Estimating mean flow of New Zealand rivers

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Abstract
Four simple models of mean annual runoff throughout New Zealand were evaluated, predominantly based on precipitation information and estimated evapotranspiration. Model results were compared to measurements and synthesised measurements of catchment runoff. Three models subtract an estimate of annual actual evapotranspiration from a precipitation surface. The first model assumes that annual actual evapotranspiration is a constant throughout New Zealand. The second model estimates annual actual evapotranspiration using a simple empirical model, which depends only on annual precipitation and annual potential evapotranspiration. The third model estimates annual actual evapotranspiration according to the ratios of potential evapotranspiration with annual precipitation, and a single water balance parameter which is estimated by independent calibration. The fourth model applies a regional bias correction to the results of the third model.

The models are assessed by making estimates of runoff at model cells throughout New Zealand, and then averaging the cell runoff over the catchment boundary upstream of each river flow recording site. The catchment estimates of runoff are then compared with measured and synthesised runoff for each catchment, which have been adjusted to a common time period, in this case 1960-2001. The third model, which uses the ratios of potential evapotranspiration and precipitation, is found to give the greatest correlation with measured river flow. In terms of area, 87% of the total tested catchment area had modelled runoff within ±25% of the measured runoff when using the third model. Regional bias correction (fourth model) further enhances this surface, which can then be used to estimate runoff for un-gauged catchments in New Zealand.

Introduction
An understanding of the water balance of New Zealand is essential for the continued efficient utilisation and planning of water resources on a national scale and for making water resource estimates for areas where no flow measurements are available. Previous work has recognised this need, with many estimates made for particular catchments (e.g., Scarf, 1972; Toebes, 1972b; Aitcheson-Earl et al., 2006). However, only Toebes (1972a) and Woods and Henderson (2003) have attempted to estimate the water balance for all New Zealand. Since the work of Toebes (1972a), New Zealand has seen the rapid expansion of water level and flow monitoring sites on a number of rivers, lakes and estuaries (Walter, 2000; Keane, 2001). Despite this expansion in flow monitoring, there are still many streams and rivers where river flow is...
unrecorded, so that estimates of flow must be made, for example, by interpolation from nearby similar catchments, or through the application of advanced hydrological models, e.g., TOPNET (Bandaragoda et al., 2004; Woods and Henderson, 2003) or SHETRAN (Ewen et al., 2000). An alternate approach to this problem, taken here, is the estimation of river flow through the application of the water balance equation, where the result is an average annual runoff map for all of New Zealand.

The mean flow provides a first-order estimate of the total water resource, and thus is useful for assessing feasibility of resource developments. However, it is rarely used on its own, and engineering design frequently requires estimates of statistics for extreme flows. Nationwide methods are available for estimating the frequency of floods (McKerchar and Pearson, 1989, 1990) and low flows (Hutchinson, 1990; Pearson, 1995; Henderson et al., 2003), but similar methods are not available for other hydrological statistics. This paper on mean annual runoff is the first of a series which will address: 1) extending monthly flow series back to 1945, 2) estimating seasonal flow regimes throughout New Zealand, 3) revising low flow and flood estimation, and 4) estimating flow duration curves for ungauged streams.

**Methods**

The water balance of a catchment can be summarised by the basic water balance equation, with inflow equal to outflow plus a gain or loss due to storage:

\[ P = AE + Q + \Delta S \]  

In this equation, \( P \) is the precipitation, \( AE \) is the actual evapotranspiration, \( Q \) is the runoff and \( \Delta S \) is the change in storage in the seasonal snow, glaciers, channels and lakes, and biological, soil moisture and groundwater storage. However, when the water balance is considered over long time periods (i.e., tens of years or more), changes in catchment water storage can be considered to be negligible. An exception is those catchments where glacier wasting provides a significant fraction of runoff (Chinn, 2001). The largest relative contribution of glacier wasting is for the Waitaki catchment, where this could account for approximately 2\% of runoff, which is small in the present context. However, this simplification can only be used when considering a whole number of years, as actual evapotranspiration has strong diurnal and seasonal fluctuations. Consequently, omitting \( \Delta S \) and rearranging the terms now provides the following simple equation for runoff:

\[ Q = P - AE \]  

