Journal of Hydrology (NZ) 64 (2): 227-245

Spatial and temporal variation of baseflow index in New Zealand

Shailesh Kumar Singh* **and George Griffiths**
New Zealand Institute for Earth Science, Christchurch, New Zealand
** Corresponding author: Shailesh.Singh@niwa.co.nz*

Abstract
The baseflow index (BFI) is the ratio of long-term mean baseflow to total streamflow, where baseflow is the portion of streamflow sustained between precipitation events. Understanding spatial and temporal variation in the BFI is of key importance in river ecology and water resource planning and management. Here a benchmark suite of 92 river flow monitoring sites with long records in natural or near-natural basins was compiled. Spatial patterns of mean annual BFI values, ranging from 0.27 to 0.86 with an average of 0.57, were identified and are strongly influenced by geological conditions. Annual mean streamflow, quickflow, baseflow and BFI results for each site were examined visually and statistically for temporal trends and shifts for the first time nationwide. No significant trends in BFI and other flow values were detected except at sites, omitted from the final suite, where activities such as streamflow abstraction and land use change have impacted streamflow. No significant shifts in BFI values were found but were detected in streamflow, quickflow and baseflow at many sites in the South Island. Shifts, up and down, match changes in phase of the Interdecadal Pacific Oscillation and also match shifts in relevant streamflow-generating annual mean rainfall values. The major findings of this study are of key importance in understanding future flow regimes and in planning and management of water resources in New Zealand. This applies particularly to streamflow abstraction, the impacts of agricultural activity on surface and groundwater water quality and the preservation of aquatic ecosystems.

Keywords
shift; trend; baseflow index, BFI, quickflow; baseflow

Introduction
Determination of the various pathways to streamflow is commonly achieved by partitioning the flow hydrograph into two components, namely quickflow (also referred to as stormflow) and baseflow (Bosch *et al.*, 2017). Quickflow contains rapid surface runoff and interflow while baseflow contains slower interflow, shallow and deep groundwater flow, and delayed flow from other impoundment sources such as lakes and canopy storage (Tallaksen, 1995; Singh and Stenger, 2019). Baseflow sustains streamflow between storm events and during periods of low or no rainfall (Delleur, 1999; Lott and Stewart, 2016) and its magnitude is important in assessing antecedent storm conditions. It is usefully characterised non-dimensionally as a baseflow index (BFI) defined as the ratio of baseflow volume to total flow volume over a specified time period (Nathan and McMahon, 1990; Smakhtin,

2001; Ladson *et al.*, 2013; Longobardi and Villani, 2008). It is the proportion of streamflow that derives from stored water sources; the higher the value of the BFI the more sustained is the flow during periods of dry weather. It is determined after hydrograph separation is completed. As a general rule, flow regimes with a relatively large number of floods and low baseflows have low BFI values. The opposite applies to more stable flow regimes.

The BFI has been determined, for example, to support low flow studies, to map recharge and discharge zones in a spatially explicit manner, to investigate the impact of climate change on groundwater resources and to relate flood responses of catchments to storm events (Farquharson *et al.*, 2015). Knowledge of BFI is fundamental to improving understanding of the hydrologic and water quality effects of many watershed processes (Bosch *et al.*, 2017) and in developing appropriate water management strategies (Santhi *et al.*, 2008). Examples include hydropower generation, irrigation, aquatic ecosystem preservation, the relationship between BFI and nitrate and dissolved organic carbon in agricultural landscapes (Heppell *et al.*, 2017), and low flow forecasting (Beck *et al.*, 2013).

Baseflow varies spatially and temporally and is influenced by several factors including climate, soils, topography, geology and land use change, with geology and soils generally being the most important catchment characteristics influencing baseflow identified in numerous studies (Beck *et al.*, 2013). In New Zealand, climate (as it affects rainfall regimes) and geology (as it affects water storage) appear to be the most important influences on BFI in natural and near-natural basins (Singh *et al.*, 2019). Current land use in these basins, where it occurs, is largely sheep, dairy and cattle farming and forestry.

The climate of New Zealand is complex and dominated by interaction between large-scale circulation patterns and a mountainous landscape (Mullan, 1995). Climate varies from warm tropical in the north to cool temperate in the south with severe alpine conditions in mountainous areas. Three climate oscillations affect New Zealand: the Interdecadal Pacific Oscillation (IPO), phases of which last from 20 to 30 years; the El Niño–Southern Oscillation (ENSO), which occurs every 2 to 7 years and lasts about a year; and the Southern Annual Mode (SAM), phases of which may last for several weeks but change quickly and unpredictably (Zhang *et al.*, 1997; Salinger *et al.*, 2001; McKerchar and Henderson, 2003; Jiang *et al.*, 2013).

The most important geological influence on baseflow in the North Island occurs in the Central Volcanic Plateau, which is comprised of andesite, rhyolite, ignimbrite and pumice. In the South Island an important geological influence is that of the Main Divide or central Southern Alps, which is comprised of greywacke, argillite and schist that is extensively folded, faulted and crushed.

Previous work on the distribution, as opposed to the prediction, of the BFI in New Zealand includes that of Hutchinson (1983) who calculated BFI values for 700 hydrological recording stations on rivers and streams. The highest values occurred in the Central Plateau region of the North Island and in the Central Southern Alps of the South Island. The lowest values were scattered throughout the country, mostly in coastal regions. Rainfall effects and vegetation type were found to have a strong influence on BFI values in small basins. Jowett and Duncan (1990) calculated BFI values at 130 sites as part of a study of flow variability and its relationship to in-stream habitat and biota. Clausen and Pearson (1995) calculated BFI values at 44 sites in three hydrologically diverse geographical regions as part of an analysis of streamflow drought. They found that the BFI was key to explaining variations in drought severity. McKerchar and Henderson (2003) examined 31 streamflow records nationally, ranging from 31 to 53 years in length, to determine whether shifts in flood and low flow regime occurred in 1977/78, corresponding to a shift in phase of the IPO. For low flows a consistent pattern of shifts was identified only in the central and southern parts of the South Island, resulting in a general increase in low flows since 1978. Shifts were larger in southern areas. Singh *et al.* (2019) calculated BFI values at 482 sites across New Zealand and mapped their spatial distribution; values were found to range from 0.2 to 0.96, with the highest values in the Central Plateau region of the North Island and in the Southern Alps of the South Island. Lowest values occurred largely in eastern coastal regions. The average long-term value of the BFI was 0.53, indicating that 53% of streamflow is likely to originate from groundwater flow and other delayed sources. Finally, a detailed study of seasonal (not annual) variation in streamflow at 53 sites for the period 1969–2019 was undertaken by Queen *et al.* (2023). At a regional scale it was found that trends were most significant in winter, increasing in the west of the South Island and decreasing in the north of the North Island. The study also found summer streamflow has significantly decreased for most of the North Island, autumn streamflow has reduced throughout New Zealand, and spring streamflow has increased along the west coast and increased along the east coast. Strong non-linear decadal variability was observed – probably caused by IPO, ENSO and ozone concentration changes. The study suggested circulation as the driving factor in streamflow behaviour, notably a strengthening and poleward shift of the southern storm tracks. Queen *et al.* (2023) recommended further work to determine to what extent snowmelt, evaporation, infiltration and anthropogenic climate change factors drive trends in streamflow.

The objective of this study is to extend earlier reconnaissance work by Singh *et al.* (2019) on the identification and documentation of the spatial distribution of annual mean BFI values in New Zealand. The focus of this earlier work was to use data from gauged sites, having a record length of at least five years, to develop a model to predict BFI values at ungauged sites. Here we have a different focus and select only natural or near-natural catchments with long records (at least 45 years) to undertake, for the first time, a national benchmark study of temporal trends and shifts in annual mean streamflow, quickflow, baseflow and BFI values. In the future our data set could form the basis for a suite of reference sites (i.e., sites minimally impacted by human intervention) similar to that of the United States Geological Survey (Carlisle *et al.*, 2019). Our methods of analysis involve statistical testing of BFI, streamflow, quickflow and baseflow time series, supported by visual examination to avoid problems of trend tests identifying apparent but specious trends caused, in fact, by shifts.

A particular aim of this study is to assist in implementing the provisions of legislation governing the granting or renewal of consents for the abstraction or discharge of water into streams and rivers in New Zealand. Many consents have been issued for a period of 35 years. It is very important that regional councils (the authorities responsible for granting consents) have as much knowledge as possible about the likely future behaviour of water resources, including possible temporal trends or shifts in river flow regimes as a result of climate oscillations.

