Low flow patterns in the Ruamāhanga River catchment: 1975-2015

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GW/ESCI-T-18/65

August 2016

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The report may be cited as:

Thompson M. 2018. *Low flow patterns in the Ruamāhanga River catchment.* Greater Wellington Regional Council, Publication No. GW/ESCI-T-18/65, Wellington.

Executive summary

Annual low flows in the lower Ruamāhanga River appear to be decreasing over time. Questions have been raised by the Ruamāhanga Whaitua Committee about the significance of this pattern and what might be causing it. This report addresses these questions and presents the findings of an examination of flow and climate data.

Several indicators of rainfall and river flow were assessed for ten Greater Wellington Regional Council (GWRC) monitoring sites spread throughout the Ruamāhanga River catchment from headwaters to the valley floor. The analyses include comparing rainfall and flow index time series between sites, an assessment of historical climate phases, statistical regressions to help explain patterns of flow in the lower Ruamāhanga River and a comparison of base flow recessions between sites and over time.

The main findings are:

- Patterns of diminishing annual 7-day flow minima since the mid-1990s are apparent at all four sites selected for analysis in the Ruamāhanga catchment. However, the tendency towards more extreme flow minima is stronger in the middle and lower reaches of the Ruamāhanga River.

- Summer seasonal rainfall minima (as characterised by the 90-day duration rainfall minima) explains significantly more variation in flow minima in the lower Ruamāhanga (Waihenga) than other rainfall metrics tested and has been either stable or diminishing in recent years across the Ruamāhanga catchment. The decreasing seasonal rainfall signal is stronger for rainfall sites on the valley floor compared with high elevation sites. Nevertheless, recent seasonal rainfall minima were not as exceptional (relative to historic record) as flow minima have been.

- The widespread flow patterns and link with seasonal rainfall implies some role being played by climate cycles such as El Niño Southern Oscillation (ENSO) and the Inter-decadal Pacific Oscillation (IPO). However, the nature of the relationship between climate cycles and flows is unclear. There has been a variable response of both seasonal rainfall minima and low flows to historical phases of ENSO and IPO with no strong pattern emerging. The recent tendency towards lower flow minima has happened during a negative IPO phase which is counter to the commonly held notion that the opposite is more likely to occur.

- Multiple linear regression analysis showed that the tendency towards lower flows at Waihenga cannot be explained by dominant climate-driven factors (ie rainfall and upstream flow). There is a downward shift in Waihenga annual flow minima since the mid-1990s that remains after adjustments to the data have been made for rainfall and upstream flow. Substantial increases in allocated water over the same time period (80 percent between 1990 and 2010) provides a plausible alternative explanation for the decreasing low flows.

- A comparison of Ruamāhanga River base flow recession curves from the 1970s, 1980s and 1990s with those occurring since 2000 indicates a change in the hydrograph at Wardells and Waihenga that is consistent with an increased abstractive effect over that time. This further implies annual low flows that have been driven progressively lower by climate are likely to have also been aggravated in the mid to lower reaches of the catchment by increasing abstraction.

- The role of groundwater in driving the patterns of low flows is uncertain and requires further investigation. Both surface and groundwater takes have increased in recent decades but groundwater takes more significantly so. It is also possible that changes in groundwater recharge over time are playing an unidentified role in the trend towards lower flows. While this study found only a poor correlation between average annual land surface recharge and river flow minima, the analysis may not have been sensitive enough to the interaction between groundwater and river water to properly characterise the relationship.

Irrespective of the how well causality has been assessed in this study, perhaps the more important question is whether the recent flow trend will persist, strengthen or weaken in coming years. Multiple regression analysis has given us a model that does a reasonable job of predicting low flows at Waihenga using the independent variables of seasonal rainfall, flow in the upper Ruamāhanga catchment and time (the model explains 85 percent of the variability in historical low flows at Waihenga). However our ability to predict how these model variables will change in the future is limited by several factors in particular:

- There is a lack of a clear relationship between known climate phases (ENSO and IPO) and seasonal rainfall in the Ruamāhanga catchment. We know generally when rainfall deficit is more likely but variability in actual rainfall response is high, and sometimes entirely inconsistent over time, such that predicting seasonal rainfall under negative or positive IPO phases with any confidence is not possible.

- There is likely to be a global warming effect interacting with background climate signals and known climate cycles that is further confounding how we use historical patterns to predict future river flow responses. This global warming effect is projected to build over time.

- Without comprehensive data on actual water use (spatial and temporal), any assessment of links with low flow patterns will remain speculative. While allocated volumes of water in the Ruamāhanga catchment have plateaued in recent years, and even reduced, it is unlikely that actual rates of use, especially during high demand parts of the season (when extreme low flows are most likely) are showing the same trend.

Notwithstanding the uncertainty just described, climatic variability and phases of IPO and La Niña and El Niño-dominated weather will continue in the future. Given the importance of rainfall in driving low flows we should expect cycles of higher and lower flow minima to also continue rather than flows diminishing unabated in a linear manner. However, future low flows will also be impacted to a progressively greater extent by a warming global climate. Quite how the climate will change in the Wairarapa, at what pace and how these changes manifest in the river flow regime is unknown at this stage. Work undertaken as part of the Ruamāhanga Collaborative Modelling Project (CMP) will help explore likely future scenarios. In general terms though, more extreme droughts and higher air temperatures are likely to create higher water stress conditions in summer and autumn. Evapotranspiration potential has already been consistently above the 30-year average over the last decade in the Wairarapa and has probably been an aggravating factor in recent low flows. There is also a possibility that the potential of all allocated water has not yet been fully realised and that further increases in actual use of water could further exacerbate extreme low flows.

Contents

1. Introduction

Questions have been raised by the Ruamāhanga Whaitua Committee about apparent declining trends in river low flows. Are the trends real and, if so, what is causing them?

To help respond to these questions, this report explores patterns in low flow in the Ruamāhanga catchment and likely drivers.

1.1 Background

1.1.1 Conceptual understanding of flow drivers in the Ruamāhanga catchment

In the hill country of the Ruamāhanga River catchment, flows are driven by rainfall. Summer base flow recessions are controlled by the storage and release of rainfall by soil and shallow groundwater. This happens in a relatively predictable manner.

Once rivers emerge on to the Wairarapa Valley plain, flow drivers become more numerous, complex and unpredictable. Patterns of rainfall on the plain are different to those in the hills but combine to cause a net rainfall effect on flow. Exchange with groundwater occurs via riparian gravel aquifers, such that some river reaches gain flow from groundwater while other reaches lose flow to groundwater. Groundwater heads drive river flows or vice versa. The pattern of interaction between ground and surface water can vary over time, sometimes in response to natural factors such as river bed degradation and sometimes in response to human activities such as gravel extraction. Abstractions from both groundwater and the rivers themselves impact low flows especially, but in different ways. Surface water abstractions have an instantaneous effect whereas flow depletion relating to groundwater takes may lag by hours, days or even weeks.

At flow monitoring sites within the Wairarapa Valley such as Wardells and Waihenga on the Ruamāhanga River, all of the above factors will play some role in generating the observed low flows.

1.1.2 Previous assessment of trends (up to 2010)

In 2012 GWRC published a report titled *Freshwater allocation and availability in the Wellington region: State and trends*. The report examined trends in several water resource indicators including annual minima in rainfall and river flow. For comparative purposes, the report focussed on a common period of 30 years between 1980 and 2010. Data from 18 rainfall sites (including five in the Ruamāhanga catchment) and 10 flow sites (including five in the Ruamāhanga catchment) were tested for statistically significant trends.

A general conclusion of the report was that "*there has not been any regional-scale, systematic or 'meaningful' change in the magnitude, frequency or duration of key indicators in the past 30 years*". However, it was also noted that there had been a tendency towards a slight drying trend in the last 10-15 years (ie, since the mid-1990s).

Further pertinent conclusions of the report were:

- That there was no evidence to suggest the drying pattern would continue beyond historical ranges in the medium term future because it was likely being driven by known climate cycles, but

- Over the longer term, it was likely the Wairarapa would become more water-stressed as a result of human-induced climate change.

1.1.3 The last five years

Since the previous assessment of trends, a further five years of monitoring data have been collected. Three recent summers (2013, 2015 and 2016) were very dry; in 2013 the lowest flows since records began around 1975 were measured across the Wairarapa Valley.

2. Methodology

2.1 Indicators of flow and rainfall

There are many different flow and rainfall statistics that provide unique information about changing water resource patterns over time. Often, the main difference between statistics used in water resource studies relates to the duration of time over which a measurement is averaged. For practical reasons it is not possible to consider all indicators of possible relevance to this study. The indicators that have been investigated in this study are:

- **Annual 7-day duration river flow minima (7DMin)** – This is the lowest average flow in any seven day period for each year of flow record. The mean of all years is the 7-day mean annual low flow (7DMALF). This duration of low flow is highly relevant to GWRC flow management policies and is also considered to represent an appropriate balance between shorter duration low flows (eg, 1DMin) and seasonal low flows (eg, 90DMin). Short duration low flows, while more extreme, may be of relatively small consequence to instream values compared with longer duration events. Seasonal averaged low flows tend to mask meaningful shorter duration low flow periods, especially in catchments such as the Ruamāhanga that rarely have recession periods of greater than six weeks and can have very large summer flood events.

- **Annual 90-day, 60-day and 30-day duration rainfall minima (90DMin, 60DMin, 30DMin)** – These are lowest rainfall totals in any 3-month, 2-month and 1-month period, respectively. In past studies (eg, GWRC 2012) there has been a focus on 90DMin as being a good general characterisation of the summer dry spells that lead to the annual low flow conditions. In this study shorter duration rainfall totals are also considered in case they emerge as being more important drivers of low flows. Rainfall totals for less than one month become fairly meaningless as they are often zero (at least for lowland sites).

- **Annual Land Surface Recharge (LSR)** – This describes the average annual amount of rainfall that is available to recharge shallow groundwater. It is derived from modelling as an estimate of the rainfall that remains after surface runoff, evapotranspiration and soil losses have been accounted for. It is useful to consider LSR alongside net rainfall totals (eg, 90DMin) in a catchment like the Ruamāhanga where groundwater is known to interact with, and influence, base flows on the valley floor.

All statistics described above were calculated using the 1 July to 30 June year (rather than calendar year) to ensure the summer sample period was not truncated.

2.2 Indicators of climate

In the Pacific region a number of studies (eg, Mosley 2000, Woods 2009, Jordan 2014) have demonstrated a relationship between stream flows and the occurrence of both the short term (4-6 year) ENSO and the longer term (20-30 year) IPO.

In this study, the IPO is of most interest since long term trends in low flow are under examination rather than short term fluctuations driven by ENSO cycles. Annual average values of the IPO[2] are compared with patterns of low flow in the Ruamāhanga River at Waihenga to see whether any obvious relationship exists.

2.3 Monitoring sites

Four flow sites within the Ruamāhanga catchment were selected to represent both natural and impacted (by abstraction) locations. Six rainfall sites were selected to represent both high elevation and valley floor rainfall.

Sites are listed in Table 2.1 and shown on Figure 2.1.

2.3.1 Flow

Two flow sites are located in the foothills of the Tararua Range upstream of all abstractions; the Ruamāhanga River at Mt Bruce and Waiohine River at Gorge. Observed (measured) flows at both sites are therefore natural flows. Both sites were established in 1975. The Waiohine River is the largest tributary of the Ruamāhanga River with the confluence located between the Wardells and Waihenga gauge sites.

The other two flow sites are on the Ruamāhanga River on the Wairarapa Valley floor; Wardells and Waihenga Bridge. Wardells is located just south of Masterton in the upper Wairarapa Valley. There are significant abstractions from the Ruamāhanga River (and tributaries) upstream of Wardells. Observed (measured) flows are therefore modified. The site was established in 1954 but only the record from 1977 is suitable for low flow analysis. The Ruamāhanga River at Waihenga Bridge site is located just west of Martinborough in the lower Wairarapa Valley; it is the most downstream flow monitoring site on the river and observed (measured) flows are therefore modified. The site was established in 1954 but only the record from 1975 is suitable for low flow analysis.

2.3.2 Rainfall

There are three high elevation rainfall sites; Angle Knob, Bull Mound and Bannister Basin. These sites are located high in the Tararua Range at elevations of between 1000 and 1,200 m above sea level. Angle Knob occupies the uppermost catchment of the Waingawa River, Bull Mound is in the headwaters of the Tauherenikau River while Bannister Basin is in the Ruamāhanga River headwaters. All sites were established in the mid-1970s.

There are also three low elevation sites. The Masterton record is a composite of four individual records from sites established in and around the Masterton urban area. The earliest site (Essex Road Met Station) was established in 1889. The record is representative of rainfall in the upper Wairarapa Valley plain (and mid-reaches of the Ruamāhanga River). Bannockburn is located about 20 km southeast of Carterton on the eastern margin of the Wairarapa Valley. It is a privately run site (D15161) with daily records submitted to the national

[2] Sourced from Washington University http://research.jisao.washington.edu/pdo/PDO.latest

Climate Database. The Waiorongomai record is a composite of two individual records from sites established at roughly the same location in the southwestern part of the Wairarapa Valley. The record is indicative of rainfall in the lower catchment of the Ruamāhanga River.

Estimates of Land Surface Recharge (LSR) were provided for three virtual sites in the upper, middle and lower Wairarapa Valley by Aqualinc Ltd using outputs from the Ruamāhanga CMP.