This approach to calculating runoff in New Zealand is very sensitive to the precipitation information, especially as the precipitation greatly exceeds actual evapotranspiration in many parts of New Zealand and there are many areas with steep precipitation gradients. Fortunately, the estimation of precipitation in New Zealand has been the focus of many previous studies (e.g., Tomlinson, 1976; Salinger, 1980; Wrett et al., 1996; Thompson et al., 1997; Henderson and Thompson, 1999), culminating with the recently published rainfall estimates for New Zealand (Tait and Turner, 2005; Tait et al., 2006). Given the practical difficulties of measuring precipitation in high altitude environments, there is a continuing need to refine precipitation surfaces; nonetheless the surface from Tait et al. (2006) is adequate for this application. Therefore, this study will focus on the estimation of the evapotranspiration term (actual evapotranspiration – \( AE \)) rather than the well studied and documented precipitation.

In this study actual evapotranspiration has been estimated in three different ways to
assess the importance of this term to runoff estimation in New Zealand and highlight any shortcomings of simple assumptions. The first model (M1) uses a constant value of 700 mm/a for the actual evapotranspiration. This value has previously been used to approximate actual evapotranspiration in catchments with more than 800 mm/a of precipitation, where measurements of actual evapotranspiration were unavailable (McKerchar and Pearson, 1997). The second model (M2) calculates actual evapotranspiration as the minimum of the precipitation or the potential evapotranspiration, to ensure that physically realistic runoff estimates were calculated in areas of low rainfall. This method is used because in many dry parts of New Zealand the potential evapotranspiration is high, but because of the lack of precipitation, the potential evapotranspiration demand is seldom satisfied. The third model (M3) calculates actual evapotranspiration according to the ratios of potential evapotranspiration and annual precipitation, and a single parameter $w$ (Zhang et al., 2004):

$$AE = PET \left( 1 + \frac{P}{PET} \left[ 1 + \left( \frac{P}{PET} \right)^w \right]^{-\frac{1}{w}} \right)$$

where $PET$ is potential evapotranspiration.

Zhang et al. (2004) provide a physically-based argument which leads to this particular functional form. Numerous alternative empirical equations have been developed (Sankarasubramanian and Vogel, 2002), as well as other physically-motivated equations (Woods, 2003). The water balance parameter $w$ was least-squares fitted to values of actual and potential evapotranspiration taken from a soil water balance model (Porteous et al., 1994) output for eighteen locations covering a very wide range of climate conditions throughout New Zealand, to give a value of 4.35 (Fig. 1). This compares with a range

![Figure 1](image-url)
of global values of $w$ between 1.7 and 5.0 (Zhang et al., 2004). The observed scatter of the eighteen data points are attributed to differences in seasonality and the intermittency of precipitation, which are not captured by an annual average approach. This estimation of the $w$ parameter is independent of the series of models used in this paper for calculating mean annual runoff.

Using these three methods for estimating actual evapotranspiration and one national map for precipitation, the average annual runoff has been modelled for all of New Zealand for the period 1960 to 2001 inclusive. The modelled runoff has then been compared with measured runoff by averaging the cell runoff over the catchment boundary upstream of each river flow recording site for 813 sites.

**Data description**

Data used in this study were obtained from two main sources: the National Climate Database and the Water Resources Archive. The National Climate Database stores the majority of New Zealand’s climate data and is maintained by NIWA in Wellington, New Zealand. The Water Resources Archive stores the majority of the stream flow, soil moisture and water level data and is maintained by NIWA in Christchurch, New Zealand. Additional streamflow data was obtained from regional data archives.

**Precipitation**

Daily precipitation data from over 500 locations were extracted from the National Climate Database for the period 1960 to 2001. Daily precipitation surfaces were generated from these data using a second-order derivative trivariate thin plate smoothing spline to interpolate points across a regular 0.05° latitude/longitude grid (Tait et al., 2006). The interpolation scheme uses latitude and longitude, and a mean annual precipitation surface derived from expert-guided contouring of data from the period 1951-80 (New Zealand Meteorological Service, 1985) as the third independent variable. The