Study area, data and methods

Study area and data

Daily river flow data were selected from hydrological recording sites in 482 catchments across New Zealand previously used by McMillan *et al*. (2016) and Singh *et al*. (2019). Only natural and near-natural catchments (as determined by Booker and Woods, 2014) with record lengths of at least 45 years were chosen, yielding 92 basins (47 in the South Island and 45 in the North Island) with a wide range of hydrological behaviour resulting from having differing topography, geology, soil type, land use and rainfall regimes (Mosley, 1981). Inter-catchment groundwater flow (Ballarin *et al*., 2022) does not appear to occur between catchments considered. Strictly speaking none of the 92 basins are completely untouched by historical and ongoing human activities, even those within national parks. Nevertheless, as we are concerned only with water quantity (not quality) we note that none of the catchments have artificial dams, diversions, abstraction or supplementation of flow and so no flow records needed to be naturalised. As a check we selected a subset of the 92 basins that we considered to be virtually untouched as they are located in national parks or in very remote, uninhabited areas and we could not detect any differences between the results from those sites and the remainder. Human interference is limited to land use change and where this has occurred it has had a minimal impact on river flows in these 92 basins. Main land uses where these occur are dairy, sheep and cattle farming and forestry (Newsome *et al*., 2000). Daily flow data for gauging stations having a high degree of continuity were obtained from the National Institute of Water and Atmospheric Research and various regional councils. All data terminated in 2022 or earlier. Details of the selected 92 catchments (Figure 1) and relevant gauging stations, sourced from Tait *et al*. (2006) and Newsome *et al*. (2000), are given by Booker and Woods (2014). Site numbers, names, locations and recording authorities are listed in Walter (2000). Lastly, lake inflow data was calculated from outflow data only where the outlet has been stable.

Baseflow separation

As the actual baseflow contribution at a site is unknown the choice of flow separation technique is somewhat subjective (Beck *et al*., 2013). Moreover, technique performance varies with soil type, antecedent moisture conditions and the nature of rainfall events (Partington, 2012). Here, as in Singh *et al*. (2019), baseflow was separated from total streamflow using the Lyne and Hollick (1979) recursive digital filter method as adapted by Nathan and McMahon (1990). The basic principle of this method is to separate the high frequency signal, that is surface runoff, from the low frequency signal, that is baseflow, in the total streamflow record.

The digital filter equation, given by Nathan and McMahon (1990), is:

$$q_f(t) = \begin{cases} \alpha q_f(t-1) + \frac{1+\alpha}{2}[q(t) - q(t-1)] & \text{for } q_f(t) > 0 \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where q is the original (total) streamflow, q_f is the quickflow, α is the filter parameter and t is the time step. We followed the standard approach to baseflow separation used by Ladson *et al*. (2013), in applying three filter passes. The filter parameter α was determined for each catchment using data given in Henderson *et al*. (2004) and Booker and Woods (2014) through assessment of the recession behaviour of the relevant measured hydrograph time series. In short, the Brutsaert and Nieber (1977) recession formula was scaled by a reference flow:

$$\frac{dQ_r}{dt} = \frac{-Q_r^b}{T_0} \quad (2)$$

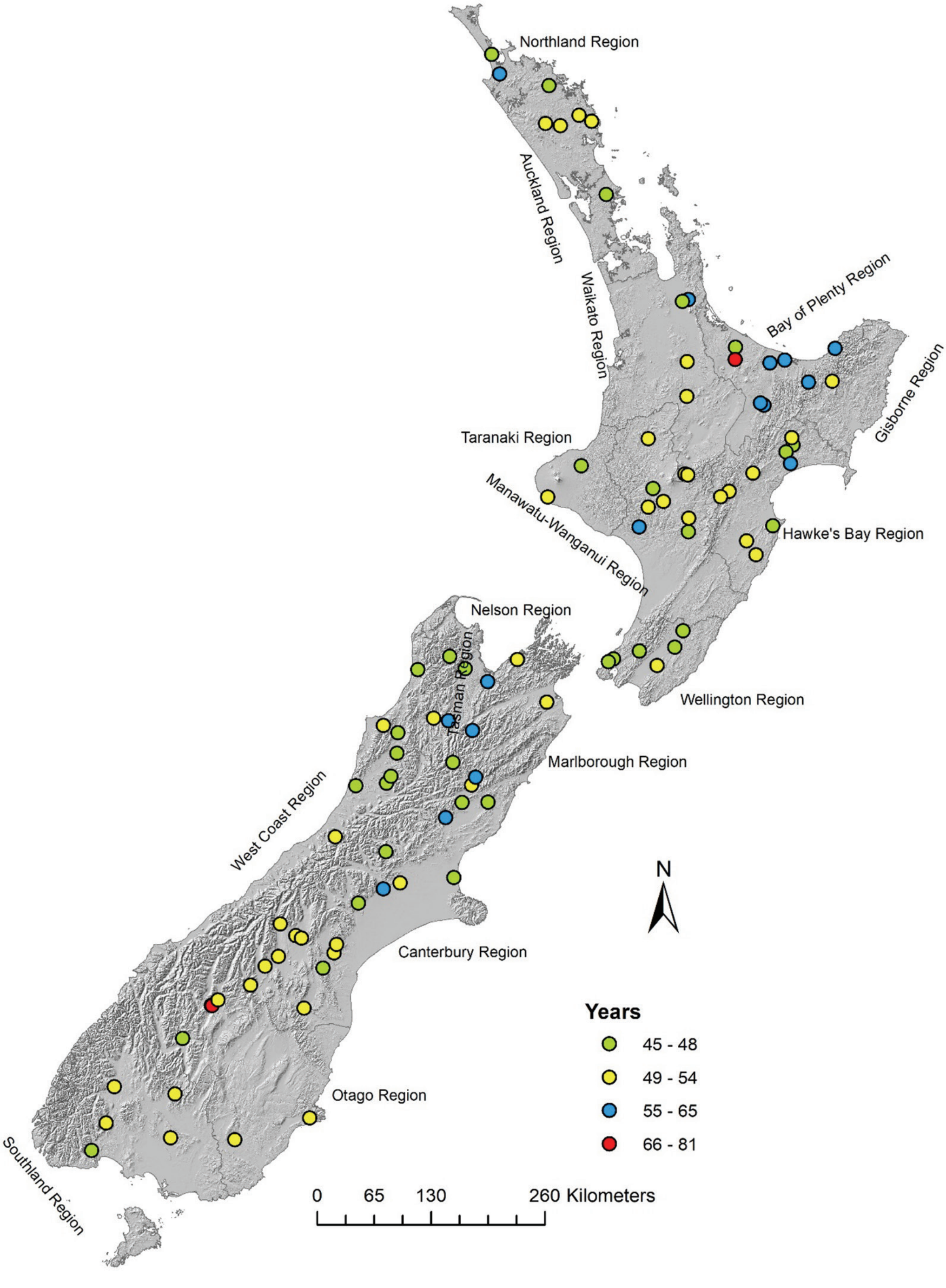

Figure 1 – Locations of the 92 flow gauging stations used in this study, coloured according to record length (years).

in which the scaled flow is defined as:

$$Q_r = \frac{Q}{Q_0} \qquad (3)$$

and T_0 [time] is defined as:

$$T_0 = \frac{Q_0^{1-b}}{\alpha} \qquad (4)$$

Here Q_0 was determined as the median of the measured flow and α and b are parameters. For each gauged site, T_0 and b were determined by geometric regression from:

$$log\left(\frac{-dQ_r}{dt}\right) = b\ log(Q_r) - log(T_0). \qquad (5)$$

Following Zhang *et al.* (2018) we estimated α for each gauged site as:

$$\alpha = exp\left(-\frac{1}{T_0}\right) \qquad (6)$$

and calculated baseflow using:

$$q_b(t) = q(t) - q_f(t) \qquad (7)$$

Baseflow was separated from mean streamflow by employing this method using a daily time step. Daily values were then averaged to produce annual mean values as described in detail by Singh *et al.* (2019). This process then allowed calculation of the corresponding annual mean quickflow and BFI values.

Methods of analysis

Spatial variations in BFI values were examined visually and interpreted alongside geological and soil maps. Where numerical values describing hydrological and physiographic catchment characteristics were available, BFI values were contoured and a cluster analysis was performed using hierarchal affinity propagation techniques described by Bodenhofer *et al.* (2011) to determine spatial patterns. Affinity Propagation (AP) was introduced by Frey and Dueck (2007). It determines a typical cluster member or exemplar for each cluster, that is, a sample that is most representative for the cluster. It has the advantage that it works for any meaningful measure of similarity between data samples. AP does not require a vector space structure and the examples are selected from the observed data samples rather than being computed as hypothetical averages of cluster samples. Bodenhofer *et al.* (2011) implemented affinity propagation as an R package and this was employed herein for BFI spatial cluster analysis.