Table 2.1: Rainfall and river flow sites assessed

Site	Type	Start of record
Ruamāhanga River at Mt Bruce	Flow (natural)	1975
Ruamāhanga River at Wardells	Flow (impacted)	1975
Ruamāhanga River at Waihenga	Flow (impacted)	1975
Waiohine River at Gorge	Flow (natural)	1975
Angle Knob	Rainfall (Tararua Range, headwaters)	1975
Bull Mound	Rainfall (Tararua Range, headwaters)	1976
Bannister Basin	Rainfall (Tararua Range, headwaters)	1975
Bannockburn	Rainfall (central eastern valley)	1937
Masterton (composite)	Rainfall (northern plains)	1889
Waiorongomai (composite)	Rainfall (southwestern plains)	1929
Virtual sites 1, 2 and 3	Land Surface Recharge (Wairarapa Valley)	1970 to 2013

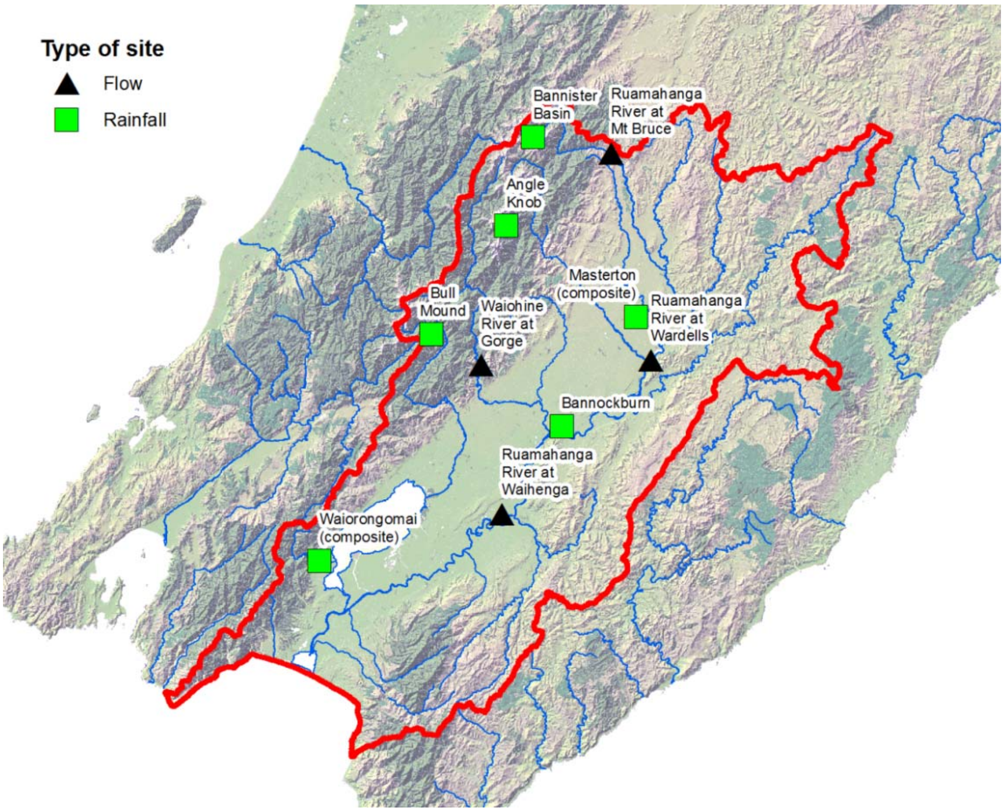

Figure 2.1: Location of flow and rainfall sites

2.4 Approach to analysis

There are three elements to the approach taken in this report:

- A narrative assessment of patterns of low flow, rainfall minima and LSR over time in the Ruamāhanga catchment based on visual observations of raw and smoothed annual time series.
- Regression analysis on the Ruamāhanga River at Waihenga flow record to explore the importance of rainfall (average and minima of various durations) and LSR as a driver of low flows. Multiple variable regression is used to further explore whether any non-natural factors could be having a significant influence on low flows.
- A comparative assessment of base flow recession curves from different time periods at the three Ruamāhanga River monitoring sites (Waihenga, Wardells and Mt Bruce) to see whether any systematic changes over time have occurred.

It was not considered appropriate to fit a linear (monotonic) trend to either full or partial annual time series. This decision was made for several reasons. Many of the available monitoring records only begin in the mid-1970s and are therefore only a little longer than a standard climatology period of 30 years[3]. We know there are climate phases of 20 to 40 years in length that influence rainfall and flow and many of the monitoring records are of insufficient length to span several of these phases. Furthermore, fitting a linear trend to a partial time series of data on the basis of an observed pattern (eg, 1990 to 2015) may produce a statistically significant result but not be particularly revealing. The selection of a trend period within a dataset invariably introduces analytical bias because of the temptation to begin at a high/low point and terminate at the opposite. In datasets with high inter-annual variability the strength of the calculated trend can be very sensitive to start and finish conditions and the strength of that trend can change significantly with small shifts in the analytical period.

2.5 Data quality

All flow and rainfall data used in this report are fully audited in accordance with normal GWRC quality assurance standards and are considered suitable for analyses undertaken. Double mass plots comparing flow over time at Waihenga with the other sites (Appendix 1) do not reveal any large step changes in the volumetric flow relationship between upstream and downstream; this provides further confidence in the quality of the flow ratings.

[3] The period of time often deemed sufficient to characterise climate averages from annual data

3. Observations from the data

Annual time series of low flow and rainfall data are presented in this section to identify patterns of interest.

3.1 Annual low flow minima

3.1.1 Un-impacted headwater sites

Figure 3.1 shows that annual low flows for the Ruamāhanga River at Mt Bruce have occupied a range of between about 0.8 m^3/sec and 1.8 m^3/sec and a full record mean of 1.3 m^3/sec. While there is significant variation between years, the three-year smoothed average suggests that there is also a cycle of higher and lower annual flows occurring approximately every five years. Furthermore, annual low flows appear to have been higher (relative to the mean) and more frequent in the first half of the record than the second half. The last 10 years in particular have been dominated by a cluster of flows well below the mean, including the lowest two flows on record (2012/13 and 2014/15). The pattern for the Waiohine River at Gorge (Figure 3.2) is similar.

3.1.2 Impacted lower Ruamāhanga River sites

Many of the features of the Mt Bruce record are also apparent in the Wardells record (Figure 3.3). There is significant variation from year to year and a similar five-year cycle of relatively high and low flows. There is also an apparent dominance of below-mean flows in the latter part of the record, consistent with Mt Bruce. One notable contrast with Mt Bruce is the increase in range of annual low flows about the mean and, in particular, the cluster of very high flow minima that occurred in the early 1990s. This cluster is important because it could exert a large influence on any assessment of trend, depending on where it features within a time period of analysis.

The pattern at Waihenga (Figure 3.4). is very similar to Mt Bruce and Wardells. Again, the cluster of high flows in the early 1990s is apparent, as well as the progression since then towards more frequent and extreme low flows. The flow of 26 m^3/sec in the summer of 1979/80 appears suspect when viewed in the context of the full record and against the other sites, however, no evidence has been found to suggest a flow measurement error or that the data should be omitted. Nevertheless, the influence of this data point should be carefully considered when undertaking any statistical analysis on either a partial or full record.

3.1.3 Synthesis

The flow data listed in Appendix 2 show that about 90 percent of all annual flow minima occur between the months of January and April (inclusive). There have been odd occasions at all four sites when annual flow minima have occurred in the shoulder months of summer (November, December and May) and on two occasions annual minima were recorded in July and August (both at Mt Bruce).

Approximately half of the annual minima events in the 40 year record coincide (within days) across the four sites. Of the remaining events, most occur at the same general time of year (within the same 3 month season) across sites. In eight years of the record, there are differences (between at least two sites) in the timing of annual minima of more than 3 months indicating probable independence of events. Overall, while there is quite a bit of variability between sites in the timing of low flow minima, the fundamental commonality is that all sites exhibit a dominant summer seasonal low flow regime.

Figure 3.5 compares the normalised flow time series for all four sites. This plot further emphasises the commonality between sites in the timing of relatively high and low flow periods during the 40 year record and also the general pattern of diminishing low flows in more recent years. The most obvious difference between sites is that the Wardells and Waihenga records seem to exhibit a larger range in variation than the upstream natural records. This is likely to reflect an increasingly complex interaction of factors, both climate/hydrology and land use (human), that begin to exert an influence on flows at Wardells and Waihenga. Of particular interest in Figure 3.5 is the extent of difference between the upstream (Mt Bruce, Waiohine) and downstream (Wardells,Waihenga) sites during the extreme low flow episodes since 2000.

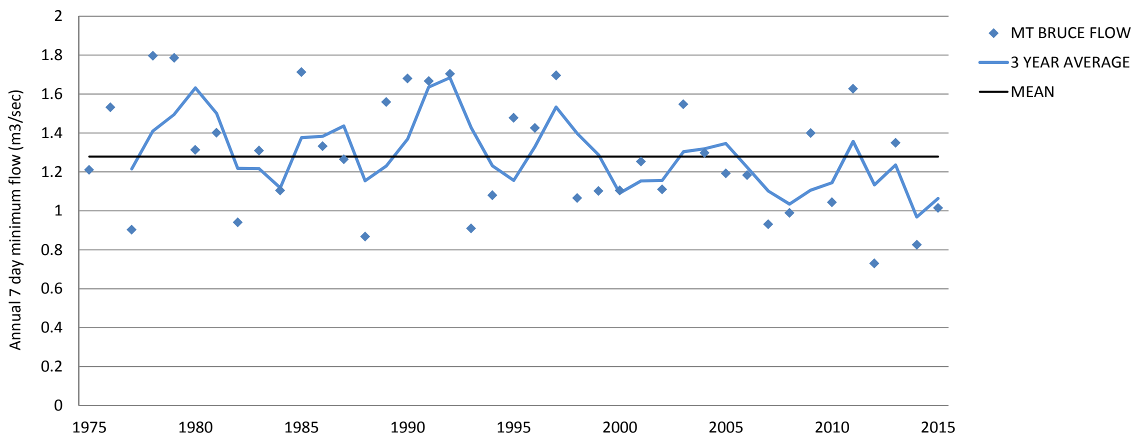

Figure 3.1: Ruamāhanga River at Mt Bruce annual 7-day duration low flow minima

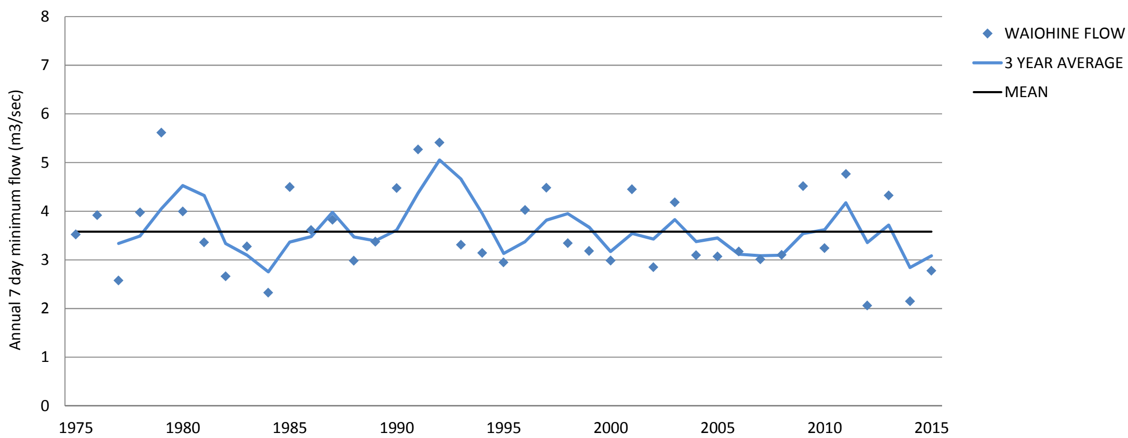

Figure 3.2: Waiohine River at Gorge annual 7-day duration low flow minima

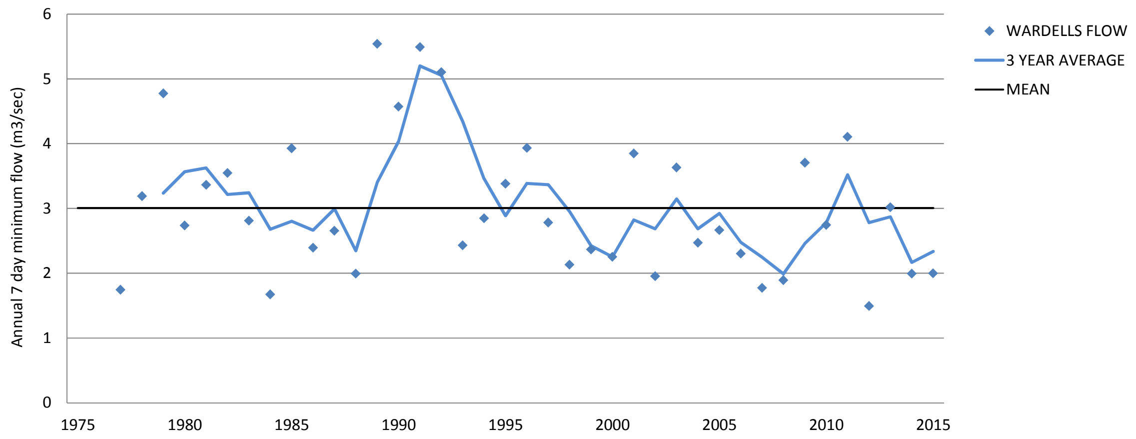

Figure 3.3: Ruamāhanga River at Wardells annual 7-day duration low flow minima

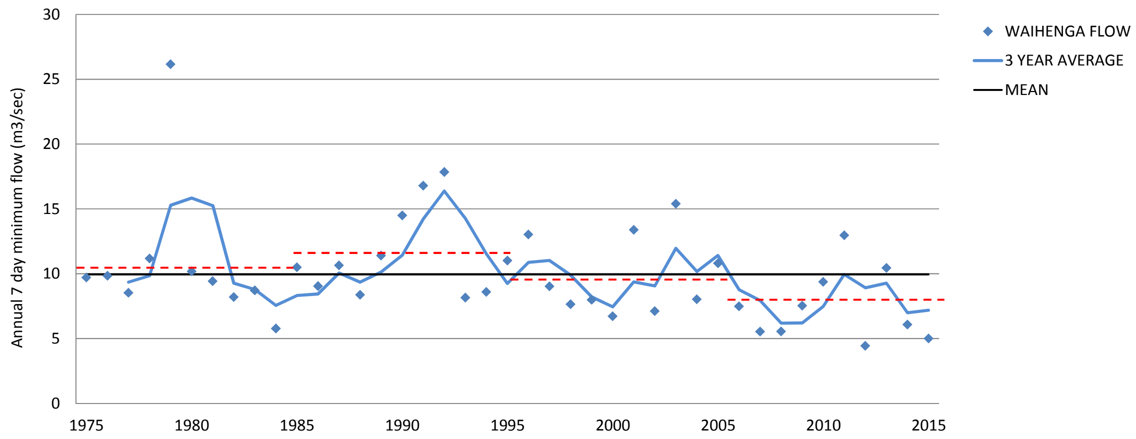

Figure 3.4: Ruamāhanga River at Waihenga annual 7-day duration low flow minima. Red dashed lines are the means for 10 year periods within the full record.