**Figure 2**

a) Annual average precipitation (mm/a) from 1960 to 2001 and

b) Penman potential evapotranspiration (mm/a) for New Zealand.
interpolated precipitation surfaces (as reported in Tait et al., 2006) were validated by comparison with measured runoff from 345 catchments. Use of the 1951-80 mean annual precipitation surface in the interpolation scheme showed a significant improvement when compared with using elevation as the third independent variable. While some systematic errors have been noted to exist in the precipitation surface, it is currently the best national data set available for this work. The daily precipitation surfaces were then used to generate an average annual precipitation surface for the period 1960 to 2001 inclusive. Figure 2a opposite shows the resulting average annual precipitation for New Zealand. Thompson et al. (1997) and Tait et al. (2006) used river flow data to validate average annual rainfall for the southern region of the North

![Figure 3](image3.png)

**Figure 3** – Modelled runoff expressed as a percentage of measured and synthesised runoff for each catchment for all four models M1, M2, M3 and M4. Nested catchments are shown by plotting the smaller catchments on top of the larger catchments.

![Figure 8](image8.png)

**Figure 8** – The M4 runoff surface for New Zealand in mm/a. This is the M3 model output with a bias correction surface applied. The presented raster has a resolution of 500 m × 500 m.
Island of New Zealand and for all of New Zealand respectively.

**Potential evapotranspiration**

In a similar analysis to that described above for precipitation, daily Penman potential evapotranspiration (Penman, 1948) data from 70 climate stations located throughout New Zealand were obtained from the National Climate Database for the period 1972 to 2003. Where possible, the Penman potential evapotranspiration value had been calculated using standard meteorological data, but for some stations without all the required meteorological observations, an estimate of the Penman potential evapotranspiration value was made using either pan evaporation or Priestley-Taylor potential evapotranspiration with an applied correction factor (Tait and Woods, accepted). Daily potential evapotranspiration surfaces were then generated for the years 1972 to 2003 using a trivariate (latitude, longitude, and elevation) thin plate spline minimizing the mean error through generalised cross-validation. When the interpolated daily potential evapotranspiration is compared with the actual measured daily potential evapotranspiration and compared across seasons, the average root mean square error (RMSE) varies between around 1 mm in the summer months to around 0.4 mm in the winter (Tait and Woods, accepted). Figure 2b (see page 98) shows the average annual potential evapotranspiration, generated from the daily surfaces for the period 1972-2003, for New Zealand.

For this paper, we required Penman potential evapotranspiration for the same time period as the precipitation data (i.e., 1960-2001). We assume that over long time periods, the Penman potential evapotranspiration at a location does not differ significantly. Spatial analysis of annually averaged Penman potential evapotranspiration for each year over the period 1972 to 2003 showed significant regional and interannual variability. However, when potential evapotranspiration was averaged over long time periods, i.e., 1972 to 2003, and compared with averages over the 16 year periods 1972 to 1987 and 1987 to 2003, only subtle, insignificant differences were noted, with 95% of New Zealand having 16 year average values of potential evapotranspiration within ± 10% of the long-term mean value for that location. Further analysis of the Penman potential evapotranspiration data at several stations with long records also showed that the decadal average of potential evapotranspiration did not vary significantly at one location over long time periods, or show distinct trends before or after 1972 (Table 1).

Both analyses of the potential evapotranspiration data showed that there was significant variability in the potential evapotranspiration data at both local spatial scales and daily temporal scales, but when averaged over long time periods the values at a point fluctuated about a stable mean. Therefore, the mean value of Penman potential evapotranspiration at a given location for the period 1972 to 2003 was used as an estimate for potential evapotranspiration at that location for the period 1960 to 2001.

**Runoff**

We require measured mean annual runoff for the period 1960 to 2001 to validate the modelled runoff surface for the same period. Unfortunately, such complete data is not available for every river, so we have synthesised flow values to fill periods with missing data. Missing flow data in the period 1960 to 2001 were synthesised as follows. Monthly flow data was generated for 813 sites that had any monthly flow data available, for any time in the period 1960 to 2001. For each site, the measured flow data were automatically examined for missing values, which were filled, including extension at either end of the record where necessary, by regression of each record with all other sites having contemporaneous data (Woods et al.,
Table 1 – Long-term means of annually averaged Penman potential evapotranspiration (PET) at five
locations in New Zealand.