Time series of annual mean values of streamflow, quickflow, baseflow and BFI were inspected visually for each site to look for trends (including cyclic) and shifts. A typical example, chosen for no specific reason, is shown in Figure 2. The non-parametric Mann-Kendall test (Mann, 1945; Kendall, 1975) was employed to detect monotonic trends in time series and their statistical significance (p value less than 0.05) and Sen's (β) (at the same level) slope to estimate trend magnitude. Both the Mann-Kendall test and Sen's slope are commonly employed to determine the statistical significance and magnitude of hydrological trends where, as in this study, no autocorrelation is found in the time series (Burn, 2008; Birsan *et al.*, 2005; Dixon *et al.*, 2006; Mallick *et al.*, 2021). Here we used the Kendall R package to estimate p and β values. Independence of annual values was assumed owing to the high variability of New Zealand streamflows. To detect shifts we used change point analysis to detect distributional change within the univariate time-ordered observations of streamflow, quickflow, baseflow and BFI. The R (R core Team, 2014) package 'ecp' was employed: this allows determination of the number and locations of change points simultaneously without prior knowledge of the number of change points. It is assumed that the annual values are independent with finite absolute

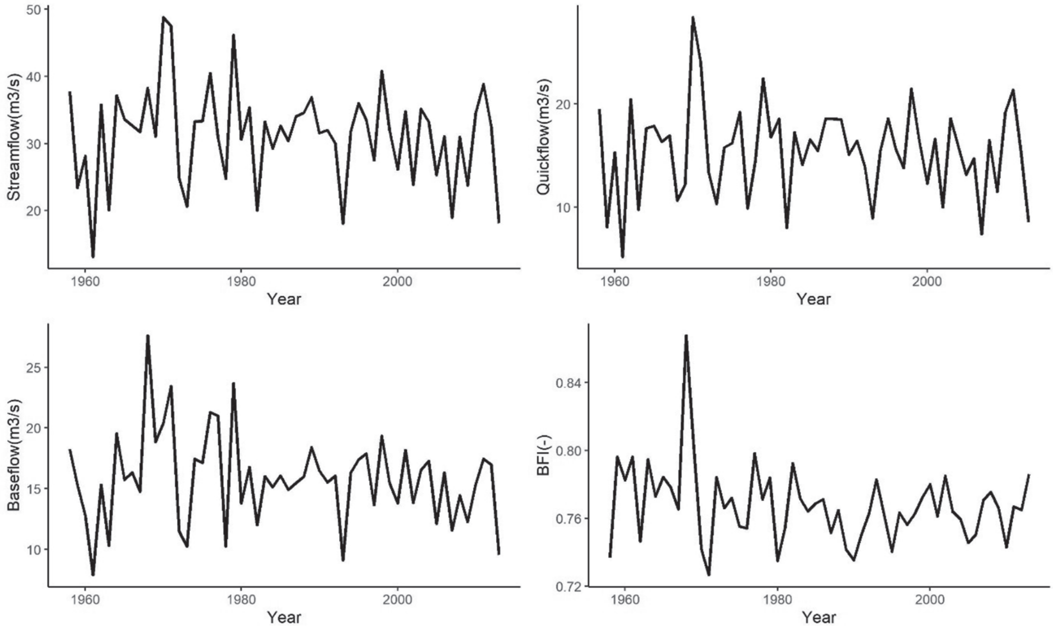

Figure 2 – Time series of annual mean values of streamflow, quickflow, baseflow and BFI at Waioeka at Gorge (Site No. 15901), North Island.

moments (Matteson and James, 2014). Lastly, at sites without trends or shifts it was found that the annual mean values of streamflow, quickflow, baseflow and BFI are positively skewed and their distribution could in most cases be well modelled by the two-parameter Gamma distribution, as verified by the Shapiro-Wilk test (Shapiro and Wilk, 1965). Monte Carlo simulation has found that this test has the greatest power for a given significance level ahead of the Anderson-Darling and Kolomogorov-Smirnov tests (Razali and Wah, 2011).

Results

Spatial variation in the BFI

The long-term mean annual BFI values for 92 sites within New Zealand are shown in Figure 3 and range from 0.27 to 0.86 with an average value of 0.57 (close to the average value of 0.53 obtained by Singh *et al.*, 2019, based on 482 sites). This means that, on average at the 92 sites, 57% of long-term streamflow arises from groundwater storage and other delayed sources. The highest values, which yield comparatively low contribution from surface flow, are found in rivers of the Central Volcanic Plateau and Bay of Plenty regions of the North Island and along the Main Divide of the South Island, as expected given the geological nature of these areas (as mentioned above). In particular, these two regions are characterised by permeable deposits where water storage potential is high, leading to high BFI values. Low values are found in the central northern region and the southeastern region of the North Island and in the north and part of the eastern region of the South Island, which are areas characterised by gravel, sand and sandstone of low permeability. These findings are consistent with earlier work by Hutchinson (1983), Jowett and Duncan (1990), Clausen and Pearson (1995) and notably that of

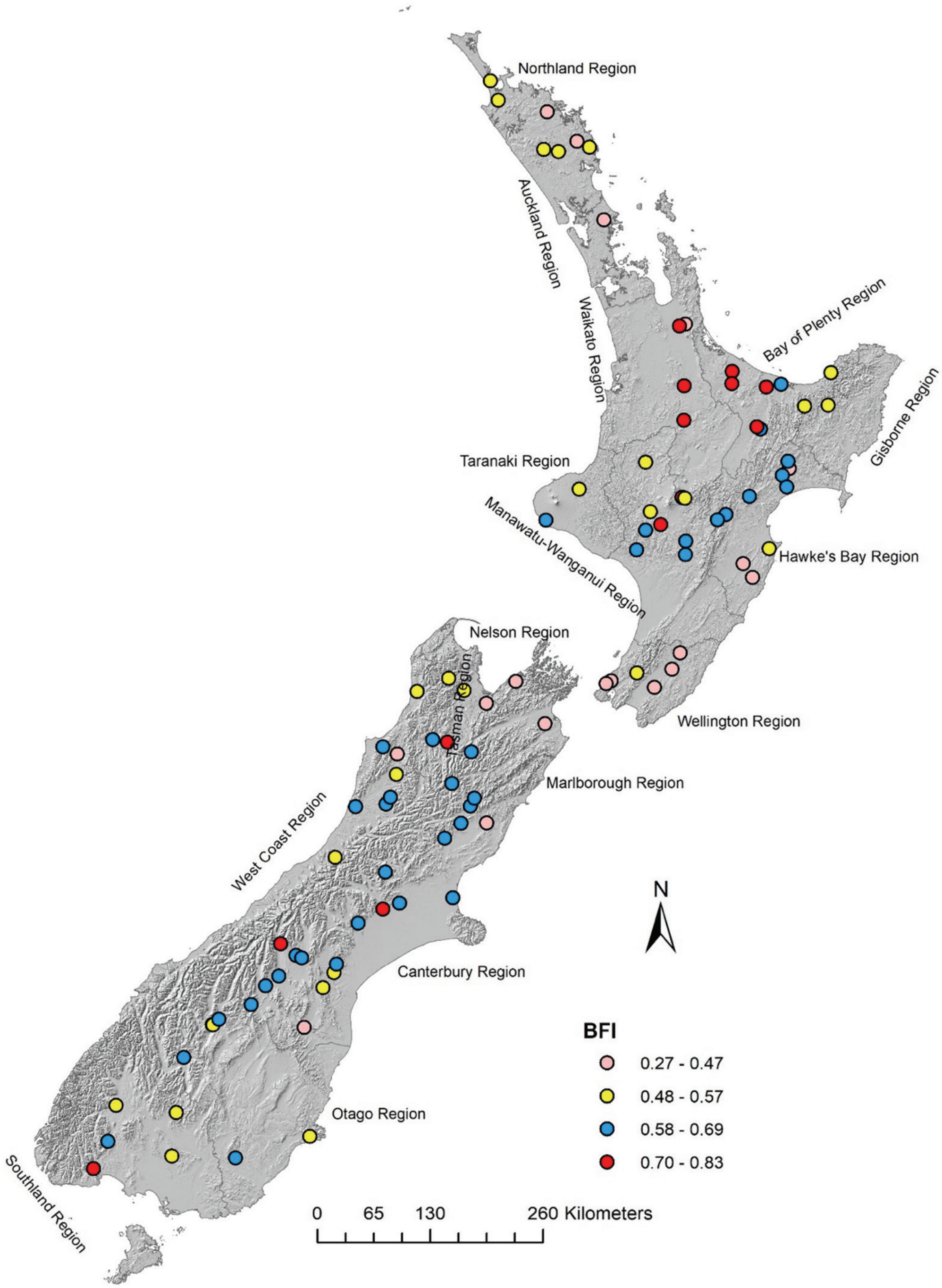

Figure 3 – Mean BFI values at the 92 flow gauging sites.

