to compare the frequencies of different drought indicators in 1993/94 during which a severe drought occurred, in particular to compare fixed duration statistics with those derived by fixed truncation. We calculated frequencies of annual maximum streamflow deficit and duration and compared these with the frequency of the annual minimum 7-day flow. Also, for the Auckland metropolitan area we examined the frequency of the total rainfall deficit over three month seasonal periods, half-annual and annual periods.

Data and Methods

Daily flow data from 16 rivers in the four regions of the North Island (Fig. 1) were used in the study (Table 1). For each record year starting 1 July, the maximum deficit volume was identified as the largest volume under a fixed flow, and standardised for comparison purposes by division by the mean flow. Hence deficit volume has dimensions of time (days). This value was recorded along with the corresponding duration, and the 7-day annual minimum flow. As truncation level for deficit volume and duration we used the mean flow since we used this flow in an earlier study (Clausen and Pearson 1995; choice of truncation level is discussed here). We chose to use annual maximum deficit because of its simplicity and since it allowed comparison with the earlier study. Other more complicated deficit volume statistics (which allow periods above the flow threshold) are given and compared by Tallaksen *et al.* (1997). The 7-day period for the annual minimum was used because it has been used frequently in earlier low flow studies both in the UK (Gustard *et al.* 1992), New Zealand (Pearson 1995), and other countries. The frequencies of the 1993/94 maximum drought deficit volume and duration, and 7-day minimum, were estimated using L-moment ratio statistics (Hosking 1990; Hosking and Wallis 1993).

For deficit volume and duration, a regional approach was used for estimating frequency distributions. The L-moment ratios (coefficients of variation, skewness and kurtosis defined using L-moments) were used to test the homogeneity of regions and the goodness-of-fit of five three-parameter distributions: General Logistic, Generalised Extreme Value, Log-Normal, Pearson Type III, and Generalised Pareto. Once an appropriate regional distribution was identified and the parameters estimated for

Table 1 – Details for flow recording sites

Site no.	River	Catchment area (km^2)	Record	Mean flow ($l\ s^{-1}\ km^{-2}$)	Mean annual 7-day minimum ($l\ s^{-1}\ km^{-2}$)
Northland					
1316	Awanui	222	1958-94	27.1	3.1
3506	Maungarerua	11.1	1967-94	21.7	3.5
3722	Waitangi	302	1979-94	25.5	3.2
46618	Mangahakia	246	1960-94	39.4	6.1
47804	Waipapa	122	1978-94	35.6	6.1
Auckland					
45702	Waiwhia	8.0	1967-94	32.3	3.3
45703	Hoteo	261	1977-94	23.5	1.6
6806	Mahurangi	46.8	1982-94	25.7	2.0
43803	Papakura	52.5	1969-94	16.3	1.0
8604	Orere	40.8	1978-94	23.6	7.7
Hawkes Bay					
21801	Mohaka	2370	1957-94	33.7	10.2
21803	Mohaka	997	1962-94	38.1	12.0
23104	Ngaruroro	370	1963-94	45.7	8.6
23106	Taruarau	259	1963-94	24.8	5.3
Wairarapa					
29244	Whangaehu	36.3	1967-94	14.6	0.57
27303	Pahao	563	1986-94	20.3	0.082

it, this was used in combination with the at-site mean of volume or duration to estimate the annual exceedance probability of the 1993/94 event for each site.

For the 7-day annual minimum, an at-site approach was used: the log-Normal distribution was fitted by the method of L moments. Justification for this approach was based on the results of Pearson's (1995) national low flow study. Northland, Auckland, Hawkes Bay and Wairarapa regions have some of the lowest mean annual 7-day minima in New Zealand. The log-Normal distribution gave the best fit to the 7-day annual minima in the low flow regions covering the Northland and Auckland regions, and it generally fitted the low flow data well. Any zero 7-day annual minima were excluded from the frequency analysis and their proportion of the number of record years was used to amend the fitted log-Normal distribution (see Nathan and McMahon 1990, or Pearson 1995, for details on this method).