<table>
<thead>
<tr>
<th>Network Number</th>
<th>Latitude (dec.deg)</th>
<th>Longitude (dec.deg)</th>
<th>Period of record</th>
<th>Mean PET*</th>
<th>Std Deviation*</th>
<th>Mean PET (≤ 1972)</th>
<th>Mean PET (≥ 1972)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ohakea Aero</td>
<td>-40.201</td>
<td>175.373</td>
<td>1960-1990</td>
<td>1041.5</td>
<td>35.4</td>
<td>1034.8</td>
<td>1043.6</td>
</tr>
<tr>
<td>Kelburn</td>
<td>-41.286</td>
<td>174.767</td>
<td>1962-1995</td>
<td>880.6</td>
<td>50.6</td>
<td>886.8</td>
<td>880.7</td>
</tr>
<tr>
<td>Nelson Aero</td>
<td>-41.299</td>
<td>173.226</td>
<td>1960-1990</td>
<td>917.0#</td>
<td>50.6</td>
<td>917.3</td>
<td>923.1#</td>
</tr>
<tr>
<td>Christchurch Aero</td>
<td>-43.493</td>
<td>172.537</td>
<td>1960-2001</td>
<td>930.2</td>
<td>44.8</td>
<td>922.5</td>
<td>933.8</td>
</tr>
<tr>
<td>Invercargill Aero</td>
<td>-46.419</td>
<td>168.329</td>
<td>1960-1994</td>
<td>773.6</td>
<td>30.0</td>
<td>759.9</td>
<td>782.2</td>
</tr>
</tbody>
</table>

* Mean PET and standard deviation are calculated for Penman PET over the available record length at the respective locations. Standard deviation and mean are for annual values.
# Annual values for 1984 and 1985 have been removed from this data set due to spurious readings in these years.

In the present paper we refer to the filled data as synthesised measurements. For each of the sites a catchment boundary and area was generated from the River Environment Classification digital stream network (Snelder and Biggs, 2002). For each synthesised monthly flow a standard error was calculated, while for observed data the error was taken to be 3% (Woods et al., in prep.).

From the total of over 813 sites with some monthly data, the final analysis set was reduced to 524 suitable sites through the application of filters to remove unreliable or inappropriate data. The filters ensured that the catchment area from the River Environment Classification was within 10% of the published value in Walter (2000), that abstraction or diversion did not have a significant effect on mean flow and that very short measured records (less than 48 months in length) were excluded. Exceptions to the above rules were permitted if simulated natural flow data was available, e.g., for the major South Island hydroelectricity lakes, Lake Taupo inflows, and the Whanganui River. The resultant 524 sites with realistic monthly values and catchment areas were then averaged for each year, and an annual average runoff and standard error for the period 1960 to 2001 were calculated for each site.

Due to the rapid expansion of flow recording sites after 1972 (Keane, 2001) there was a concern that the synthesised flow data before 1972 would have intolerably large standard errors. An analysis of the distribution of the standard error data sets from 1960 to 2001 compared with those for the period 1972 to 2001 showed that the 1960 to 2001 data set had a higher mean standard error of 12% compared with 10% for the 1972 to 2001 dataset. Analysis of means using the Mann-Whitney U test (Neter et al., 1978) and Kolmogorov-Smirnov test (Neter et al., 1978) suggested that the means of the standard error of the two groups of data are marginally significantly different at the p<0.05 level. We consider that the additional length in the 1960 to 2001 dataset outweighs the small increase in the standard error in this data. A more detailed discussion of errors in synthesised flows is given in Woods et al. (in prep.).
Results and discussion

Three models (M1, M2, M3) used for estimating runoff in New Zealand have been compared to measurements and synthesised measurements of river flow data for the period 1960 to 2001 for the 524 flow sites and their associated catchments. The comparison has been done in relative terms, where the modelled runoff has been expressed as a percentage of the river runoff for that catchment. The 524 catchments have a total sum area of 342,650 km$^2$, greater than the total area for all of New Zealand, due to large catchments being nested within one another.

M1 results

The first model (M1), which used a constant value of 700 mm/a for actual evapotranspiration, shows reasonable agreement (within ±25%) with the measured and synthesised runoff over significant portions of the North Island, but did less well in the South Island (Fig. 3 – see page 99). A summary table of the areas which had anomalously high or low modelled runoff when expressed as a percentage of measured runoff can be seen in Table 2.