Singh *et al*. (2019) (based on records as short as five years) and add to that study a longer-term perspective on BFI behaviour in near-natural basins. Lastly, the coefficient of variation (CV) of the BFI values is shown in Figure 4. They range from 0.12 to 0.45 with a median value of 0.32. Note that low values of CV generally correspond with high values of mean BFI (Figure 3) particularly in the Central Volcanic Plateau and Bay of Plenty region of the North Island.

Trends

Significant and sustained trends in annual mean BFI values were found to occur at a number of sites (not included in the final 92 selected) either within part of, or over the whole, site record. However, in all cases the observed trend could be attributed to human influences and these sites were omitted from the original data set of 482 catchments. For example, the upper catchment of the Waiharakeke River contains an extensive wetland that has been gradually modified during the period of record by various drainage works to increase farmable area. This has resulted in a downward trend in streamflow, quickflow and baseflow, which flattens out after about the late 1980s (Figure 5). There is no trend evident in the BFI because baseflow and streamflow trend similarly and the ratio remains relatively constant throughout the flow record. Another example involving land use change is the Tarawera River, where the upper catchment was planted in pine trees in the period from 1964 to 1981 (Dons, 1986). Originally the planted area, comprising some 30% of the catchment, was covered in sparse, light scrub and native bush of low stature. The effect of the planting has been to reduce Tarawera River streamflow and baseflow significantly, with a downward flattening trend. No trend is evident in quickflow and BFI (Figure 6). A final example showing human influence occurs in the Tongariro River where a major power scheme involving three power stations was constructed during the period 1973–2008. This activity resulted in a major drop and flattening in streamflow, quickflow and baseflow and a rise and fall in BFI values (Figure 7). The BFI rise between about 1978 and 1998 occurred because of a large drop in streamflow and quickflow but with a lesser proportional change in baseflow. These examples demonstrate the importance of visually examining streamflow, quickflow, baseflow and BFI time series at a site because, for instance, no trend may be evident in BFI values, suggesting that the record is from a natural or near-natural catchment, but in fact major modification of flow owing to human interference may have taken place.

The 92 sites in natural or near-natural catchments exhibited no trend in BFI, streamflow, quickflow or baseflow. This finding is consistent with that of Queen *et al*. (2023) who noted that such individual annual records rarely show significant trends.

Shifts

No significant and sustained shifts in BFI values were found at any site. This simply means that the ratio of the baseflow to streamflow has remained constant over time, which is a very interesting and practically useful result. However, shifts were detected in annual mean streamflow, quickflow and baseflow at many sites but only in the South Island (Figure 8). An example of shifts is given in Figure 9 where there is a clear, high correlation between the initiation and termination of shifts and phase changes in the IPO. Moreover, the timing of flow shifts also matches the timing of shifts in mean annual rainfall, as expected, given that rainfall drives flows (Figure 10). We found that these rainfall-driven shifts in mean flow were matched in time with shifts in baseflow and that BFI values remained constant irrespective of physical catchment characteristics such as geology and topology. Note here that the Milford Sound rain gauge, although

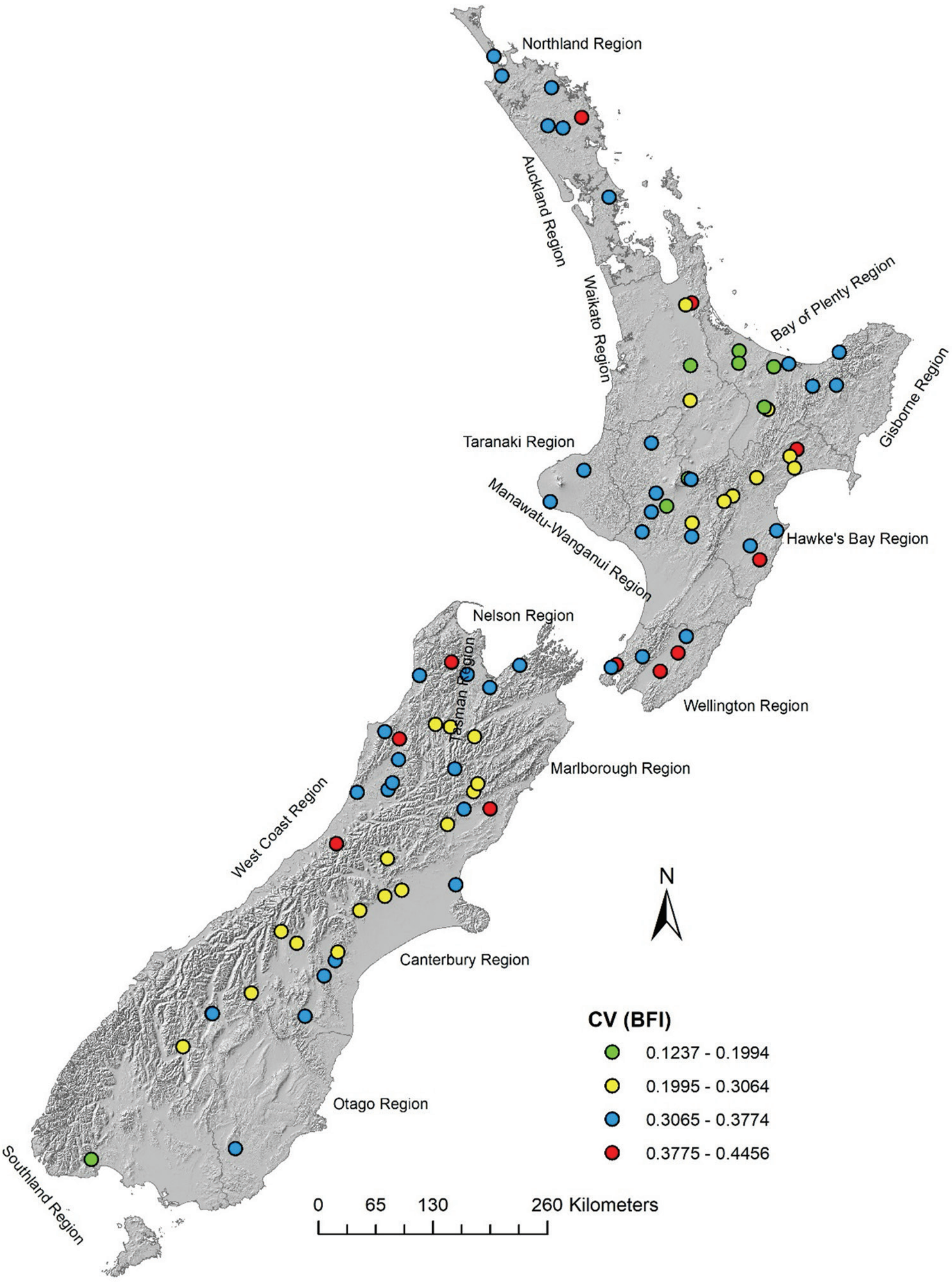

Figure 4 – Coefficient of variation (CV) of BFI values at the 92 flow gauging sites.