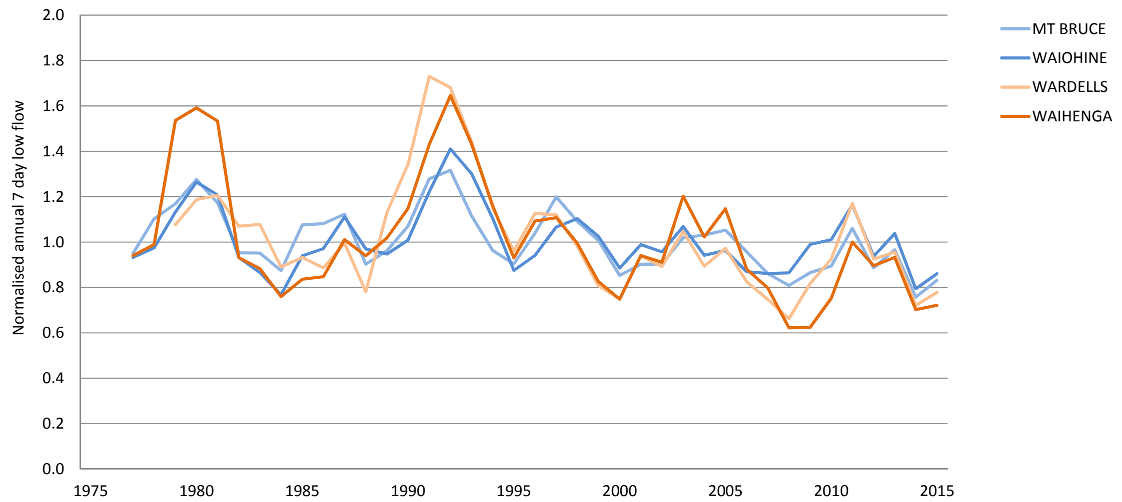

Figure 3.5: Normalised annual 7-day duration low flow minima for all sites

3.2 Rainfall

Temporal patterns in several indicators of rainfall are examined in this section including annual totals, land surface recharge totals and three-month duration minima.

3.2.1 Annual rainfall total – deviation from mean

Figure 3.6 shows the cumulative departure from average annual rainfall for six rainfall sites spread across the Ruamāhanga catchment. Absolute values are not important (or comparable) in these plots, rather it is the direction of the plot that is important.

The three sites on the left are in the Tararua Range and show a broadly similar pattern over most of their record; lower than average rainfall from the mid-1970s to mid-1980s (dry phase) followed by higher than average rainfall until about 2005 (wet phase). However, since then the three sites have behaved quite differently with Angle Knob showing a tendency towards slightly lower than average rainfall, Bull Mound to the south showing a much steeper move towards low rainfall and Bannister Basin to the north showing a dampened continuation of the earlier wet phase.

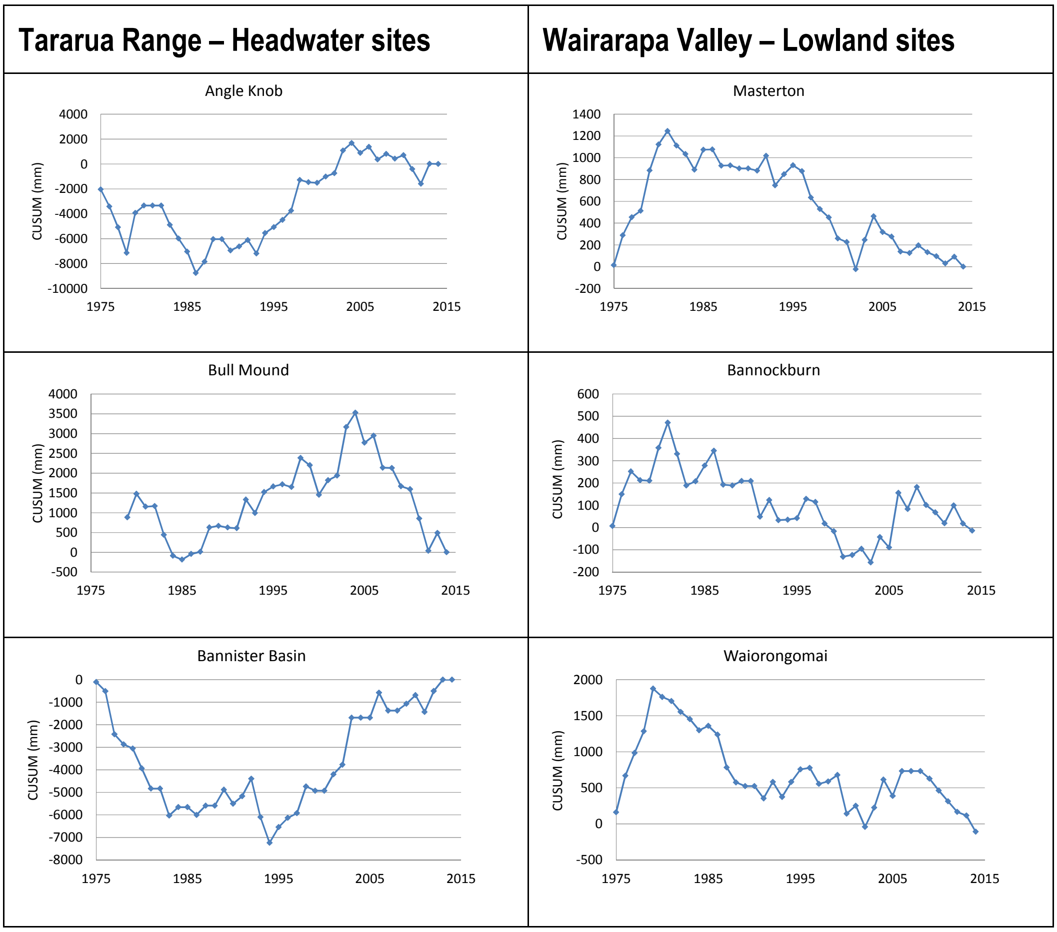

Figure 3.6: Cumulative sum of the departure from mean annual rainfall (CUSUM) over the period 1975 to 2015. Decreasing CUSUM indicates periods of consistently lower than average rainfall (dry periods) and increasing CUSUM the opposite (wet periods).

The valley floor sites (shown on the right) show a pattern of change in CUSUM that is opposite to the pattern observed for the high elevation sites; higher than average rainfall occurred from the mid-1970s to mid-1980s (ie, a wet phase) followed by consistently lower than average rainfall until about 2000 (ie a dry phase). A short period of increasing rainfall occurred at this point but since about 2008, all three sites show a continuation of the earlier dry phase.

3.2.2 Land Surface Recharge

The upper graph in Figure 3.7 shows the modelled annual average LSR totals (mm) for the Wairarapa Valley over the past 30 years. There is a large degree of variability with LSR ranging between about 200-300 mm in dry years up to about 800 mm in wettest years. The lower graph shows the cumulative departure from annual average LSR. The pattern is very similar to that seen for CUSUM of net annual rainfall at the valley floor sites in Figure 3.6 with a predominant trend of drying since the late 1990s (and arguably since about 1980).

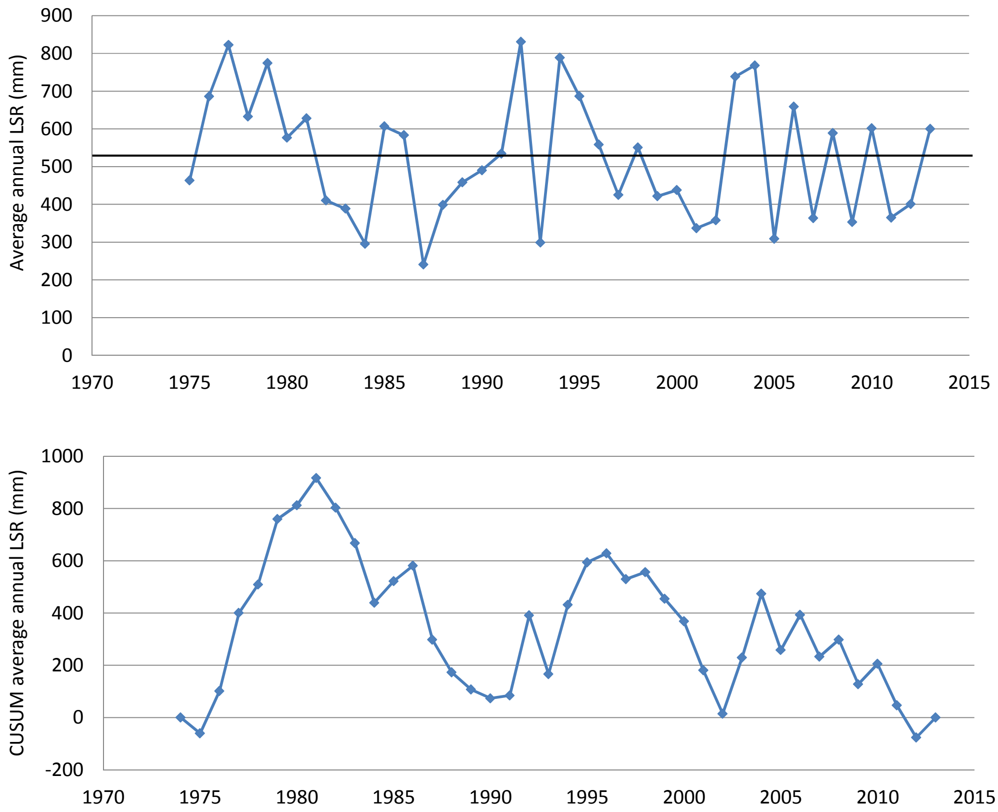

Figure 3.7: Upper graph: Average annual LSR (mm) for the Wairarapa Valley (mean shown by the black horizontal line). Lower graph: Cumulative departure (CUSUM) from average annual mean of LSR.

3.2.3 Annual rainfall minima

In this section data for the annual 90-day duration minimum rainfall (90DMin) are presented. Analysis in Section 4.1 of this report shows that 90DMin were more strongly correlated with low flows than other rainfall metrics.

a) High elevation sites

Figures 3.8 to 3.10 show that the distribution of 90DMin over the past 30 years about the mean is quite different between sites, notably between the northernmost site (Bannister Basin) and the southernmost (Bull Mound). Variability between years is much higher high at Bannister Basin and there is a period of consistently high rainfall between about 1985 and 1995 that is not nearly as prominent in the Bull Mound record. Bull Mound displayed a period of high variability in the late 1970s but since then variability has reduced.

Overall, while there are no strong visual signals of systematic change with time at high elevation sites, there is an apparent tendency towards lower 90DMin since the late 1980s at Bull Mound that is not evident at the other sites.

The high variability between sites is somewhat unexpected. While spatial variability in rainfall is high in mountainous environments and slightly different site exposures to prevailing weather systems can have large impacts on patterns of rainfall, a 90 day duration rainfall metric would normally create greater homogeneity than is observed. More analysis is required to better understand whether the extent of variability is real and representative of the upper Ruamāhanga catchment or whether there are particular site characteristics that need further consideration.

b) Low elevation sites

Full records for each site are shown in Figures 3.11 to 3.13 with the more recent period (common to the high elevation rain gauge and flow site data) highlighted in the red boxes. In contrast to the high elevation sites, there appears to be a higher degree of consistency between low elevation sites in patterns of 90DMin. This probably reflects the lower rainfall gradient with distance and less chaotic rainfall profile on the valley floor. All three sites show a clear tendency towards lower 90DMin since about the mid-1990s. However, when viewed in the context of the long term historical record this recent pattern does not appear to be out of the ordinary. In fact, a very similar shift occurred between about 1950 and 1970 at all three sites (as judged by the form of the three-year averages. It is an important point that this previous shift pre-dates the river flow records so we do not know what influence it may have exerted.