In terms of catchments, 284 (see histogram in Figure 4) of the 524 catchments, or 54%, had modelled runoff within ±25% of the measured runoff. However, in terms of area, approximately 205,000 km$^2$ of the 343,000 km$^2$, or 60% had modelled runoff within ±25% of the measured runoff. When measured and synthesised runoff is plotted against M1 modelled runoff (excluding negative modelled runoff values) on a log-log plot, the trend can be approximated by the power relationship, $y = 0.836 \times 1.006^x$ with an $R^2$ of 0.66. M1 tends to underestimate the runoff for areas with very low measured runoff and areas of very high measured runoff, with larger differences at the very highest runoff values (Fig. 4).

![Figure 4](image-url)
M2 results
The second model (M2), which used the minimum of precipitation or potential evapotranspiration as the actual evapotranspiration, shows reasonable agreement (within ±25%) with the measured and synthesised runoff over most of the North Island and is a significant improvement over M1 in the South Island (Fig. 3). A summary of the areas that had anomalously high or low modelled runoff when expressed as a percentage of measured runoff is given in Table 2.

In terms of catchments, 322 (see histogram in Figure 5) of the 524 catchments, or 61% had modelled runoff within ±25% of the measured runoff. However, in terms of area, approximately 276,000 km$^2$ of the 343,000 km$^2$, or 81%, had modelled runoff with ±25% of the measured runoff. When measured and synthesised runoff is plotted against M2 modelled runoff on a log-log plot, the trend can be approximated by the power relationship, $y = 0.7305 \times 1.0239^x$ with an $R^2$ of 0.83. Model M2, like M1, generally underestimates the runoff for areas with very low measured runoff and areas of very high measured runoff, with larger differences at the very highest runoff values (Fig. 5).

M3 results
The third model (M3), which used the Zhang et al. (2004) equation to calculate the actual evapotranspiration, shows reasonable agreement (within ±25%) with the measured and synthesised runoff over most of the North and South Island, with noticeable improvements over M2 (Fig. 3). A summary of the areas that had anomalously high or low modelled runoff when expressed as a percentage of measured runoff is given in Table 2.

In terms of catchments, 358 (see histogram in Figure 6) of the 524 catchments, or 68%, had modelled runoff within ±25% of the measured runoff. However, in terms of area approximately 297,000 km$^2$ of the 343,000 km$^2$, or 87% had modelled runoff

Figure 5 – Measured and synthesised runoff and M2 modelled runoff for each catchment on a log-log plot with a frequency histogram of modelled runoff expressed as a percentage of measured and synthesised runoff as an inset (top left).
with ±25% of the measured runoff. When measured and synthesised runoff is plotted against M3 modelled runoff on a log-log plot, the trend can be approximated by the power relationship, \( y = 2.274 x^{0.8703} \) with an \( R^2 \) of 0.87. M3 underestimates the runoff for areas with very high measured runoff, but is a significant improvement on M1 and M2 for the low precipitation areas (Fig. 6 and Table 2).

**Discussion**

When applying the water balance equation, \( Q = P - AE \), to the 524 study catchments, runoff is generally measured quite accurately, whereas both precipitation and actual evapotranspiration may have significant uncertainty, so that the water balance does not close. Below we examine the mismatches in water balance, discuss the likely causes, and propose a pragmatic approach to estimating mean runoff for ungauged New Zealand river catchments.

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**Table 2** – Summary of bias for regions for models M1, M2 and M3. Bias has been represented in the 5 categories shown in Figure 3.

<table>
<thead>
<tr>
<th>Region</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northland</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Northern Waikato</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Central Waikato</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Eastern Bay of Plenty</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Inland Hawkes Bay</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Southern Hawkes Bay</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Northern Manawatu</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Northern Tararua Range</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Coastal Wairarapa</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Central West Coast</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Isolated Nelson</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Northwest Nelson</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Coastal Marlborough</td>
<td>–</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Inland Marlborough</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Northern Canterbury</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Central Canterbury</td>
<td>–</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Southern Canterbury</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Coastal Otago</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Central Otago</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Northern Southland</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Southern Southland</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

Modelled runoff as % of measured runoff is:

- <50% = – –
- 51-75% = –
- 76-125% = –
- 126-150% = +
- >150% = + +

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**Figure 6** – Measured and synthesised runoff and M3 modelled runoff for each catchment on a log-log plot with a frequency histogram of modelled runoff expressed as a percentage of measured and synthesised runoff as an inset (top left).
While there are clear differences between the three models for the driest catchments of New Zealand, they all underestimate the runoff in parts of eastern Bay of Plenty, inland Hawkes Bay, northern Tararua Ranges, inland Marlborough, central West Coast, central Otago and northern Southland. Since most of these places have high precipitation, the problem is most likely to be in the precipitation surface. None of the three models are able to produce unbiased estimates of runoff for catchments with more than 4000 mm/a of runoff. This is a shortcoming of the precipitation estimate, and requires further research into the precipitation in these areas. All three models also overestimate runoff in the central and northern Waikato and northern Manawatu. These regions are generally drier and the problem could be the precipitation surface, the potential evapotranspiration surface, or the simplistic equations being used to estimate actual evapotranspiration. Other possibilities include erroneous river flow data or catchment boundaries.

The under estimation of runoff by M1 in the driest parts of New Zealand is to be expected. The M1 model is not applicable in the driest areas because the constant of 700 mm/a is too high, which leads to negative values of modelled runoff in these areas. M2 has similar problems in the driest areas, so that while it does not produce negative runoff values, the modelled runoff values are significantly lower than those measured. M3 does not have the same problem in the driest areas and tends to slightly overestimate the runoff from these regions. We conclude from this that methods M1 and M2 are not recommended for general use.

Some of the shortcomings of the models relate to the methods being used. All three models tested here are extremely simple and so should be expected to have only limited ability to explain the observations. The models do include the essential features of the water balance, that is, the competition between evapotranspiration and runoff processes, so they are expected to produce useful results. However, none of the models are able to account for between-catchment differences in climate seasonality and rainfall intermittency, or different soils, land use and land cover, topography and geology. This means that the models reported in this paper can not be reliably used to estimate the effects of potential future changes in any of those factors.

Despite these shortcomings, we do note an overall improvement in the runoff prediction as the models become more complex, with the M3 model showing better prediction of runoff for New Zealand than the M1 and M2 models (Table 3).

In reviewing the results of these three models (M1 to M3) it is clear that the three components of the water balance, precipitation, actual evapotranspiration and measured runoff, do not balance exactly. Maintaining our earlier assumption that storage changes are negligible over the 42-year averaging interval used here, the mismatch can be potentially attributed to uncertainty in each of these three parameters. However,

Table 3 – Summary statistics for the comparison of the four model outputs.

<table>
<thead>
<tr>
<th></th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of catchments within ±25% (n=524)</td>
<td>284</td>
<td>322</td>
<td>358</td>
<td>484</td>
</tr>
<tr>
<td>% of catchments within ±25%</td>
<td>54</td>
<td>61</td>
<td>68</td>
<td>92</td>
</tr>
<tr>
<td>Summed catchment areas (km²) within ±25%</td>
<td>204,690</td>
<td>276,167</td>
<td>297,377</td>
<td>320,920</td>
</tr>
<tr>
<td>% of total catchment areas within ±25%</td>
<td>60</td>
<td>81</td>
<td>87</td>
<td>94</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.66</td>
<td>0.83</td>
<td>0.87</td>
<td>0.97</td>
</tr>
<tr>
<td>Slope of the best fit line (log-log plot)</td>
<td>1.006</td>
<td>1.0239</td>
<td>0.8736</td>
<td>0.9411</td>
</tr>
</tbody>
</table>
we believe that most of the uncertainty in this approach can be found in the rainfall, which varies strongly in space and is difficult to measure accurately at high altitude where the largest rainfalls often occur (Henderson and Thompson, 1999). By comparison, potential and actual evaporation have smaller spatial variability than rainfall, while catchment runoff is measured more accurately than catchment rainfall.

While M3 does show a reasonably good correlation with runoff across most areas of New Zealand, if this model is to be used for estimating the runoff in un-gauged catchments, the regional discrepancies noted above must be removed. For this purpose we have generated a bias correction surface for the M3 model to improve the prediction for the un-gauged catchments. The bias correction attempts to remove these systematic regional errors between measured and synthesised runoff and the modelled runoff. This is achieved through the generation of a smooth bias surface which is then used to correct the M3 runoff results. We have chosen not to directly interpolate the bias map from Figure 3, because we consider it important to consider the cause of the bias, rather than blindly correcting for it.