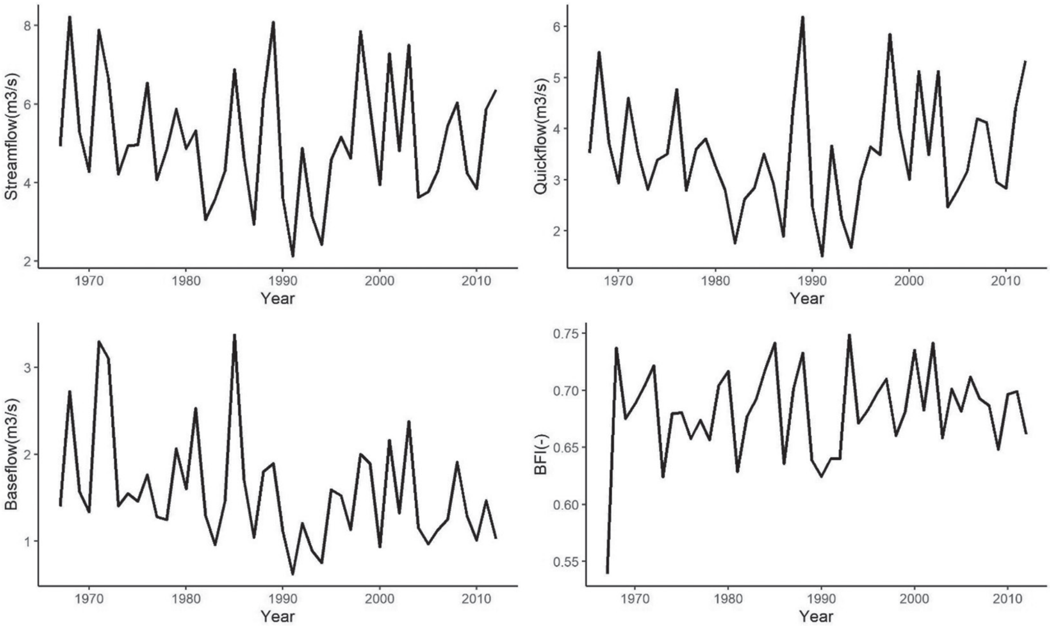

Figure 5 – Time series of annual mean values of streamflow, quickflow, baseflow and BFI at Waiharakeke at Willowbank (Site No. 3819), North Island.

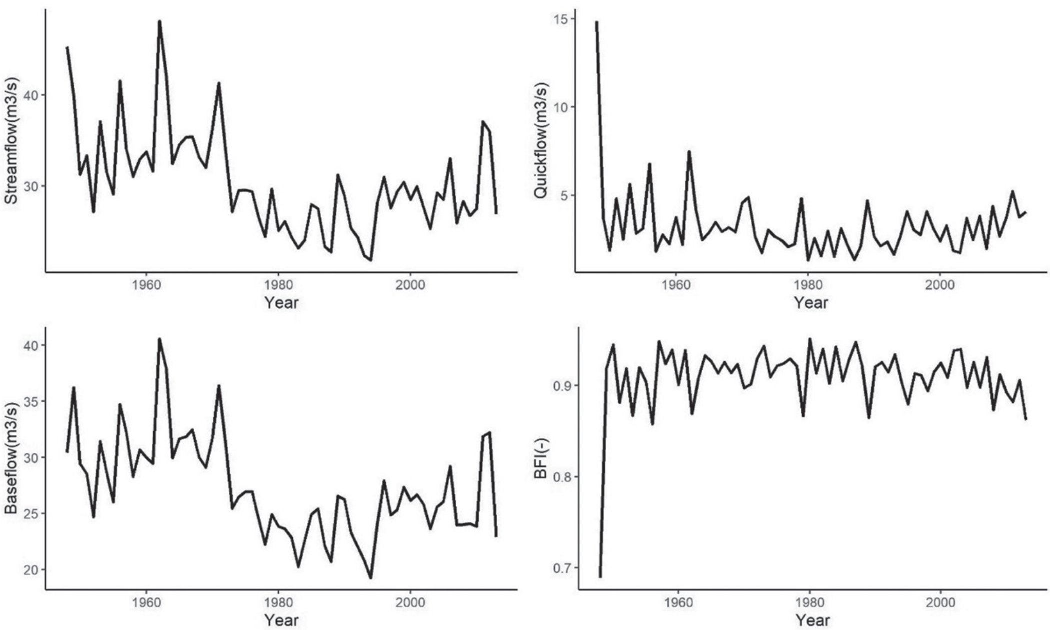

Figure 6 – Time series of annual mean values of streamflow, quickflow, baseflow and BFI at Tarawera at Awakaponga (Site No. 15302), North Island.

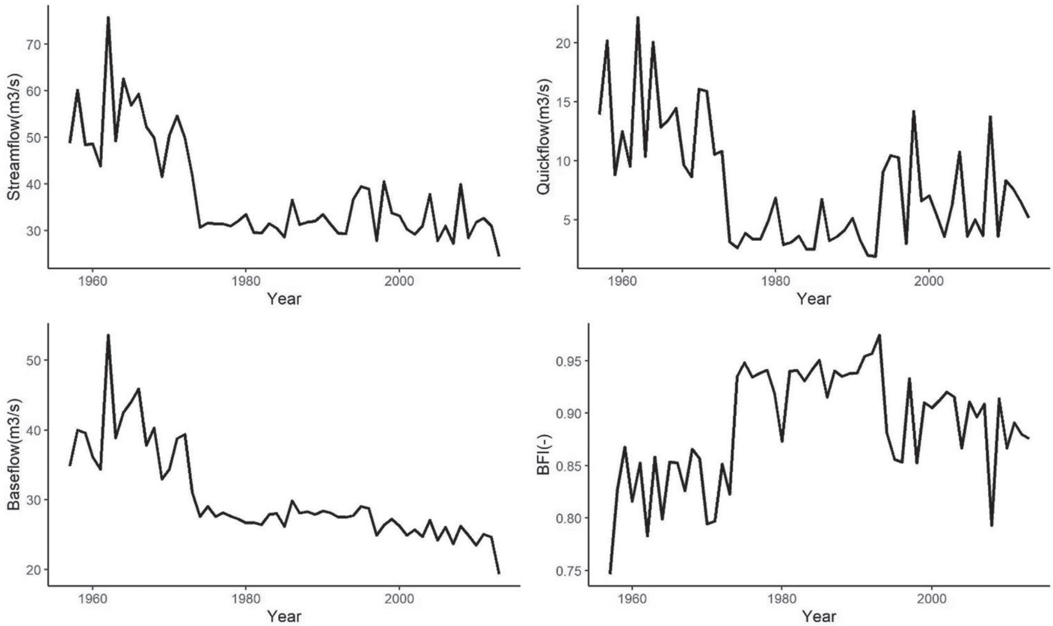

Figure 7 – Time series of annual mean values of streamflow, quickflow, baseflow and BFI at Tongariro at Turangi (Site No.1043459), North Island.

located adjacent to the Te Anau catchment, provides a reasonably accurate temporal record of rainfalls that correlate well with Te Anau inflows. However, the correlation is poor for low rainfalls as evidenced in the interval 1998–2020 in Figure 10. These overall findings are consistent with those of McKerchar and Henderson (2003).

Discussion

We have compiled a benchmark suite of long, reliable flow records from 92 natural or near-natural New Zealand basins. We have examined spatial and temporal variation in annual mean values of BFI and temporal variation in annual mean values of streamflow, quickflow and baseflow.

Mean annual BFI values vary spatially from 0.27 to 0.86 with an average of 0.57, indicating that some percentage of long-term streamflow is contributed from groundwater and other delayed sources. The main influence on the spatial variation in high and low BFI values is geological, as found previously by Singh *et al.* (2019).

No significant and sustained trend was found annual mean streamflow, quickflow, baseflow and BFI at any of the 92 sites comprising the benchmark suite. Where trends were detected at sites in the original data set of 482 catchments (i.e., not the benchmark suite), they could be ascribed to human influences such as streamflow additions or abstractions, forest or scrub planting or removal, wetland drainage, land use changes and urbanisation. This finding strongly suggests that where trends are found in a streamflow record, or indeed in any of the quickflow, baseflow or BFI components, the possibility of human cause should be carefully investigated. A further useful check is to examine the streamflow records of similar nearby sites and nearby rainfall sites for parallel trends.