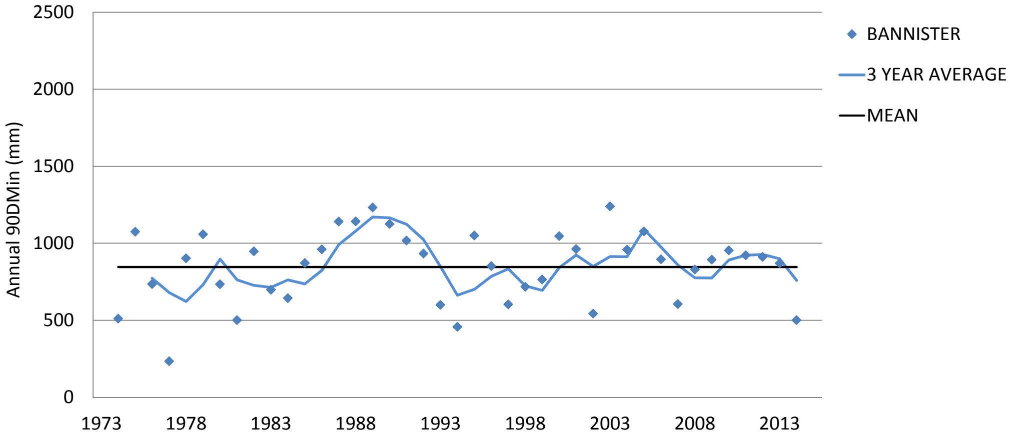

Figure 3.8: Bannister Basin 90DMin

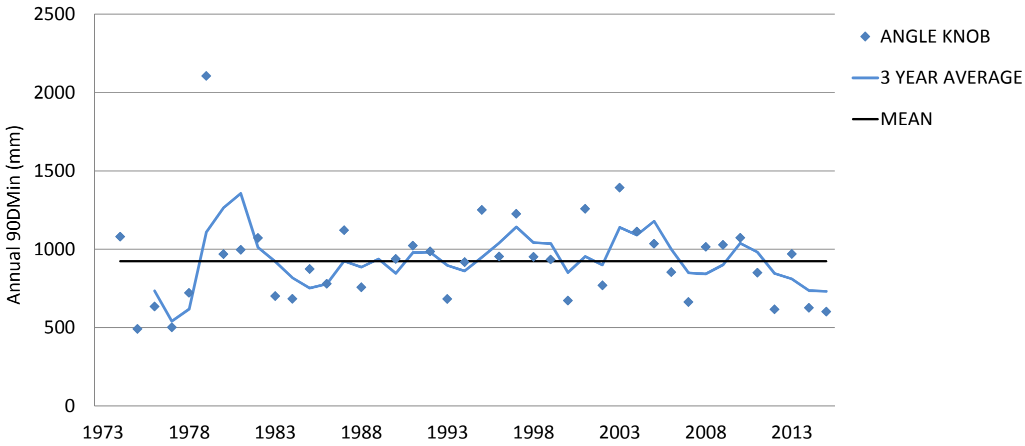

Figure 3.9: Angle Knob 90DMin

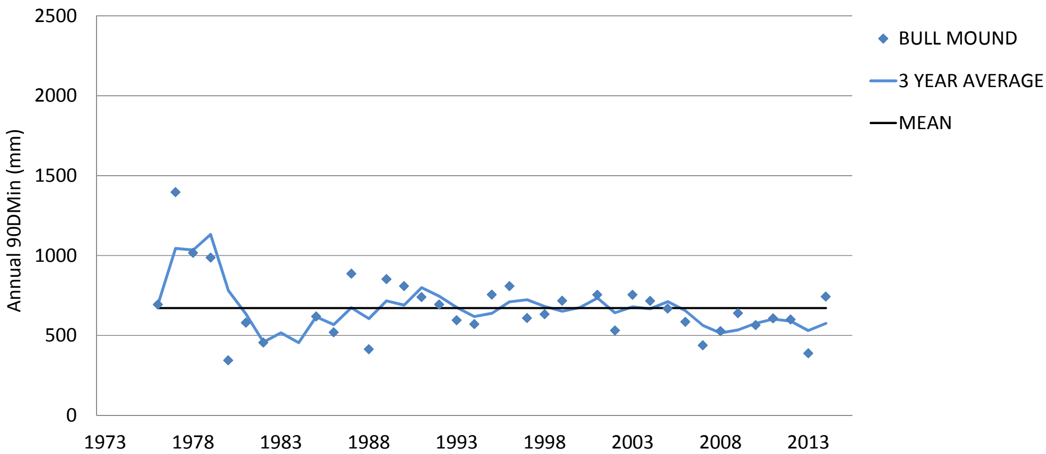

Figure 3.10: Bull Mound 90DMin

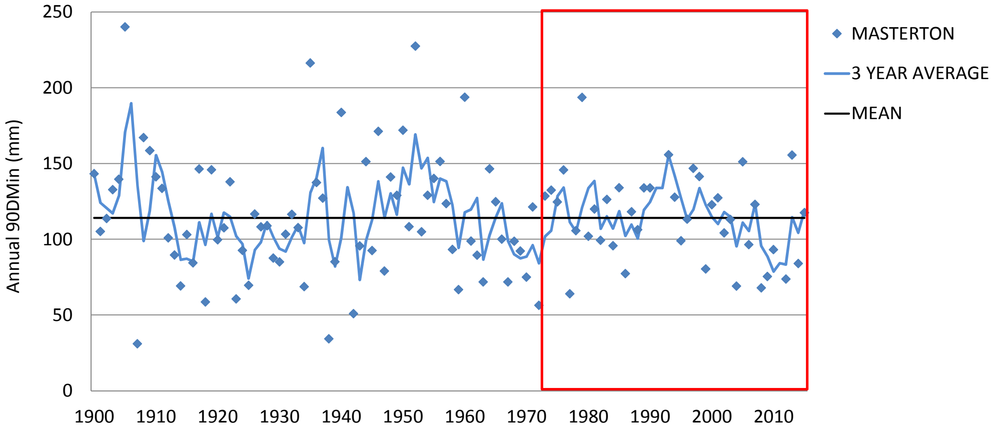

Figure 3.11: Masterton 90DMin

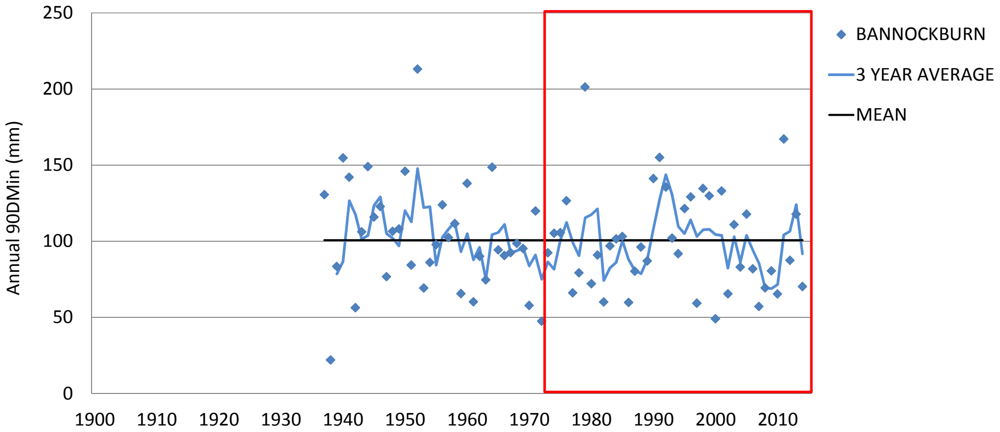

Figure 3.12: Bannockburn 90DMin

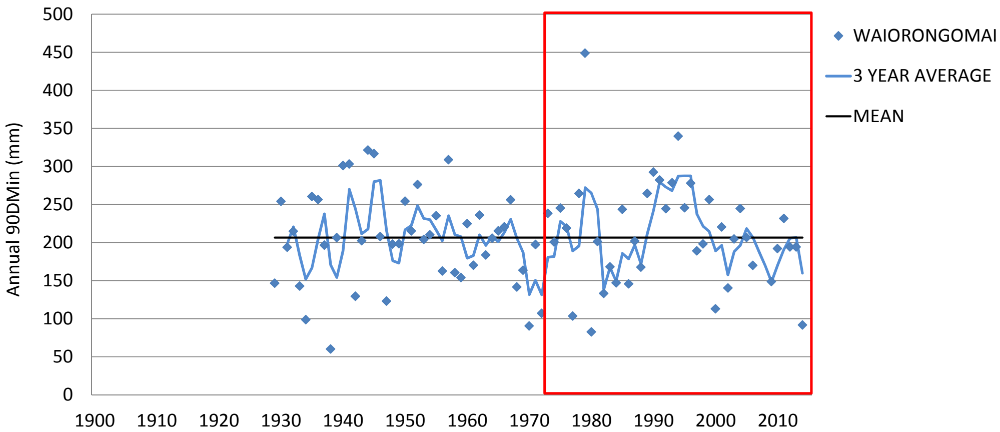

Figure 3.13: Waiorongomai 90DMin

3.2.4 Synthesis

To compare all site records, normalised 90DMin are plotted in Figure 3.14. While there is a broadly similar pattern across all sites with time, the comparatively high degree of consistency between the low elevation sites (orange shades) is clear. It is also apparent that the tendency towards diminishing 90DMin since the mid-1990s signalled in the low elevation site records is much less apparent in the high elevation site records.

The difference in rainfall profile between the Wairarapa Valley and the Tararua Range reflects a significant difference in the weather systems that influence each area. In general terms, the Tararua Range receives 'spill over' rainfall from predominant north westerly systems. This rain does not reach the Wairarapa Valley where rainfall profiles are driven by the less frequent southerly or easterly weather systems. With two quite different rain-producing weather systems exerting an influence, interpreting the consequences for river base flows is more complicated than in catchments with more homogenous rainfall profiles. This is discussed more in Section 4.2.

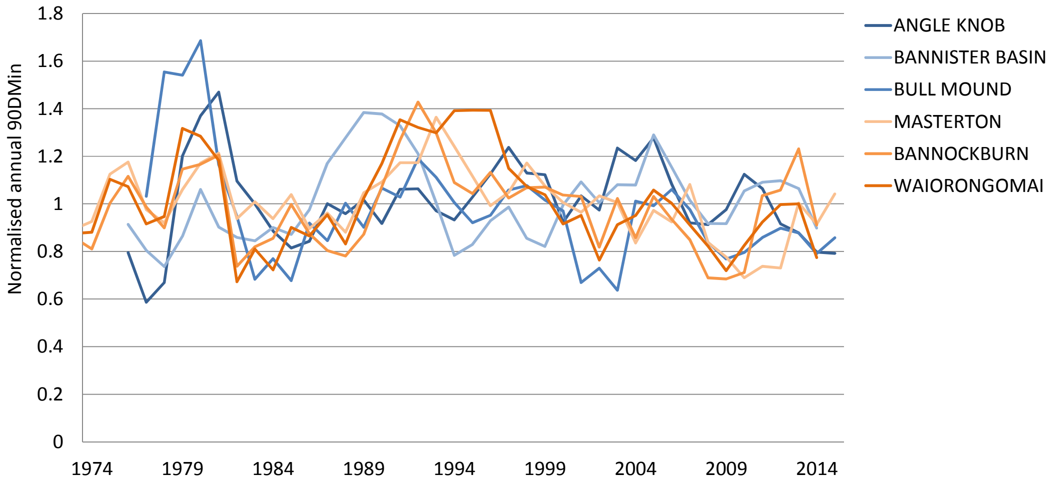

Figure 3.14: Normalised 90DMin for all sites

4. Possible causes of low flows

Since GWRC last reported on trends in low flows and rainfall in 2012 there have been three very dry summers. At many sites in the Wairarapa, the two lowest flow years on record occurred in 2013 and 2015. The consequence of these extremely dry years is that the apparent tendency towards lower flows noted in 2012 has strengthened. The diminishing pattern in low flows since 1990 is apparent (to varying degrees) in all four flow sites examined in this report.

Patterns in flow can be caused by both natural and human factors. Natural variability and cycles in climate and weather normally plays a large role but the modification of catchment hydrology by human activities can be important as well. In developed catchments such as the Ruamāhanga, both natural and human factors are likely to be influencing low flows.

In this section, analysis focuses on the Waihenga flow record only. The pattern of diminishing flow minima is strongest at this site and the potential impact from human activities the highest.

4.1 Rainfall

Rainfall is typically the primary climate driver of river flow. However, the dominant mechanisms by which rainfall influences summer base flows can be hard to discern. Rainfall events have an obvious immediate impact but there are also less direct effects of rainfall that occur over various time lags (weeks to months) due to processes such as groundwater recharge and discharge.

In this study the dependence of low flows at Waihenga (7DFlowMin) was tested using simple linear regression with several different metrics of rainfall. These metrics (described in more detail in Section 3.1) are:

- Total annual rainfall
- Average annual LSR
- 30DMin, 60DMin, 90DMin

Regression plots are shown in Figure 4.1. The results (all statistically significant at the 95 percent confidence level) show how much of the annual variation in low flow minima at Waihenga can be explained by the different rainfall metrics. The upper plots suggest that annual rainfall and LSR, with R^2 values of less than 0.25, are relatively weak predictors of low lows. Rainfall minima, shown in the middle and lower plots, are better predictors with R^2 values ranging from 0.51 for 30DMin to 0.73 for 90DMin. The results suggest that 90DMin exerts the most dominant influence of those tested.

Variability in rainfall is determined to an extent by known climate cycles and these are examined in the next section.