Therefore, to generate a bias surface for New Zealand an error value \( \text{Err} \) is first determined for every catchment, according to the following equation (Tait et al., 2006):

\[
\text{Err} = \frac{(P - (Qm + AE))}{(Qm + AE)}
\]  

where \( \text{Err} \) is the error term for each catchment, \( P \) is the estimated catchment precipitation, \( Qm \) is measured catchment runoff, and \( AE \) is estimated catchment actual evaporation as calculated for the M3 surface. The \( \text{Err} \) term has been expressed in this format to allow us to estimate the likely error in precipitation, since, as noted above, it seems likely that most of the bias results from precipitation errors. Using these point values of \( \text{Err} \), a surface for \( \text{Err} \) can be interpolated across New Zealand and used to correct the modelled runoff. Following our discussion of errors, we assume that all the error is in the precipitation surface, from which it follows that the corrected runoff, \( Q^* \), is given by

\[
Q^* = \frac{P}{\text{Err} + 1} - AE
\]  

We generate a final runoff model, known as M4, using precipitation \( P \), actual evapotranspiration \( AE \) and \( \text{Err} \) from M3. The M4 surface (Figs. 3 and 7) shows the expected significant improvement over the M3 surface, so that 484 of the 524 catchments (92%) had modelled runoff within ±25% of the measured runoff. In terms of area, approximately 321,000 km\(^2\) of the 343,000 km\(^2\) (94%) had modelled runoff within ±25% of the measured runoff (Table 3). When measured runoff is plotted against M4 modelled runoff on a log-log plot, the trend can be approximated by the power relationship, \( y = 1.5061 x^{0.9411} \) with an \( R^2 \) of 0.97 (Fig. 7 and Table 3).

Therefore, we suggest the use of the M4 runoff surface (as presented in Table 3, and Figs. 7 and 8 [see page 99 for Fig. 8]), for use in estimating runoff in mm/a for un-gauged catchments. One practical way to implement this is to use the digital river network of the River Environment Classification (Snelder and Biggs, 2002). Every one of the approximately 576,000 river reaches has a digital catchment that drains to it, and so the M4 runoff surface can be averaged over any of those catchments to create an estimate of catchment runoff.

Since New Zealand has a very wide range of precipitation and significant areas where precipitation greatly exceeds actual evapotranspiration, the runoff modelling results are very sensitive to the precipitation data and associated uncertainty, which are described in detail by Tait et al. (2006). Any future improvements in precipitation data
should therefore lead to improvements in runoff estimation.

The period of this study (1960 to 2001) includes years from within two phases of the Interdecadal Pacific Oscillation (IPO) cycle (Salinger et al., 2001). The two phases are a negative phase from 1945 to 1978 and a positive phase from 1979 to 1999 (Salinger et al., 2001; Folland et al., 2002). The years from 1999 onwards may be the beginning of another negative phase of the IPO (Salinger et al., 2001). In other studies these phases of the IPO have been shown to result in significant differences in terms of floods and low flows (McKerchar and Henderson, 2003) and mean monthly flow (Woods et al., in prep.).

**Summary and conclusion**

This study has compared three models of mean annual runoff for New Zealand, based predominantly on precipitation information and potential evapotranspiration, and compares them to measurements and synthesised measurements of runoff. The models have been assessed through the comparison of modelled runoff with measured runoff for each catchment for the time period 1960-2001. The third model (M3), which uses the ratios of potential evapotranspiration and precipitation, is found to give the greatest correlation with measured runoff, but it still contains regional bias, which is apparently due mainly to inaccuracy in rainfall estimates. A simple adjustment is applied to correct for this, until improved rainfall estimates are available.

The resulting model provides estimates of mean flow throughout New Zealand, on every reach of the River Environment Classification network, and is suggested for use in estimating mean annual runoff for ungauged catchments.

Since New Zealand has steep precipitation gradients and significant areas where precipitation greatly exceeds actual evapotranspiration, these runoff results are very sensitive to the precipitation information,
and can be revised when improved precipitation data becomes available. Further work is underway to reduce the scatter of model estimates around measured values without resorting to time-stepping simulation models, by taking account of the seasonality and intermittency of precipitation, as well as soil, vegetation and topographic features, using the methods of Woods (2003).

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