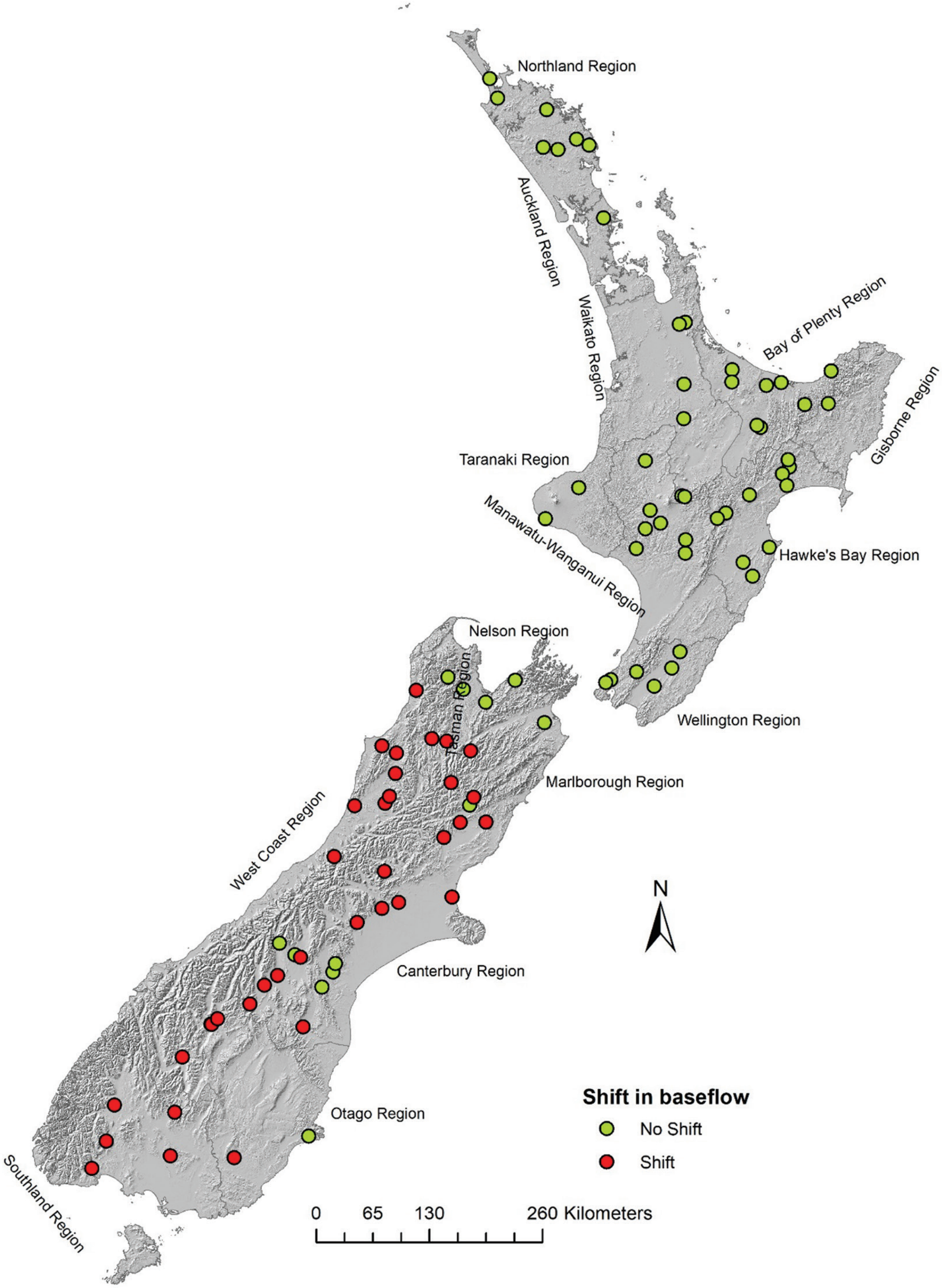

Figure 8 – Sites exhibiting shifts in annual mean baseflow values in South Island, New Zealand.

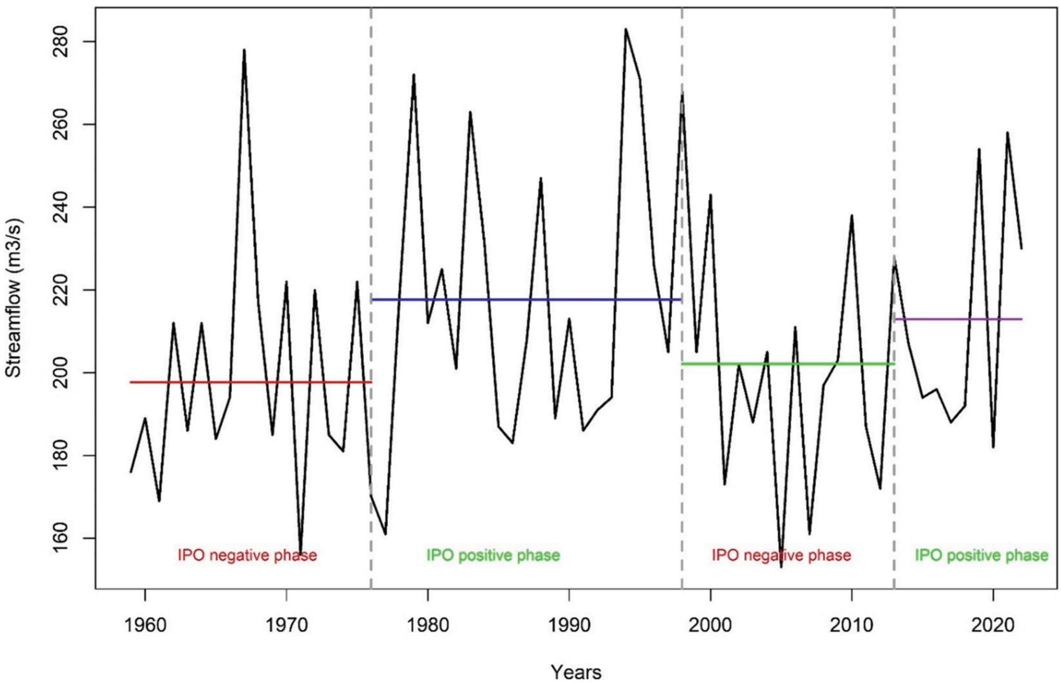

Figure 9 – Time series of annual mean values of streamflow recorded at Rakaia at Gorge (Site No. 68502), South Island. Horizontal lines represent mean values for IPO phases.

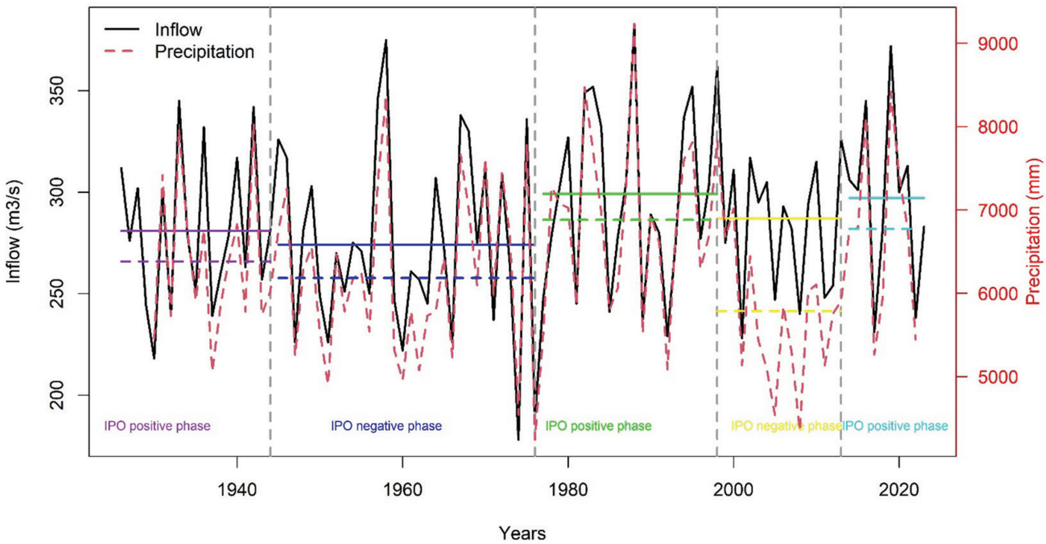

Figure 10 – Lake Te Anau inflows and Milford Sound rainfall (both in the South Island) along with IPO phases. Horizontal lines represent mean values for IPO phases.

No significant or sustained shifts in annual mean BFI values were found for any of the 92 sites. However, clear shifts were detected both visually and by statistical testing in streamflow, quickflow and baseflow at most sites in the South Island except for in the north and, in places, east. Timing of shifts (up and down) corresponds to shifts in phase of the IPO and matches corresponding shifts in mean annual rainfall. These findings underpin the usefulness of visual checking of streamflow records for the occurrence of shifts.

Given the above, our approach can provide a diagnostic tool, at least at a reconnaissance level at a site to see if occurrence of shifts in, and the BFI value for, a site record occurs in areas of the country where shifts are prevalent. Also, there is a need to check any trends present for causation and where shifts match the timing of phases of the IPO.