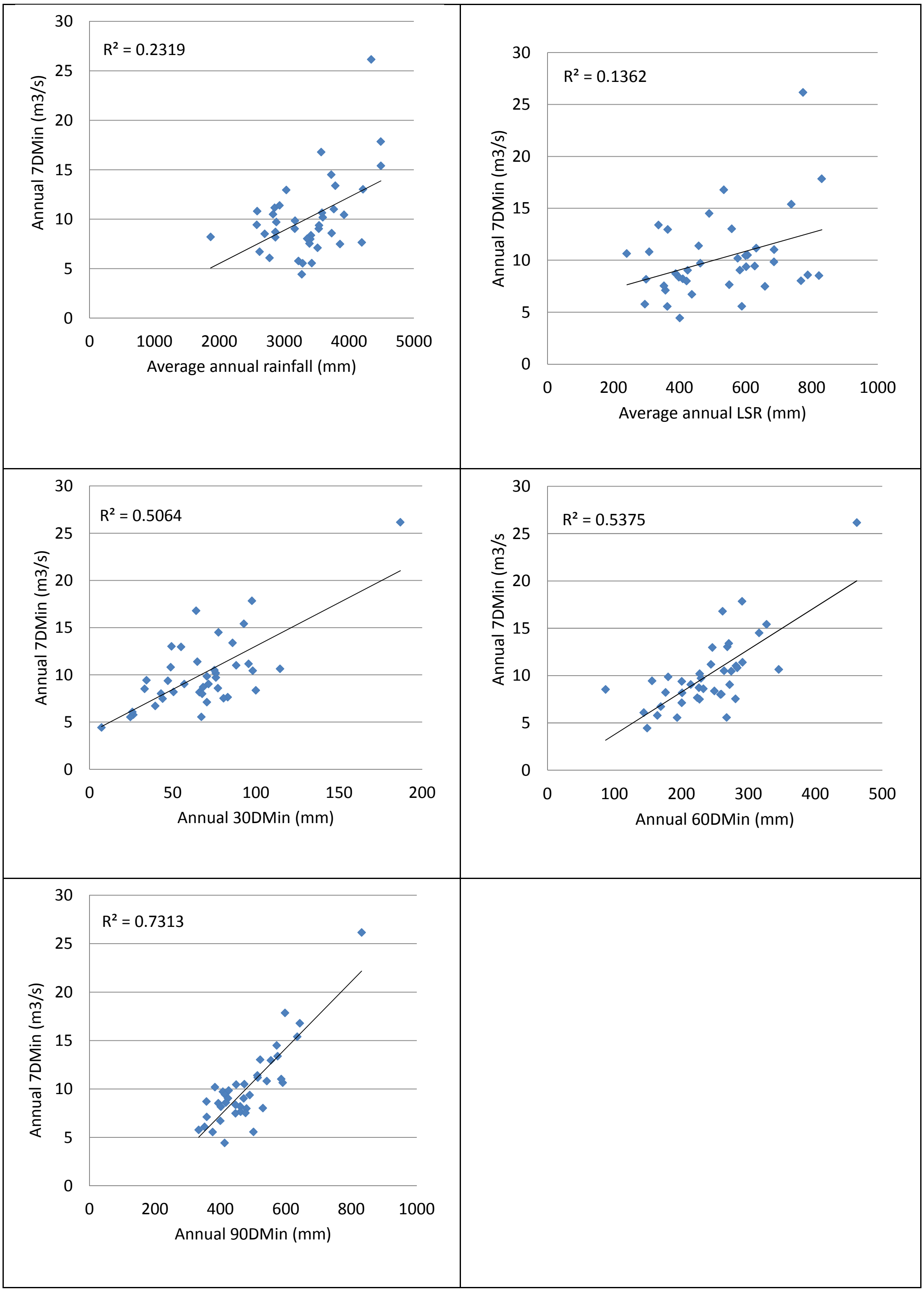

Figure 4.1: Linear regression of annual 7-day low flow (7DMin) at Ruamahanga River at Waihenga with rainfall metrics

4.2 Climate cycles

The primary temporal processes causing climate variability within the Pacific region are the El Niño Southern Oscillation (ENSO) and the Inter-decadal Pacific Oscillation (IPO). Both are driven by cycles in sea surface temperatures and sea level pressures but operate on different time scales. ENSO results in an oscillation of four to six years between periods dominated by El Niño and those dominated by La Niña. The IPO tends to modulate the frequency of ENSO and has positive and negative phases of 20-30 years in which El Niño and La Niña dominate, respectively.

4.2.1 The broad picture

The role of the ENSO and the IPO in influencing rainfall and river flows in New Zealand has been the subject of several studies (eg, Mosley 2000, Salinger et al 2001, Woods 2011, Jordan 2014). The picture is a complex one. In general terms, El Niño (and periods of positive IPO) tend to give more rain in the south and west of New Zealand and drier conditions in the northeast. La Niña (and periods of negative IPO) give the opposite. However, the interpretation of how these general patterns of rainfall influence seasonal river flows is difficult to characterise in a meaningful way for water resource managers. This is partly because many river records are not long enough to span multiple IPO phases, and partly because the impacts can be subtle and highly spatially variable. Furthermore, the Wellington Region lies in a transition zone between parts of the country where the impacts of ENSO and IPO are more certain and measurable (the south and west of the South Island, and north and east of the North Island). Interpreting the influence of climate cycles on rainfall and flow in the Wellington Region is, therefore, especially fraught.

4.2.2 Role of ENSO in the Ruamāhanga catchment

In the Wairarapa, extreme low summer rainfall has occurred during both La Niña and El Niño events. Overall, El Niño has a greater influence due to the enhanced westerly air flow and the rain shadow effect of the Tararua Range. Extended dry spells can also occur during a La Niña summer, although they tend to be punctuated by heavy rain events due to enhanced easterlies and the influence of ex-tropical cyclones. In general, if an El Niño event is present the chance of low summer rainfall in the Ruamāhanga catchment increases, and if a La Niña event is present the chance of low autumn rainfall in the Ruamāhanga catchment increases (Harkness 2000).

Figure 4.2 shows that of the 20 annual low flow minima at Waihenga that are well below the mean, seven occurred during El Niño years, five during La Niña years and eight during years when neither condition has been dominant (neutral). While these data support the general notion that flows in the Ruamāhanga catchment are more likely to be lower during El Niño years than La Niña, the pattern is highly variable. Of particular note is the fact that at least one of the most extreme low events in Figure 4.2 (1985/86, 2007/8, 2008/9, 2012/13 and 2015/16) occurred in each of the three ENSO states.

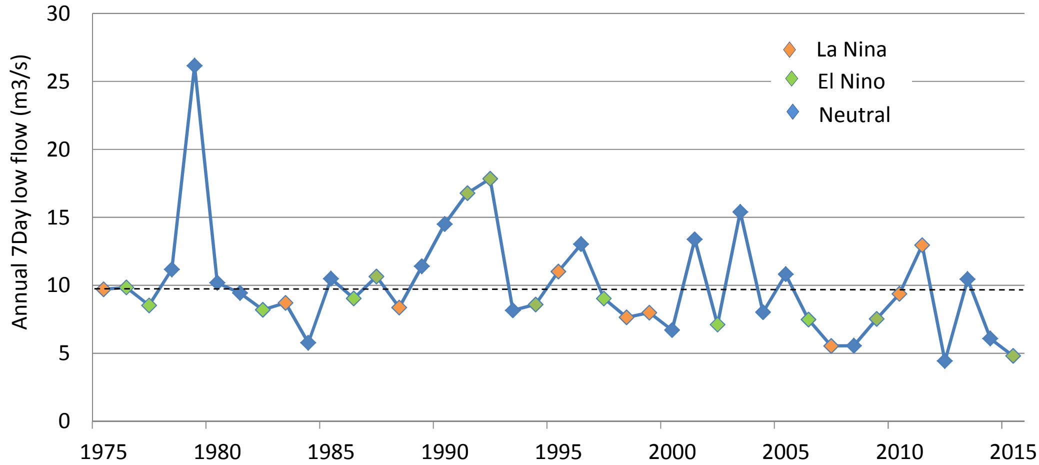

Figure 4.2: Annual low flow minima (7DFlowMin) for the Ruamāhanga River at Waihenga showing when El Niño, La Niña or neutral climate conditions4 were present

Mosley (2000) examined the low flow responses of 18 New Zealand rivers throughout New Zealand, including the Ruamāhanga River, to historic ENSO episodes. It was found that the rivers that exhibited the strongest response – most commonly significantly reduced flows in El Niño episodes – were located in the north and east of the North Island or the south and west of the South Island. The Ruamāhanga River (at Waihenga) showed a slight tendency towards greater negative departures from mean low flow during El Niño episodes but not markedly so.

4.2.3 Role of IPO in the Ruamahanga catchment

The Wairarapa received, on average, less rainfall during the last positive phase of the IPO than the preceding negative phase. Ministry for the Environment (2004) showed the magnitude of reduction in annual average rainfall between phases was between about four and eight percent for the Wairarapa. However, while patterns of change in average annual rainfall driven by IPO phases will undoubtedly have some bearing on low flows, the assessment in Section 4.1 showed that low flows in the Ruamāhanga River are much more dependent on summer rainfall.

Figure 4.3 shows the positive and negative phases of the IPO between 1900 and 2015. On the same graph, the 90DMin rainfall time series for the Masterton site has been plotted. Figure 4.3 shows:

- Phase 1 (1924-1945): The IPO was positive (El Niño dominant) and the average 90DMin for this period was below the long term average.
- Phase 2 (1946-1978): The IPO was negative (La Niña dominant) and the average 90DMin for this period was above the long term average.

[4] Historical climate state sourced from the Australian Bureau of Meteorology at the following website: http://www.bom.gov.au/climate/enso/outlook/#tabs=ENSO-Outlook-history

- Phase 3 (1979-1999): The IPO was positive and the average 90DMin for this period was above the long term average. This pattern is opposite to that observed in the earlier positive IPO phase.
- Phase 4 (2000 onwards): The IPO is negative and the average 90DMin for this period (so far) is well below the long term average. This pattern is opposite to that observed in the earlier negative IPO phase (1946–1978).

Overall, the 90DMin for the Masterton site does not appear to exhibit a clear or consistent relationship with IPO signal. Higher rainfall minima coincide with negative IPO and vice versa in the first two phases, but this relationship reverses in phases 3 and 4. Of particular note is that the descent into negative IPO in the current phase coincides with the *decreasing* trend in rainfall minima; this relationship is entirely opposite to that seen during the previous move from positive to strongly negative IPO during the 1940s.

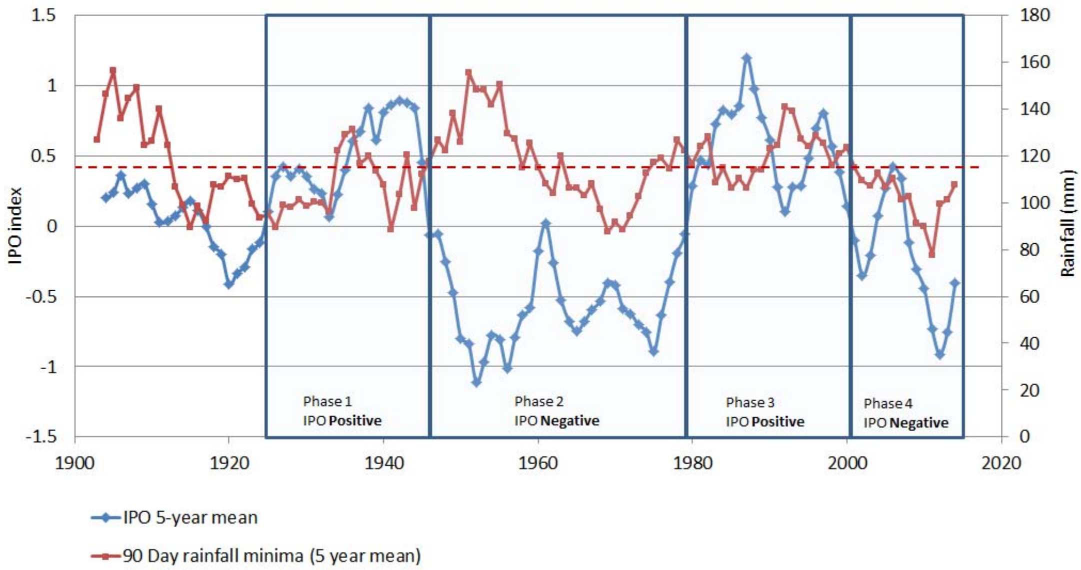

Figure 4.3: IPO phases and average 90DMin for the Masterton site. The red dashed line is the average 90DMin across the full data period.

4.2.4 Synthesis of climate cycle relationships with low flows

There is clearly a strong link between changes in seasonal rainfall and observed patterns of low flow over time in the Ruamāhanga catchment. The most compelling evidence of this link is that the tendency towards lower flows is observed at all four flow gauges, two of which represent unmodified catchment areas and can only be responding to climate drivers.

However, while a systematic climate driver is implied, the assessment of ENSO and IPO in this study has not revealed any obvious link between these climate cycles and patterns of seasonal rainfall and low flow. Furthermore, while previous studies have found that relatively low summer rainfall in the Wairarapa is more likely during El Niño-dominated conditions (and positive IPO), recent patterns of reducing low flows during a negative IPO are counter to this notion. Overall, it is not possible, based on the data assessed, to conclude what role ENSO and IPO have played in influencing the recent pattern of flows.