Further, rainfall data from eight long-term raingauges located within the greater Auckland metropolitan region were used (Table 2). Rainfall statistics examined were seasonal three month totals (winter: June-August, spring: September-November, summer: December-February, autumn: March-May), six months totals, and annual totals. The normal distribution was fitted to each series after testing that it was applicable using normal probability plots. This provided an estimate of the probabil-

Table 2 – Estimated non-exceedance probabilities (%) for 1993/94 rainfall totals at eight raingauges located within the greater Auckland metropolitan region.

Site no.	Name	Record	Win. 1993	Spr. 1993	Sum. 1993 /1994	Aut. 1994	Last 6 m. 1993	First 6 m. 1994	July 93- June 94
647702	Albany	1967-94	57	15	22	13	7	5	4
648701	Albert Park	1872-1993	59	12	18	-	9	-	-
648601	Henderson	1925-94	53	19	16	22	12	6	3
649901	Howick	1964-94	22	18	15	12	5	6	2
649742	Mangere	1960-94	34	8	18	33	2	8	2
649704	Onehunga	1965-94	36	6	20	14	3	7	2
649740	Owairaka	1950-94	20	13	14	16	3	5	1
649803	Pakuranga	1972-94	21	14	18	13	6	5	2

ity of non-exceedance of each event for the 1993/94 year. The normal distribution was expected to be applicable to rainfall totals of three months or greater by virtue of the central limit theorem of statistical theory. Furthermore, estimating the frequency of most of the 1993/94 rainfall events involved interpolation of the fit of the frequency distribution to the observed data, rather than extrapolation. Hence there was not expected to be significant differences between different distributions.

Results

Annual Exceedance Probabilities of 1993/94 Maximum Deficit Volume and Duration

Mean values of annual maximum deficit volume (standardardised by mean flow) and duration (both in units of days, Table 3) were, on average, highest in the Wairarapa region. Then followed Auckland, while the lowest were in Hawkes Bay. All mean values were, however, relatively high compared with average values found by Clausen and Pearson (1995) for two hydrologically unique regions in New Zealand (one topographically steep region with high and frequent rainfalls leading to shorter durations between flood events, and the other region with high yielding volcanic soils implying higher low flows). The third region analysed by Clausen and Pearson had average deficit volumes and durations in line with those in Table 3 since the hydrographs tend to have longer durations combined with lower flows when below the mean flow.

The L-moment ratio homogeneity tests showed that the catchments can be considered as one homogeneous region with respect to both severity and duration, *i.e.*, only one dimensionless distribution (one for severity and one for duration) with fixed pa-

Table 3 – Regional averages of: mean annual maximum values of deficit volume (standardised by mean flow) and duration; mean annual specific 7-day minima; annual exceedance probability (AEP) and annual non-exceedance probability (ANEP) for the 1993/94 maximum and minimum events, respectively.

Region	Mean Annual Values: Volume (days)	Duration (days)	7-day minimum ($l\ s^{-1}\ km^{-2}$)	1993/94 Probabilities: Volume AEP (%)	Duration AEP (%)	7-day minimum ANEP (%)
Northland	61	83	4.4	9.0	10.7	16.4
Auckland	71	93	3.1	4.7	5.9	9.6
Hawkes Bay	49	83	9.0	1.6	1.4	15.8
Wairarapa	117	132	0.3	24.3	24.8	34.2

Table 4 – Hosking and Wallis (1993) goodness-of-fit test results for deficit volume and duration, based on comparison of sample L-moment ratios from annual maximum deficits and theoretical L-moment ratios for the three parameter distributions listed below. The test statistic (z) is a standard normal distribution test statistic.

Three Parameter Distribution	Severity z	Duration z
Generalised Logistic	2.54	2.42
GEV	0.96*	0.75*
Generalised Normal (log-Normal)	0.54*	0.40*
Pearson Type III	-0.30*	-0.35*
Generalised Pareto	-2.68	-3.02

* $-1.96 < z < 1.96$, significant at 95% level

rameters was required for either the severity or duration data scaled by their mean values. The goodness of fit tests showed that the two most likely three-parameter candidate distributions for both deficit volume and duration were the log-normal distribution and the Pearson type III (see Table 4). Because the former was found to be the best in the earlier study it was applied here to calculate the frequencies of the 1993/94 drought parameters.

The exceedance probabilities of the 1993/94 maximum deficit volume and duration (Table 3) were most extreme in Hawkes Bay and less extreme in the Wairarapa region. However, because the mean values varied oppositely the absolute values were not very different.