The most recent report from the Intergovernmental Panel on Climate Change (Bodeker *et al.*, 2022) has two key findings relevant to this study concerning the likely effects of anthropogenic activity on climate change. The first key finding is that future effects of the ENSO cycle on New Zealand climate are hard to predict but are not expected to change significantly this century, while the future of trends in the SAM and the location of the mid-latitude jet stream depend upon the ozone hole recovery rate and effectiveness of greenhouse gas mitigation. As regards ENSO, characterised by the Southern Oscillation Index, we found that La Niña and El Niño episodes affect mean flow, quickflow, baseflow and BFI seasonally, but no trends were found in annual mean values. Baseflows are particularly affected during La Niña episodes, being generally lower in the southwest and higher in the northeast of the country. Overall responses to La Niña and El Niño vary widely throughout New Zealand and differ significantly between rivers. These findings support earlier observations made by Mosley (2006). Conclusions about the future behaviour of the IPO are rather uncertain. However, there is medium confidence that a wetter and high frequency IPO is expected under global warning which in turn will affect the frequencies of El Niño and La Niña events. The second key finding of the IPCC report is that annual rainfall patterns (and streamflow) are expected to change, with increases in the west and south and less rainfall and flow in the east and north. The strongest harbinger of climate change in New Zealand rivers is forecast to be an increase in mean winter flow beginning at about 2050 or later under sustained anthropogenic forcing. In general, mean autumn and spring stream flows are expected to increase in the west and south and decrease in the north and east. During summer rivers with decreasing flows are likely to outnumber those with increasing flows (Collins, 2021). Of most importance for this study, the greatest impact of anthropogenic influences is likely to be experienced first in changes in extremes rather than in means. The implication from the key finding is that only small spatial and temporal changes in the BFI and baseflow are to be expected by the end of this century. Moreover, it is worth noting that while there is agreement in projections for temperature change, there is more limited model agreement for rainfall changes in Australasia as a whole (Bodeker *et al.*, 2022). Judging from progress to date this issue should be resolved in less than a decade.

We have found that shifts have occurred in baseflow and streamflow but not in BFI (their ratio) and the timing of shifts or their temporal variability matches phase changes in IPO. However, we do not understand the reason for the spatial variability of sites with shifts. Further meteorological investigation is needed to resolve this question.

There remains the important question as to what implications our findings have for understanding and practical application to water resource planning and management in general in New Zealand. Knowledge of the spatial variation of mean annual BFI values and the absence of temporal trends and shifts in these annual values in natural or near-natural basins, coupled with the likelihood of only small changes in these values by, say, the year 2100, is extremely useful for practitioners. Our findings apply particularly to the management of streamflow abstraction, assessing impacts of agricultural activity on surface and groundwater quality and in the preservation of aquatic ecosystems. The lack a of trend in annual mean streamflow, quickflow and baseflow values is an important result for the management of extremes. As well, knowledge of where shifts in these flows might occur along with possible estimates of their size and deviation as they correspond with changes in phase of the IPO should be very valuable in flow forecasting. Finally, it is of the first importance to observe that our findings apply only to annual mean values and not to seasonal values where marked trends have been observed by Queen *et al.* (2023) and which will very probably be significantly affected by the impact of anthropogenic activity or climate change.

Conclusions

New Zealand BFI values for natural or near-natural catchments vary spatially from 0.27 to 0.86 with an average 0.57. The highest values occur in rivers of the Central Volcanic Plateau of the North Island and in the central Southern Alps of the South Island where, because of the geology, water storage potential is high. Low values occur in the north and southeast of the North Island and in the north and east of the South Island, which are all areas having low permeability. No significant and persistent trend was detected in annual mean streamflow, quickflow, baseflow and BFI values at any of the benchmark suite of 92 sites. Where trends were detected at other sites (within the 482 originally examined sites) these could be ascribed to human influences on streamflow thus highlighting the importance of checking for such influences when examining streamflow records. No significant or persistent shifts in annual mean BFI values were found. Shifts were, however, detected in streamflow, quickflow and baseflow at many South Island sites except the upper northern and eastern region. The reason for this spatial pattern is unknown. The detected shifts correspond to changes in the phase of the IPO and are evidently driven by matching shifts in annual mean rainfall values. The occurrence of shifts may yield a positive result for trend when applying statistical testing. These can be resolved by visual examination of streamflow records. Likely effects of climate change on BFI values are expected at this stage to be small by 2100, in contrast to impacts on extremes of streamflow and seasonal mean values, which are forecast to be significant. Finally, our findings apply to annual mean values of flows in a suite of natural or near-natural basins and provide useful key background fact.

References

Ballarin, A.S.; Oliveira, P.T.S.; Marchezepe, B.K.; Godoi, R.F.; Campos, A.M.; Campos, F.S.; Almagro, A.; Meira Neto, A.A. 2022. The impact of an open water balance assumption on understanding the factors controlling the long-term streamflow components. *Water Resources Research 58(10)*, e2022WR032413. https://doi.org/10.1029/2022WR032413

Beck, H.E.; van Dijk, A.I.J.M.; Miralles, D.G.; de Jeu, R.A.M.; Bruijnzeel, L.A.; McVicar, T.R.; Schellekens, J. 2013. Global patterns in base flow index and recession based on streamflow observations from 3394 catchments. *Water Resources Research 49*: 7843–7863. https://doi.org/10.1002/2013WR013918

Birsan, M.V.; Molnar, P.; Burlando, P.; Pfaundler, M. 2005. Streamflow trends in Switzerland. *Journal of Hydrology 314*(1-4): 312–329. https://doi.org/10.1016/j.jhydrol.2005.06.008

Bodenhofer, U.; Kothmeier, A.; Hochreiter, S. 2011. APCluster: an R package for affinity propagation clustering. *Bioinformatics 27*(17): 2463–2464. https://doi.org/10.1093/bioinformatics/btr406

Booker, D.J.; Woods, R.A. 2014. Comparing and combining physically-based and empirically-based approaches for estimating the hydrology of ungauged catchments. *Journal of Hydrology 508*: 227–239. https://doi.org/10.1016/j.jhydrol.2013.11.007

Bosch, D.D.; Arnold, J.G.; Allen, P.; Lim, K.; Shik, Y. 2017. Temporal variations in baseflow for the Little River Experimental Watershed in South Georgia, USA. *Journal of Hydrology: Regional Studies 10*: 110–121. https://doi.org/10.1016/j.ejrh.2017.02.002

Bodeker, G.; Cullen, N.; Katurji, M.; McDonald, A.; Morgenstern, O.; Noone D.; Renwick, J.; Revell, L.; Tait, A. 2022. Aotearoa New Zealand climate change projections guidance: Interpreting the latest IPCC WG1 report finding. Prepared for Ministry for the Environment. Report Number CR 501, 51p.

Brutsaert, W.; Nieber, J.L. 1977. Regionalized drought flow hydrographs from a mature glaciated plateau. *Water Resources Research 13*: 637–643. https://doi.org/10.1029/WR013i003p00637

Burn, D.H. 2008. Climatic influences on streamflow timing in the headwaters of the Mackenzie River Basin. *Journal of Hydrology 352*(1-2): 225–238. https://doi.org/10.1016/j.jhydrol.2008.01.019

Carlisle, D.; Wolock, D.M.; Konrad, C.P.; McCabe, G.J.; Eng, K.; Grantham, T.E.; Mahler, B. 2019. Flow modification in the Nation's streams and rivers. *US Geological Survey Circular 1461*. 75p. https://doi.org/10.3133/cir1461

Clausen B.; Pearson, C.P. 1995. Regional frequency analysis of annual maximum streamflow drought. *Journal of Hydrology 173*: 111–130. https://doi.org/10.1016/0022-1694(95)02713-Y

Collins, D.B. 2021. Hydrological sentinels and the relative emergence of climate change signals in New Zealand river flows. *Hydrological Sciences Journal 66*(15): 2146–2154. https://doi.org/10.1080/02626667.2021.1987439

Delleur, J.W. 1999. *The Handbook of Groundwater Engineering*. Boca Raton, Florida, USA, CRC Press.

Dixon, H.; Lawler, D.M.; Shamseldin, A.Y. 2006. Streamflow trends in western Britain. *Geophysical Research Letters 33*(19). https://doi.org/10.1029/2006GL027325

Dons, A. 1986. The effect of large-scale afforestation on Tarawera river flows. *Journal of Hydrology (New Zealand) 25*(2): 61-73. https://www.jstor.org/stable/43944576

Farquharson, F.; Beran, M.; Bromley, J.; Gustard, A.; Houghton-Carr, H.; Rees, G.; Sutcliffe, J.; Young, A. 2015. Water Resources Security. In: Rodda, J.C.; Robinson, M. (Eds) *Progress in Modern Hydrology: Past, Present and Future.* John Wiley & Sons, Ltd, Chichester, UK.