It is probable that a more detailed statistical assessment of a broader range of climate, rainfall and flow metrics would reveal a clearer picture. However, any such work will still be hampered by a lack of long (pre-1970s) climate and rainfall records in the Tararua Range. This is an area that exerts an important influence on river flows but is also in a transition zone across which climate responses to ENSO and IPO differ markedly (and possibly inversely, as illustrated by rainfall patterns in Figure 3.6) to the Wairarapa Valley.

A further complicating factor is that the historical influence of ENSO and IPO on seasonal rainfall and low flows will not necessarily hold in the future. Global warming is predicted to result in increasing levels of water stress in the Ruamāhanga catchment and this process may already be superimposed on existing shorter term climate phases and altering the overall response of rivers. For example, the presence of blocking high pressure anticyclones has been a feature of the warm Wairarapa summers in recent years and may have played an aggravating role in the extreme low flows. An increase in summer pressures over New Zealand has already been observed over the past 100 years (Porteous and Mullan 2013) and global climate modelling suggest the trend will continue.

It is expected that climate driven trends towards peaks and troughs in seasonal rainfall will continue in the future and that low flow patterns will, to an extent, reflect this. However, the complex nature of the relationship between known climate phases and seasonal rainfall, which may also be evolving with a global warming signal, makes predicting the future patterns of extreme low flow highly uncertain.

4.3 The role of human activities

While climate and rainfall have been identified as drivers of observed low flow patterns, human activities are possibly also exerting an effect. Activities that have the potential to alter low flow hydrology in meaningful ways include large scale river engineering undertaken as part of the flood management schemes in the Wairarapa Valley. This work has certainly changed the hydrology in parts of the Ruamāhanga catchment but generally predates our flow records. Ongoing flood management works (eg, gravel extraction) can have localised hydrological effects but the extent to which these activities have changed in recent times and may be influencing low flows at the catchment scale is unknown and cannot be considered further here. Large scale dam or diversion canal schemes can be ruled out as they do not feature in the Ruamāhanga catchment.

Abstraction for public water supply and irrigation are likely to result in the largest human influence on low flow hydrology. 'Abstraction' refers to the amount of water that is actually used within the limits of resource consents. 'Allocation' refers to the amount of water permitted to be taken by resource consent, and therefore characterises the maximum amount of water that can be taken. Comparing trends in abstraction to trends in low flow for the period 1990 to 2015 would be a useful way of exploring potential causality. However, abstraction data can only be obtained from water meter records and meters have only become widespread among water users in the last five years. It is therefore not yet possible to meaningfully assess trends in actual water use.

Consented water use (allocation) in the Wairarapa occurs almost exclusively in the Ruamāhanga catchment and Figure 4.4 shows that the annual volume increased by about 80 percent between 1990 and 2010. Since 2010, annual allocation has reduced such that the net increase between 1990 and 2015 is 55 percent. Most of the recent reduction relates to surface water consents, although the annual rate of surface water allocation remains about double that of groundwater allocation. Annual volumes of groundwater allocated have essentially plateaued since 2010. Category A groundwater makes up the large majority (~65 percent) of all groundwater allocated. Category B and C comprise ~20 percent and ~15 percent, respectively.

As of 2015, the total increase in the annual volume of surface water allocated since 1990 was 24 million m^3/year (18 percent) while the volume increase in groundwater allocation was almost three times that at 60 million m^3/yr (370 percent). The increase in groundwater allocation is proportionally much more significant as groundwater use was relatively limited in 1990.

While trends in the annual rates of allocation provide a good indication of changes in overall abstractive pressure, changes in the volume of water used on a daily basis are probably more pertinent to interpreting likely seasonal impacts on water resources. Historical data on the volume of daily allocation is unfortunately less complete than for annual allocation, however Figure 4.5 shows the pattern of change that has occurred over the past five years. Rather than decrease like the annual volumes (Figure 4.4), total daily allocation (groundwater and surface water) has plateaued in the past five years. There has been a slight reduction in recent years in the allocation of daily volumes of surface water but this is offset by a similar magnitude increase in groundwater volumes.

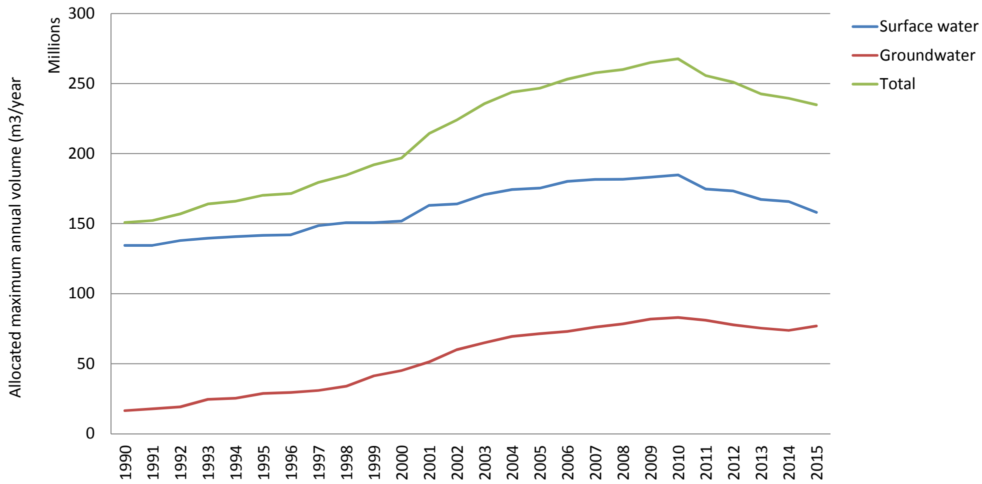

Figure 4.4: Maximum annual volume of water allocated by resource consent in the Wairarapa between 1990 and 2015

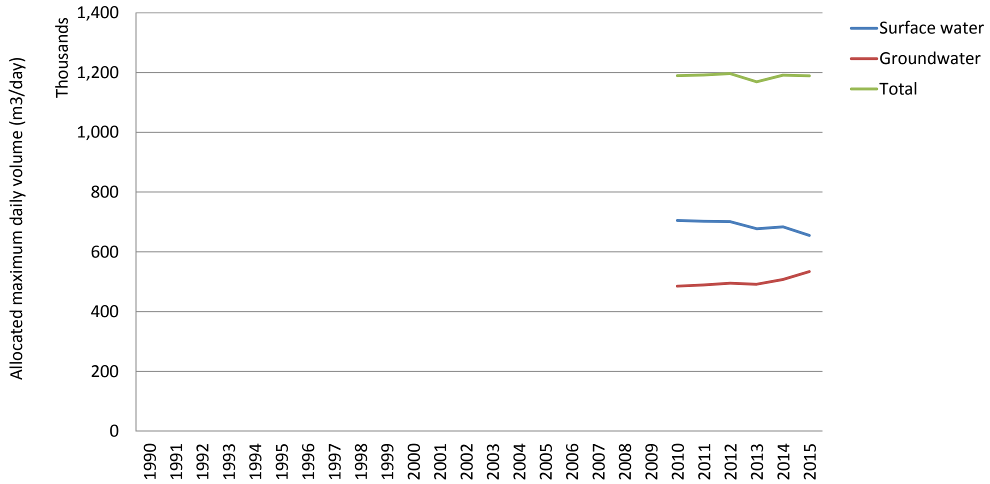

Figure 4.5: Maximum daily volume of water allocated by resource consent in the Wairarapa between 2010 and 2015

Comprehensive data on *actual* water use (ie, water metering data) is not available to compare with maximum allocated rates[5]. While actual water use has almost certainly followed the same general increasing trajectory as annual allocation since 1990, it is considered unlikely to have declined in the same way in recent years and may not have plateaued either. It is possible that abstractions associated with existing allocations that have not been fully utilised in the past have continued to increase towards their limits in recent years. This could be driven by higher demand requirements in recent dry summers and/or intensifying farm activities.

Either way, it is logical to form a hypothesis that low flows in recent years will generally have been more highly impacted than those in earlier years because of increased allocation over the period 1990 to 2015. This impact could include lower annual minima at sites downstream of abstraction than would otherwise occur due to just climate drivers.

4.3.1 Removing the influence of rainfall and upstream flow from the Waihenga record

We know from previous observations that annual flow minima at Waihenga are partially related to river flows from the upper catchment and summer rainfall. One way of exploring the extent to which other non-modelled factors may be exerting an influence on low flows is to remove the effect of upstream flows and rainfall from the Waihenga flow data and see what pattern remains. The remaining pattern represents the variation in flow that is not explained by upstream flow or rainfall.

Following the approach taken in a similar study on the lower Selwyn River by McKerchar and Schmidt (2007), a multiple linear regression was fitted to the Waihenga annual flow minima data. An initial regression gave Equation 1,

[5] While metering has been required on large takes since 2011, the overall metering data set is not yet complete enough to draw firm conclusions about patterns of change.

where WF and MBF are Waihenga and Mount Bruce flows, respectively, and RF is the 90DMin for a six-site composite record:

$$WF = 0.03*RF + 3.03*MBF - 7.7 \quad (1)$$

$[R^2 = 0.77]$

Predictions from this equation are compared to observed values in Figure 4.6a and residual errors from the regression (ie, observed minus predicted Waihenga flows) are shown in Figure 4.6b. In the absence of any non-modelled factors exerting a systematic influence on flow, regression theory requires that residuals should be more or less randomly distributed about zero. Figure 4.6b shows that this is not the case and that there is an apparent decrease over the time period analysed.

Incorporation of time as a third independent variable into the regression gave Equation 2, where MTH is the number of months since 1 January 1900:

$$WF = 0.03*RF + 3.24*MBF - 0.01*MTH + 1.74 \quad (2)$$

$[R^2 = 0.85]$

Predictions from this equation (Equation 2) are compared to observed values in Figure 4.6c and show an improvement in fit relative to predictions from Equation 1 (especially for the more recent data). The residual errors associated with Equation 2 (Figure 4.6d) are distributed more randomly about zero. The R^2 value for Equation 2 indicates that the linear regression with three independent variables (Mount Bruce flow, 90DMin and time) accounts for 85 percent of the variation in Waihenga low flow.

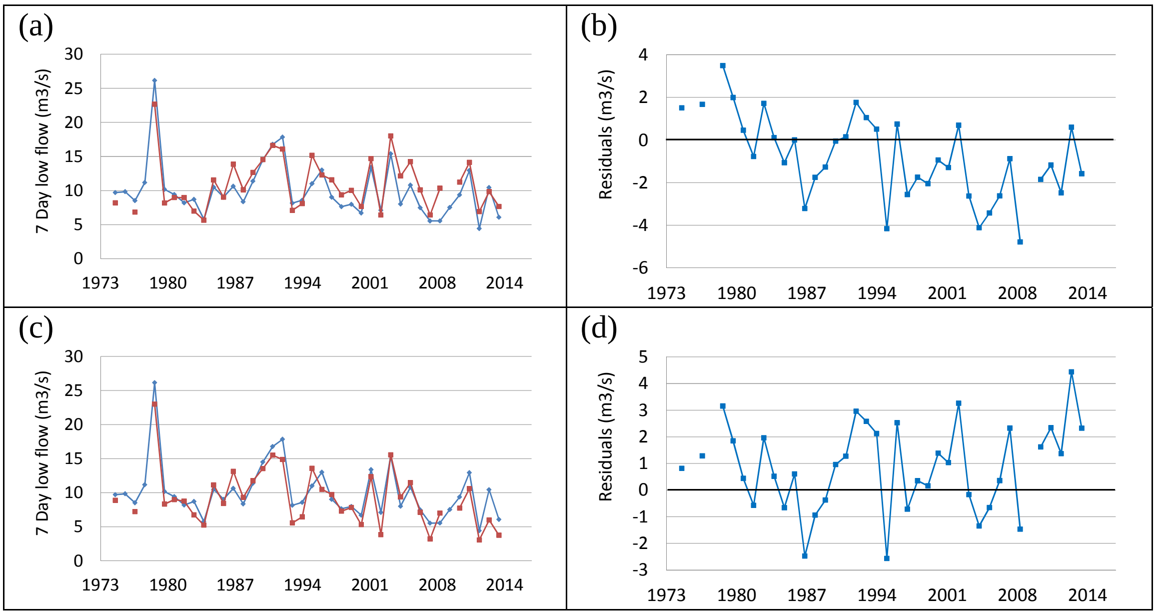

Figure 4.6: Observed (blue) and predicted (red) Waihenga low flows using Equation 1 (a) and with time incorporated in Equation 2 (c). Residuals (Waihenga observed minus predicted) are shown in (b) and (d) alongside the plots for the respective model equations

Since dominant climatic factors are accounted for in the rainfall and upstream (Mount Bruce) flow data, the presence of a time trend in the Waihenga low flow data must be due to other causes. It is possible that there are groundwater recharge drivers that the rainfall and LSR analysis in this study has not been sensitive to, or targeted enough, to identify. Another climate factor – evaporation – has also not been explicitly included in this analysis and could be exerting some influence on lower catchment flows. Modelling by NIWA indicates potential evapotranspiration (PET) during summer in the Wairarapa Valley has been predominantly above the long term average since the mid-1990s and below it before that (Figure 4.7).