Comparison with the 1993/94 7-day Minimum Flow

The specific mean annual minimum 7-day flow vary in a similar manner to the drought severity and duration (Tables 1 and 3). Highest mean values occur in Hawkes Bay with values up to 12 $l\ s^{-1}\ km^{-2}$. Northland values are in the range 3 to 6 $l\ s^{-1}$

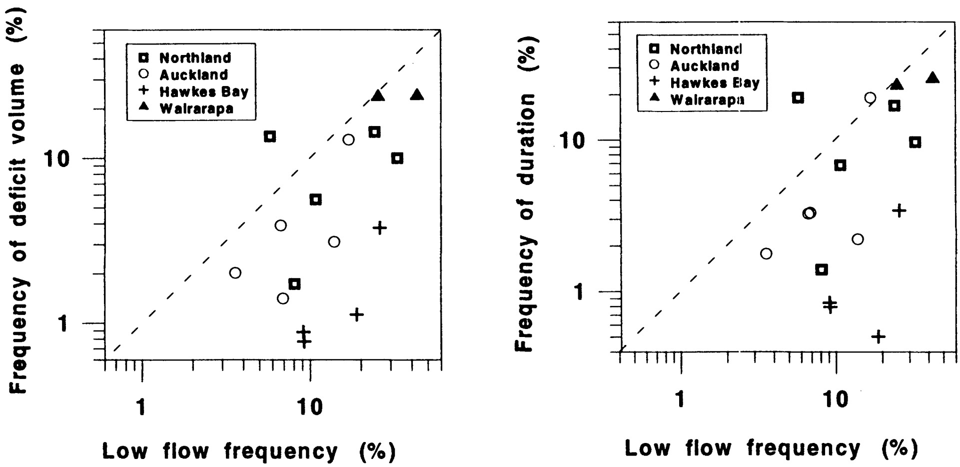

Fig. 2. Frequencies of 1993/94 maximum drought deficit volume and duration *versus* 7-day annual minimum flow frequency for 16 flow recording river sites.

km^{-2}, and most Auckland streams are around 1 to 3 $l\ s^{-1}\ km^{-2}$. Lowest values from about 0.1 to 0.6 $l\ s^{-1}\ km^{-2}$ occur for the two Wairarapa rivers.

The non-exceedance probabilities of the 1993/94 7-day minima are compared with the frequencies of the drought measures in Fig. 2 and Table 3. The non-exceedance probabilities of the 7-day minima are generally higher (most values > 10%) than the exceedance probabilities of the drought measures (most values < 10% except from Wairarapa). The frequencies for Wairarapa are not particularly extreme for both the 7-day minimum and the drought measures. Note that a high non-exceedance probability for annual minimum flow means that it is likely that the minimum flow will be less than the given value; in other words, the given flow is not especially low. On the other hand, a flow less than say the 10% annual non-exceedance probability value is expected in only 1 in 10 years (on average). Thus a flow with 10% annual non-exceedance probability might be taken to signify drought conditions.

Rainfall in the Auckland Region

The non-exceedance probabilities of the rainfall (Table 2) show that the longer duration rainfalls were more extreme than the shorter duration rainfalls. Average non-exceedance probability of the July 1993 – June 1994 year was 2%, corresponding to a return period of 50 years. Of the four seasons examined, the average non-exceedance probability of spring 1993 rainfall was most extreme (13%, or a return period of 7-8 years).

The average annual non-exceedance probability of the 1993/94 rainfalls of 2% compares well with the annual exceedance probabilities of the Auckland 1993/94 streamflow deficit volumes and durations (from Fig. 2).

Discussion and Conclusions

The results from investigating the 1993/94 drought in four North Island regions of New Zealand revealed the importance of distinguishing between different definitions of droughts in that droughts can be extreme in one way, but not in the other. The study showed that the accumulated deficit in flow for streams was particularly extreme for Hawkes Bay and Auckland, which led to a water supply crisis facing Auckland during 1994. Paradoxically the 7-day minimum for 1993/94 was not exceptionally low compared with other years. The drought in Auckland was caused by low rainfall during all of 1993/94, an event occurring only once every 50 year on average. However, shorter duration rainfall totals within that year were not particularly extreme. Thus, the conclusion for the 1993/94 drought is that it was extreme because of its duration rather than its magnitude.