Frey, B. J.; Dueck, D. 2007. Clustering by passing messages between data points. *Science 315*(5814): 972–976. https://doi.org/10.1126/science.1136800

Heppell, C.M.; Binley, A.; Trimmer, M.; Darch, T.; Jones, A.; Malone, E.; Collins, A.L.; Johnes, P.J.; Freer, J.E.; Lloyd, C.E.M. 2017. Hydrological controls on DOC: nitrate resource stoichiometry in a lowland, agricultural catchment, southern UK. *Hydrology and Earth Systems Science Discussions 21*: 4785–4802. https://doi.org/10.5194/hess-21-4785-2017.

Henderson, R.D.; Woods, R.A.; Schmidt, J. 2004. A new low flow model for New Zealand-part 3. Paper presented at the New Zealand Hydrological Society conference, Queenstown, November 2004.

Hutchinson, P.D. 1983. Calculation of a base flow index for New Zealand catchments. Report WS818, Ministry of Works and Development, Christchurch, New Zealand, 18 pp.

Jiang, N.; Griffiths, G.; Lorrey, A. 2013. Influence of large-scale climate modes on daily synoptic weather types over New Zealand. *International Journal of Climatology 33*(2): 499–519. https://doi.org/10.1002/joc.3443

Jowett, I.G.; Duncan, M.J., 1990. Flow variability in New Zealand rivers and its relationship to in-stream habitat and biota. *New Zealand Journal of Marine and Freshwater Research 24*(3): 305–317. https://doi.org/10.1080/00288330.1990.9516427

Kendall, M.G. 1975. Rank correlation *methods*. 4th ed. Charles Griffin, 202 pp.

Ladson, A.R.; Brown, R.; Neal, B.; Nathan, R. 2013. A standard approach to baseflow separation using the Lyne and Hollick filter. *Australiasian Journal of Water Resources 17*(1): 25–34, https://doi.org/10.7158/W12-028.2013.17.1

Longobardi A.; Villani P. 2008. Baseflow index regionalization analysis in a mediterranean area and data scarcity context: Role of the catchment permeability index. *Journal of Hydrology 355*: 63–75. https://doi.org/10.1016/j.jhydrol.2008.03.011

Lott, D.A.; Stewart, M.T. 2016. Base flow separation: a comparison of analytical and mass balance methods. *Journal of Hydrology 535*: 525–533, http://doi.org/10.1016/j.jhydrol.2016.01.063.

Lyne, V.; Hollick, M. 1979. Stochastic time-variable rainfall-runoff modelling. Proceedings of the Hydrology and Water Resources Symposium, Perth, 10-12 September. Institution of Engineers National Conference Publication, No. 79/10, pp. 89-92.

McKerchar, A.I.; Henderson, R.D. 2003. Shifts in flood and low-flow regimes in New Zealand due to interdecadal climate variations. *Hydrological Sciences Journal 48*(4): 637–654. https://doi.org/10.1623/hysj.48.4.637.51412

Mallick, J.; Talukdar, S.; Alsubih, M.; Salam, R.; Ahmed, M.; Kahla, N.B.; Shamimuzzaman, M. 2021. Analysing the trend of rainfall in Asir region of Saudi Arabia using the family of Mann-Kendall tests, innovative trend analysis, and detrended fluctuation analysis. *Theoretical and Applied Climatology 143*: 823–841. https://doi.org/10.1007/s00704-020-03448-1

Mann, H. B. 1945. Nonparametric Tests Against Trend. *Econometrica 13*(3): 245–259.

Matteson, D.S.; James, N.A. 2014. A nonparametric approach for multiple change point analysis of multivariate data. *Journal of the American Statistical Association 109*(505): 334–345. https://doi.org/10.1080/01621459.2013.849605

McMillan, H.K.; Booker, D.J.; Cattoën, C. 2016. Validation of a national hydrological model. *Journal of Hydrology 541*: 800–815. https://doi.org/10.1016/j.jhydrol.2016.07.043

Mosley, M.P. 1981. Delimitation of New Zealand hydrologic regions. *Journal of Hydrology 49*: 173–192. https://doi.org/10.1016/0022-1694(81)90211-0

Mosley, M.P. 2006. Regional differences in the effects of El Nino and La Nina on low flows and floods. *Hydrological Sciences Journal 45*(2): 249–267. https://doi.org/10.1080/02626660009492323

Mullan, A.B. 1995. On the linearity and stability of Southern Oscillation-climate relationships for New Zealand. *International Journal of Climatology 15*(12): 1365–1386. https://doi.org/10.1002/joc.3370151205

Nathan, R.J.; McMahon, T.A. 1990. Evaluation of automated techniques for base-flow and recession analyses. *Water Resources Research 26*: 1465–1473. https://doi.org/10.1029/WR026i007p01465

Newsome, P.F.J.; Wilde, R.H.; Willoughby, E.J. 2000. Land Resource Information System spatial data layers. Landcare Research, Technical report, Palmerston North, New Zealand, 74 p.

Partington, D.; Brunner, P.; Simmons, C.T.; Werner, A.D.; Therrien, R.; Maier, H.R.; Dandy, G.C. 2012. Evaluation of outputs from automated baseflow separation methods against simulated baseflow from a physically based, surface water – groundwater flow model. *Journal of Hydrology 458-459*: 28-39. https://doi.org/10.1016/j.jhydrol.2012.06.029

Queen, L.E.; Dean, S.; Stone, D.; Henderson, R.; Renwick, J. 2023. Spatiotemporal Trends in Near-Natural New Zealand River Flow. *Journal of Hydrometeorology 24*(2): 241–255. https://doi.org/10.1175/JHM-D-22-0037.1

Razali, N.M.; Wah, Y. B. 2011. Power comparisons of Shapiro-Wilk, Kolmogorov-Smirnov, Lilliefors and Anderson-Darling tests. *Journal of Statistical Modeling and Analytics 2*(1): 21–33.

Salinger, M.J.; Renwick, J.A.; Mullan, A.B. 2001. Interdecadal Pacific Oscillation and South Pacific climate. *International Journal of Climatology 21*(14): 1705–1721. https://doi.org/10.1002/joc.691

Santhi, C.;Allen, P.M.; Muttiah, R.S.; Arnold, J.G.; Tuppad, P. 2008. Regional estimation of base flow for the conterminous United States by hydrologic landscape regions. *Journal of Hydrology 351*(1–2): 139–153. https://doi.org/10.1016/j.jhydrol.2007.12.018

Shapiro, S.S.; Wilk, M.B. 1965. An analysis of variance test for normality (complete samples). *Biometrika 52*(3/4): 591–611. https://doi.org/10.2307/2333709

Smakhtin, V. U. 2001. Low flow hydrology: A review. *Journal of Hydrology 240*: 147–186. https://doi.org/10.1016/S0022-1694(00)00340-1

Singh, S.K.; Stenger, R. 2019. Indirect Methods to Elucidate Water Flows and Contaminant Transfer Pathways through Meso-scale Catchments – a Review. *Environmental Processes 5:* 683–706. https://doi.org/10.1007/s40710-018-0331-6

Singh, S.K.; Pahlow, M.; Booker, D.J.; Shankar, U.; Chamorro, A. 2019. Towards baseflow index characterisation at national scale in New Zealand. *Journal of Hydrology 568*: 646–657. https://doi.org/10.1016/j.jhydrol.2018.11.025

Tait, A.; Henderson, R.; Turner, R.; Zheng, X. 2006. Thin plate smoothing spline interpolation of daily rainfall for New Zealand using a climatological rainfall surface. *International Journal of Climatology 26*(14): 2097–2115. https://doi.org/10.1002/joc.1350

Tallaksen, L.M. 1995. A review of baseflow recession analysis. Journal of Hydrology 165: 349–370. https://doi.org/10.1016/0022-1694(94)02540-R

Zhang, Y.; Wallace, J.M.; Battisti, D.S. 1997. ENSO-like interdecadal variability: 1900–93. *Journal of Climate 10*(5): 1004–1020. https://doi.org/10.1175/1520-0442(1997)010%3C1004:ELIV%3E2.0.CO;2

Zhang, Y.; Chiew, F.H.S.; Li, M..; Post, D. 2018. Predicting runoff signatures using regression and hydrological modelling approaches. *Water Resources Research 54*(10): 7859–7878. https://doi.org/10.1029/2018WR023325

Manuscript received 22 February 2025; accepted for publication 20 August 2025