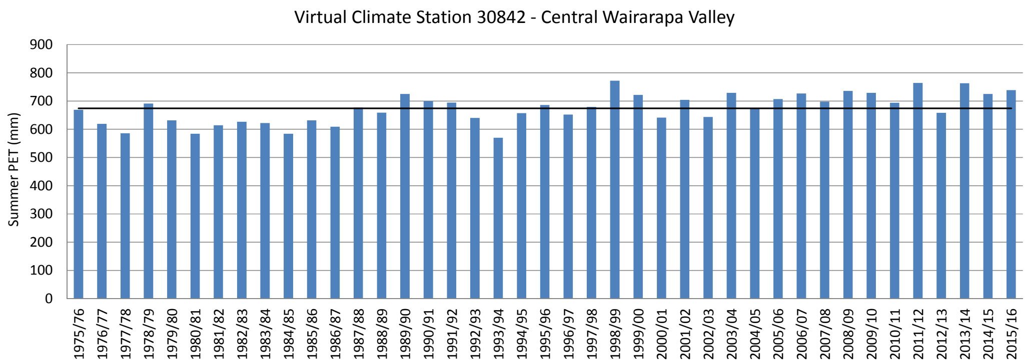

Figure 4.7: Total summer Potential Evapotranspiration (PET) for NIWA Virtual Climate Station 30842, located in the central Wairarapa Valley. The horizontal black line is the mean.

Another possibility is that the decrease in low flows is a consequence of an increase in abstraction. The next section explores this potential link further.

4.4 Have base flows in the Ruamāhanga River changed?

Modelling tells us that as abstraction from a river increases, the natural base flow recession curve will steepen, low flows (eg, MALF) are reached more quickly and the duration of time spent at low flows increases. If the abstractions are solely direct takes from the river and all are subject to full cease take at a certain flow threshold (minimum flow) then no impact on the magnitude of low flows and annual minima below this threshold would be expected, even if overall abstraction rates increased over time. However, many abstractions in the Ruamāhanga catchment are from groundwater and some of these takes are only partially regulated at times of low flow. It is expected therefore that some abstractive effect on the rivers and streams continues beyond cease take thresholds and that this may exacerbate extreme low flows.

To investigate this potential effect, base flow recession curves have been compared for the three sites on the Ruamāhanga River; Mount Bruce, Wardells and Waihenga (noting that significant groundwater abstraction occurs upstream of both Wardells and Waihenga, but not Mt Bruce). For each site, the most significant unbroken summer base flow recessions were extracted from the full flow record and normalised to allow comparative plotting (Figure 4.8 a, c and e). Recessions that occurred during the 1970, 1980s and 1990s were then combined into an average curve for each site and compared with the average curve for recessions that have occurred since 2000 (Figure 4.8 b, d and f). A total of twelve independent recession events were considered, ranging in length from 13 days (1989) to 37 days (2013). Nine of the twelve recession events were common to all three sites.

Key observations from Figure 4.8 are:

- At Mount Bruce there is variation in the way each recession has unfolded, but the general gradient and form is reasonably consistent and there is no obvious distinction between how curves from the early years fall within the envelope compared with more recent curves (Figure 4.8a). This is highlighted further by the close match of the average curves in Figure 4.8b.

- In contrast with Mount Bruce there is a distinction between the form of early and recent recession curves at Wardells. Early recessions tend to occupy the upper part of the curve envelope (Figure 4.8c) while more recent curves have been steeper and fallen further before the a plateauing. It is interesting to note that one curve from the 1980s (March 1985) followed a recession form almost identical to that which occurred in 2013. The different in average shape of early and recent curves is highlighted in Figure 4.8d (insufficient data were available to extend the comparison beyond about 12 days but the emergent pattern is clear).

- The difference between early and late recessions is even more apparent at Waihenga. Recession curves from the 1980s and 1990s almost exclusively occupy the upper part of the curve envelope while more recent curves lie in the lower part (Figure 4.8e). The maximum difference in flow between the average early and recent curves (Figure 4.8f) equates to about 2.0 m^3/s, occurs roughly in the flow range between 7 and 13 m^3/s and between 5 and 10 days into the recession. Beyond 10 days, and below the minimum flow, the difference between curves reduces and the two curves begin to converge again at the extreme low flows (ie, $<6\ m^3/sec$). On average, the minimum flow (8.5 m^3/s) is reached four or five days earlier in recent recessions compared with those in the 1980s.

Overall, the differences in recession behaviour that are apparent at Wardells and Waihenga but not Mount Bruce are consistent with a hypothesis that base flow hydrology in the lower Ruamāhanga River has been modified by human activities. More specifically, the nature of the observed changes at Wardells and Waihenga − steeper recession curves leading to more extreme/prolonged low flows – is consistent with those expected under a regime of increased abstraction.

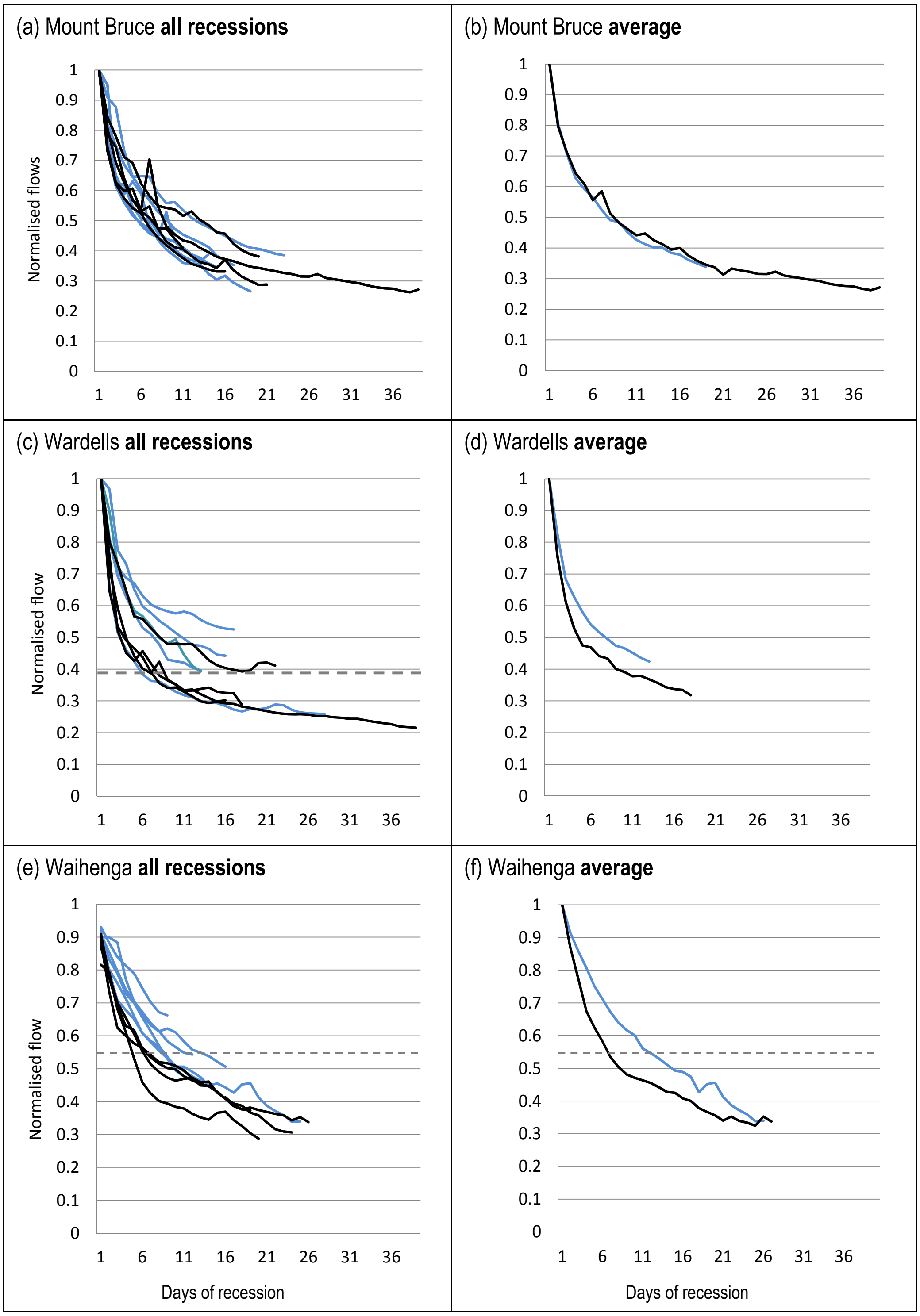

Figure 4.8: Comparison of base flow recessions on the Ruamāhanga River at Mt Bruce (a), Wardells (c) and Waihenga (e). Blue lines are individual recessions from the 1970s, 1980s and 1990s. Black lines are recessions from 2000 onwards. The same groupings are used to derive the 'average' curves in the right hand panels. Horizontal grey dashed lines indicate the approximate position of minimum flow thresholds used to restrict and suspend takes.

To what extent increased groundwater abstraction is playing a role in the modified river hydrology (relative to surface water abstraction) is not clear. The distribution of takes throughout the catchment, lag times associated with both the onset and regulation of takes and lack of actual take data all cloud the interpretation. Nevertheless, we know that the increase in groundwater allocation since 1990 has been larger than surface water in both absolute and proportional terms; it is reasonable, therefore, to expect a relatively large effect associated with groundwater abstraction.

It is possible that changes (other than abstraction) in the developed parts of the Ruamāhanga catchment have also contributed to the changes in recession behaviour. For example, quicker surface run off associated with any widespread reduction in shallow soil permeability (soil compaction) could modify the receding limb of the hydrograph in ways that are generally consistent with observations in Figure 4.8.

5. Main findings and discussion

5.1 Main findings

The main findings of this analysis are:

- There are patterns of diminished annual 7-day flow minima (7DMin) since the mid-1990s at four sites selected for analysis. The tendency towards more extreme 7DMin is stronger in the middle and lower reaches of the Ruamāhanga River. Three recent summers (2013, 2015 and 2016) were very dry; in 2013 some of the lowest flows since records began (around 1975) were measured across the Wairarapa Valley.

- Over much the same period in which 7DMin have diminished, patterns of rainfall across the Ruamāhanga catchment have been variable. Annual rainfall has tended towards higher than average values at high elevation sites (Tararua Range) while the opposite is true for low elevation (valley) sites. Seasonal rainfall minima (as characterised by the 90-day duration rainfall minima, 90DMin) has been either stable or diminishing in recent years across the Ruamāhanga catchment, although the signal is stronger for rainfall sites on the valley floor compared with high elevation sites.

- Regression analyses suggests that 90DMin (derived as a composite value from six mixed elevation rainfall sites) explains significantly more variation in 7DMin at Waihenga than other rainfall metrics tested (including both shorter duration minima, annual average rainfall and land surface recharge). Seasonal rainfall is therefore considered a relatively important driver of low flows. Nevertheless, recent low values of 90DMin were not as exceptional (relative to historic record) as flow minima have been.

- The most compelling evidence of a strong climate link is that the tendency towards lower flows is observed at all four flow gauges, two of which represent unmodified catchment areas and can only be responding to climate drivers. However, the relationship between known climate cycles (ENSO and IPO) and low flows in the Ruamāhanga catchment is unclear. There has been a variable response of both seasonal rainfall minima and low flows to historical phases of ENSO and IPO with no strong pattern emerging. The recent tendency towards lower flow minima has happened during a negative IPO phase which is counter to the commonly held notion that the opposite is more likely to occur.

- Multiple linear regression analysis showed that the tendency towards lower flows at Waihenga cannot be fully explained by dominant climate-driven factors (ie, rainfall and upstream flow). There is a downward shift in Waihenga annual flow minima since the mid-1990s that remains after adjustments to the data have been made for rainfall and upstream flow.

- There are insufficient data on changes in water use over time to meaningfully examine possible links with low flow patterns. However, allocation (maximum consented use) is known to have increased by 80 percent between 1990 and 2010 in the Wairarapa (with some subsequent decline in the last five years) and an overall increase in water use is likely to at least mirror this. Groundwater use in particular is much more significant now than in 1990.

- A comparison of Ruamāhanga River base flow recession curves from the 1970s, 1980s and 1990s with those occurring in the last 10-15 years years indicates a change in the hydrograph at Wardells and Waihenga that is consistent with an increased abstractive effect over that time. This implies annual low flows that have been driven progressively lower by climate are likely to have been further aggravated in the mid to lower reaches of the catchment by increasing abstraction.

5.2 Discussion

The tendency towards lower flows in recent years in the Ruamāhanga catchment appears to be driven by both natural (climate) and non-natural factors. Summer seasonal rainfall is clearly an important driver while a link with increased abstractive impact is also implied (although unquantified).

While the most recent summers have been very dry, there is no evidence from long term monitoring sites that the rainfall minima are exceptional. Equally low, or lower, summer rainfall minima have occurred on several occasions in the past as have 'drying' phases similar to the one that is presently apparent (eg, 1940 to 1970). Unfortunately however, low flows have only been reliably measured at key sites in the Ruamāhanga catchment since the 1970s and the records do not span previous low rainfall phases. We cannot, therefore, be certain about how the rivers responded at the time or whether the most recent low flows are historically unprecedented. The only river in the Wellington Region that originates in the Tararua Range (like the Ruamāhanga River) but also has a longer reliable low flow record is the Hutt River. The Hutt River at Kaitoke site (unmodified hydrology) has shown a pattern of declining low flows since the 1990s similar to the Ruamāhanga but there was a cluster of low flows on this river in the late 1960s and early 1970s (ie, before the Ruamāhanga records began) of a similar magnitude to those seen more recently (Figure 5.1). While these observations cannot be directly extrapolated, they provide a hint that there may have been periods of more frequent and extreme low flows than is suggested by Ruamāhanga catchment flow records that begin in the mid-1970s.