In general we have shown that the use of a statistic based on series of annual minimum 7-day low flows can miss important drought characteristics associated with very long-term deficits. It is difficult to formulate a general hypothesis regarding this phenomenon but this is left for future work. There is no specific reason why the North Island of New Zealand should be unique with regard to this phenomenon.

Acknowledgements

NIWA and regional council field teams are thanked for ongoing data collection. Charles Pearson was funded by New Zealand Foundation for Research Science and Technology, Contract no. CO1319. We appreciate the constructive comments from the two anonymous reviewers.

References

Beran, M. A., and Rodier, J. A. (1985) Hydrological aspects of drought, Studies and reports in hydrology 39, UNESCO-WMO, Paris, 152 pp.

Chang, T. J., and Stenson, J. R. (1990) Is it realistic to define a 100-year drought for water management? *Water Resources Bulletin, Vol. 26(5)*, pp. 823-829.

Clausen, B., and Pearson, C. P. (1995) Regional frequency analysis of annual maximum streamflow drought, *Journal of Hydrology, Vol. 173*, pp. 111-130.

Dracup, J. A., Lee, K. S., and Paulson, E. G. (1980) On the definition of droughts, *Water Resources Research, Vol. 16(2)*, pp. 297-302.

Gustard, A., Bullock, A., and Dixon, J. M. (1992) Low flow estimation in the United Kingdom. Report no. 108. Institute of Hydrology, Wallingford, UK, 88 pp+App.

Hosking, J. R. M. (1990) L moments: analysis and estimation of distributions using linear combinations of order statistics, *Journal of Royal Statistical Society, B, Vol. 52(2)*, pp. 105-124.

Hosking, J. R. M., and Wallis, J. R. (1993) Some statistics useful in regional frequency analysis, *Water Resources Research, Vol. 29 (2)*, pp. 271-281.

McPike, A. (1995) The effect of the drought in Auckland's water supply catchments and drought management. In: Current, No. 6, New Zealand Hydrological Society Newsletter, Wellington, pp. 6-8.

Nathan, R. J., and McMahon, T. A. (1990) Practical aspects of low-flow frequency analysis, *Water Resources Research, Vol. 26 (9)*, pp. 2135-2141.

Pearson, C. P. (1995) Regional frequency analysis of low flows in New Zealand rivers, *Journal of Hydrology (NZ), Vol. 33(2)*, pp. 94-122.

Poff, N. L. (1992) Regional hydrologic response to climate change: An ecological perspective. In: *Global climate change and freshwater ecosystems*, Springer-Verlag New York, pp. 88-115.

Riggs, H. C., Caffey, J. E., Orsborn, J.F., Schaake, J. C., Singh, K. P., and Wallace, J. R. (1980) Characteristics of low flows, report of an ASCE Task Committee, *Journal of Hydraulic Engineering, Vol. 106 (5)*, pp. 717-731.

Salinger, J. (1995) Rainfall and weather patterns and the role of El Nino during 1993 and 1994 – A long-term perspective. In: Current, No. 6, New Zealand Hydrological Society Newsletter, Wellington, 4.

Tallaksen, L. M., Madsen, H., and Clausen, B. (1997) On the definition and modelling of streamflow drought duration and deficit volume, *Hydrological Sciences Journal, Vol. 42(1)*, pp. 15-33.

Yevjevich, V. (1967) An objective approach to definitions and investigations of continental hydrologic droughts, Hydrology Papers No. 23, Colorado State University, Fort Collins, Colorado, USA, 18 pp.

Zelenhasic, E., and Salvai, A. (1987) A method of streamflow drought analysis, *Water Resources Research, Vol. 23*, pp. 156-168.

Received: 26 August, 1996
Revised: 9 April, 1997
Accepted: 16 April, 1997

Address:
Bente Clausen,
Dept. of Civil Eng.,
University of Canterbury,
Private Bag 4800,
Christchurch,
New Zealand.
Email: b.clausen@civil.canterbury.ac.nz.

Charles P. Pearson,
National Inst. of Water and Atmospheric Research Ltd.,
(NIWA),
PO Box 8602,
Christchurch,
New Zealand.
Email: c.pearson@niwa.cri.nz