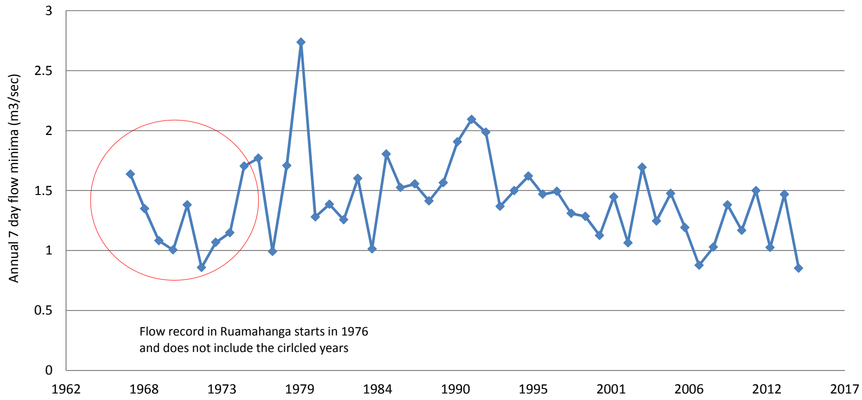

Figure 5.1: Annual 7-day duration flow minima (7DMin) for the Hutt River at Kaitoke. The red circle highlights a cluster of low flows in the late 1960s and early 1970s similar in magnitude to those observed in recent years.

Notwithstanding limitations associated with the length of flow data record available, there is evidence of a time trend of decreasing flow minima in the Ruamāhanga River that cannot be fully explained by rainfall. Similar trends have been found elsewhere in New Zealand in similar settings. For example, McKerchar and Schmidt (2007) found a decreasing trend in seasonal low flows for the lower Selwyn River in Canterbury (for the period 1984-2006). In that case, two possible explanations for the trend were suggested by the authors; the first, and considered most likely, was increased abstraction for irrigation. An alternative suggestion was that the trend was caused by long-term depletion of groundwater from naturally occurring high levels in the 1950s (further work was needed to investigate this possibility).

In the case of the Ruamāhanga River, water takes are also implicated based on the broadly coincident pattern of increasing rates of allocation and the apparent changes in base flow recession curves at sites downstream of takes. Both surface and groundwater takes have increased in recent decades but groundwater takes more significantly so. It is also possible that changes in groundwater recharge over time are playing an unidentified role in the trend towards lower flows. While this study found only a poor correlation between average annual LSR and river flow minima, the analysis may not have been sensitive enough to features of the interaction between groundwater and river water to properly characterise the relationship.

Irrespective of the how well causality has been assessed in this study, perhaps the more important question is whether the recent flow trend will persist, strengthen or weaken in coming years. Multiple regression analysis has given us a model that does a reasonable job of predicting low flows at Waihenga using the independent variables of seasonal rainfall, flow in the upper Ruamāhanga catchment and time (the model explains 85 percent of the variability in historical low flows at Waihenga). However our ability to predict how those model variables will change in the future is limited by several factors in particular:

- There is a lack of a clear relationship between known climate phases (ENSO and IPO) and seasonal rainfall in the Ruamāhanga catchment. We know generally when rainfall deficit is more likely, but variability in actual rainfall response is high, and sometimes entirely inconsistent over time. Therefore, predicting seasonal rainfall under negative or positive IPO phases with any confidence is not possible.
- There is likely to be a global warming effect interacting with background climate signals and known climate cycles that is further confounding how we use historical patterns to predict future river flow responses. This global warming effect is projected to build over time.
- Without comprehensive data on actual water use (spatial and temporal), any assessment of links with low flow behaviour will remain speculative. While allocated volumes of water in the Ruamāhanga catchment have plateaued in recent years, and even reduced, it is unlikely that actual rates of use, especially during high demand parts of the season (when extreme low flows are most likely) are showing the same trend.

Notwithstanding the uncertainty just described, climatic variability and phases of IPO and La Niña and El Niño-dominated weather will continue in the future. Given the importance of rainfall in the generation of low flows we should expect cycles of higher and lower flow minima to continue rather than flows diminishing unabated in a linear manner. However, future low flows will also be impacted to a progressively greater extent by a warming global climate.

Quite how the climate will change in the Wairarapa, at what pace and how these changes manifest in the river flow regime is unknown at this stage. Work undertaken as part of the Ruamāhanga CMP will help explore likely future scenarios. In general terms though, more extreme droughts and higher air temperatures are likely to create higher water stress conditions in summer and autumn. Evapotranspiration potential has already been consistently above the 30-year average over the last decade in the Wairarapa and has probably been an aggravating factor in recent low flows.

There is also a possibility that the potential of all allocated water has not yet been fully realised and that further increases in actual use of water could further exacerbate extreme low flows.

Acknowledgements

Several people provided very helpful comments on draft versions of this report, including Dr Alex Pezza, Tamsin Mitchell and Mike Harkness from GWRC and Andy Duncan (EQOnz Ltd and Ruamāhanga whaitua committee member).

The report was independently peer reviewed by Graeme Horrell of Graeme Horrell Consulting Ltd (formerly of NIWA).

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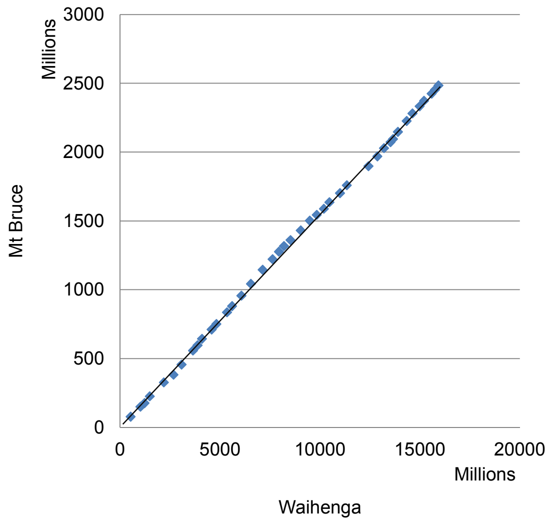
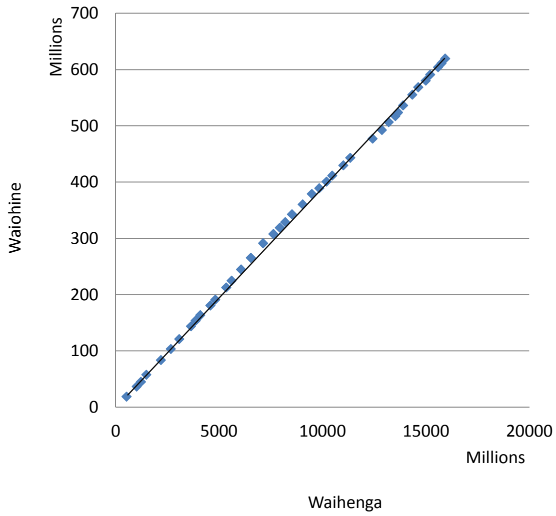
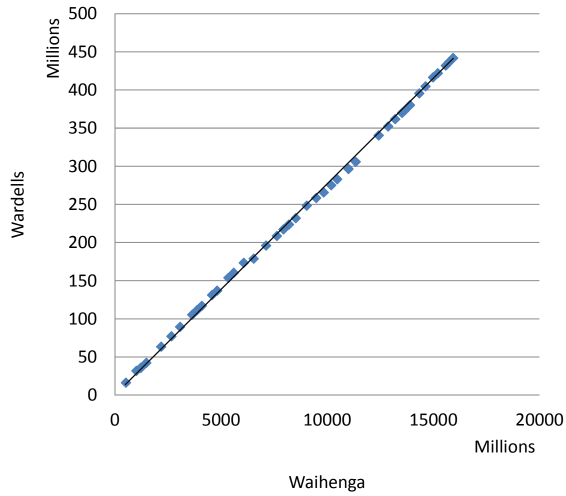
Appendix 1: Double mass (flow) plots

Units are m³/sec







Appendix 2: Annual 7Day flow minima (7DMin)

Cells with grey shading indicate periods in which 7DMin for an upper catchment site (Waiohine, Mt Bruce and Wardells) occurred at a significantly different time of year to that at Waihenga (ie, more than 3 months apart). Such discrepancies are considered to represent independent flow events.

Year starting	Ruamāhanga (Mt Bruce)		Ruamāhanga (Wardells)		Waiohine (Gorge)		Ruamāhanga (Waihenga)	
	Period start	Flow (m^3/s)	Period start	Flow (m^3/s)	Period start	Flow (m^3/s)	Period start	Flow (m^3/s)
1975	16 Mar 1976	1.211	16 Mar	3.515	16 Mar	3.523	16 Mar 1976	9.708
1976	14 Feb 1977	1.532	6 Mar	3.679	6 Mar	3.918	6 Mar 1977	9.842
1977	12 Mar 1978	0.903	29 Jan	1.745	12 Mar	2.575	13 Mar 1978	8.520
1978		GAP	29 Jan	3.191	3 Nov	3.974	29 Jan 1979	11.169
1979	7 May 1980	1.786	8 May	4.775	7 May	5.615	8 May 1980	25.536
1980	30 Jan 1981	1.313	3 Apr	2.736	3 Apr	3.995	3 Apr 1981	10.182
1981	11 Feb 1982	1.401	12 Feb	3.364	11 Feb	3.36	12 Feb 1982	9.428
1982	22 Feb 1983	0.941	22 Feb	3.547	22 Feb	2.66	23 Feb 1983	8.198
1983	26 Feb 1984	1.309	26 Feb	2.81	19 Apr	3.275	27 Feb 1984	8.709
1984	7 Apr1985	1.105	10 Feb	1.672	7 Apr	2.326	8 Apr 1985	5.770
1985	20 Sep 1985	1.713	9 Feb	3.927	20 Sep	4.498	9 Feb 1986	10.492
1986	7 Jan 1987	1.332	7 Jan	2.393	7 Jan	3.615	7 Jan 1987	9.037
1987	28 Jan 1988	1.264	28 Jan	2.655	28 Jan	3.822	29 Jan 1988	10.642
1988	4 Mar 1989	0.867	5 Mar	1.994	4 Mar	2.981	21 Jan 1989	8.365
1989	9 Aug 1989	1.559		GAP	2 Mar	3.376	2 Mar 1990	11.390
1990	20 May 1991	1.680	22 Mar	4.57	21 May	4.477	22 Mar1991	14.498
1991	1 Mar 1992	1.667	20 Apr	5.491	19 Apr	5.271	19 Jan 1992	16.781
1992	5 Mar 1993	1.704	13 Feb	5.102	5 Mar	5.411	13 Feb 1993	17.839
1993	6 Apr 1994	0.910	6 Apr	2.429	6 Apr	3.309	6 Apr 1994	8.157
1994	13 Feb 1995	1.080	14 Feb	2.848	13 Feb	3.143	14 Feb 1995	8.587
1995	17 Jan 1996	1.478	18 Jan	3.38	17 Jan	2.949	6 Jan 1996	11.014
1996	16 May 1997	1.426	16 May	3.934	11 May	4.023	17 May 1997	13.020
1997	22 Mar 1998	1.696	22 Mar	2.781	22 Mar	4.483	22 Mar1998	9.027
1998	13 Feb 1999	1.066	13 Feb	2.132	13 Feb	3.344	14 Feb1999	7.644
1999	6 Mar 2000	1.102	4 Mar	2.367	6 Mar	3.185	6 Mar 2000	7.988
2000	19 Mar 2001	1.105	20 Mar	2.253	26 Apr	2.985	20 Mar 2001	6.707
2001	9 Jul 2001	1.253	13 May	3.849	20 Apr	4.452	15 May 2002	13.382
2002	22 Mar 2003	1.110	22 Mar	1.954	22 Mar	2.847	23 Mar 2003	7.109
2003	21 Apr 2004	1.548	12 Jan	3.633	21 Apr	4.181	12 Jan 2004	15.396
2004	20 Feb 2005	1.298	20 Feb	2.47	20 Feb	3.097	20 Feb2005	8.022
2005	8 Sep 2005	1.192	14 Mar	2.666	8 Sep	3.072	14 Mar 2006	10.806
2006	16 Feb 2007	1.183	19 Feb	2.303	6 Mar	3.172	6 Mar 2007	7.479
2007	4 Feb 2008	0.931	5 Feb	1.774	3 Feb	3.012	4 Feb2008	5.320
2008	3 Feb 2009	0.989	3 Feb	1.892	3 Feb	3.103	4 Feb 2009	5.679
2009	7 Apr 2010	1.399	7 Apr	3.706	7 Apr	4.513	4 Dec 2010	13.092
2010	30 Nov 2010	1.044	15 Mar	2.746	30 Nov	3.239	12 Jan 2011	7.531
2011	20 Apr 2012	1.627	23 Dec	4.105	20 Apr	4.764	24 Dec2011	12.955

Year starting	Ruamāhanga (Mt Bruce)		Ruamāhanga (Wardells)		Waiohine (Gorge)		Ruamāhanga (Waihenga)	
	Period start	Flow (m^3/s)	Period start	Flow (m^3/s)	Period start	Flow (m^3/s)	Period start	Flow (m^3/s)
2012	10 Mar 2013	0.730	11 Mar	1.492	10 Mar	2.06	11 Mar 2013	4.430
2013	31 Mar 2014	1.349	31 Mar	3.019	31 Mar	4.323	1 Apr 2014	10.444
2014	27 Feb 2015	0.826	28 Feb	1.993	27 Feb	2.148	6 Jan 2015	6.082
2015	27 Feb 2016	0.948	2 Mar 2016	1.624	10 Feb	2.738	8 Mar 2016	4.801