Taihoro Nukurangi

Surface water components of New Zealand's National Water Accounts, 1995-2010

Prepared for Statistics New Zealand

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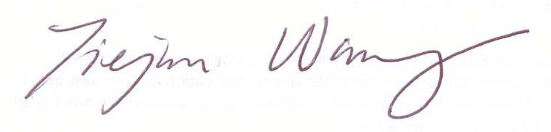

Dr Tiejun Wang

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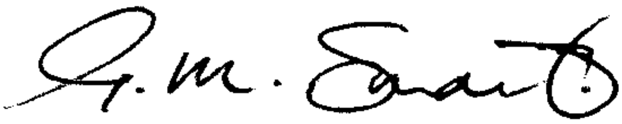


Dr Graeme Smart

1. Executive summary

The National Institute of Water and Atmospheric Research Ltd (NIWA) has been commissioned by Statistics New Zealand to estimate eleven components of the national and regional water balance of New Zealand for each of the sixteen years from 1 July 1994 to 30 June 2010. This information is for use by Statistics New Zealand in a set of annual national water accounts they are developing, as part of a set of environmental accounts for New Zealand. Specifically, this work is a contribution to the Water Physical Stock Accounts.

The eleven components of the accounts developed in this report are Precipitation, Inflows from rivers, Evapotranspiration, Abstraction by hydro-generation companies, Discharges by hydro-generation companies, Outflows to sea from surface water, Outflows to other regions (regional scale only), Net change in lakes and reservoirs, Net change in soil moisture, Net change in snow storage, and Net change in ice storage.

The accounts are presented at two levels of spatial detail: national and regional. The 16 areas administered by regional councils and unitary authorities define the regional boundaries.

Three methods were used to develop the eleven components of the accounts listed above: direct calculation from measurements, spatial mapping, and simulation modelling. A significant task within the project was the operation of a national hydrological model, using NIWA's Topnet modelling system. This was necessary to estimate some of the account components for which very few measurements are available.

The resulting accounts capture the broad temporal and regional variability of water movement and storage in New Zealand. They show that precipitation is the dominant component of those prepared in this report, and that, when taken together, river flow to the sea and evapotranspiration account for most of this precipitation. The use of water for hydrogeneration is a significant component of the national accounts, but it should be noted that this is a non-consumptive use, and that the water has been counted each time it is used for hydrogeneration. By comparison, inter-region flows and the various net changes in storage are relatively small at the annual-national scale.

The estimation of precipitation across New Zealand remains a key step in the development of the accounts, and the latest accounts use new methods for this. Further development is needed to improve on both the precipitation, and on estimates of actual evaporation in many areas of New Zealand. However, in their present form, they already provide detailed information on year-to-year trends around the nation. Although outside the scope of this project, two outstanding issues remain: to integrate changes in groundwater storage with these surface water accounts, and to obtain data on water use and link it to these accounts. Research in the Waterscape research programme funded by the Ministry of Science and Innovation, will make contributions to both issues, but coordinated input from many other parties is needed to address these two outstanding issues adequately.

2. Introduction

The National Institute of Water and Atmospheric Research Ltd (NIWA) has been commissioned by Statistics New Zealand to estimate eleven components of the national and regional water balance of New Zealand for each of the sixteen years from 1 July 1994 to 30 June 2010. This report is a revision and update of two previous reports on surface water information: Woods and Henderson (2003), and Henderson et al (2007).

This information is intended for use by Statistics New Zealand to assist them in updating the Water Physical Stock Accounts, as part of the set of environmental accounts[1]. The first set of water accounts were produced in 2004, comprising a set of physical stock accounts (with supporting reports on surface water, groundwater, snow and glaciers) and a partial set of monetary stock accounts. The first set of accounts covered the period 1995-2001. The second set of accounts was produced in 2007[2], and covered the period 1995-2005.

2.1 Components of the accounts

The eleven components of the accounts developed in this report are listed in Table 1: unless noted otherwise, all components are reported at both national and regional scales. These eleven items are described in more detail in the next section.

Table 1: The components of the water accounts covered by this report

Component Name
1. Precipitation
2. Inflows from rivers (regional scale only)
3. Evapotranspiration
4. Abstraction by hydro-generation companies
5. Discharges by hydro-generation companies
6. Outflows to sea from surface water
7. Outflows to other regions (regional scale only)
8. Net change in lakes and reservoirs
9. Net change in soil moisture
10. Net change in snow
11. Net change in ice

2.2 Accounting time periods

The water accounts prepared in this report cover sixteen accounting years. Each year runs from 1 July to 30 June, and is referred to by the year at the end of the period (e.g. the 1995 year runs from 1 July 1994 to 30 June 1995).

Although the resource accounts require only annual data, most of the components of these accounts have been derived using information at much finer timescales (e.g. daily information). This foreshadows the expected future development of accounts with more temporal detail, so that, for example, seasonal surpluses and deficits within a year can be quantified. Most (but not all) measured hydrological data are recorded at very fine

[1] http://www.stats.govt.nz/browse_for_stats/environment/natural_resources/environmental-accounts.aspx
[2] http://www.stats.govt.nz/browse_for_stats/environment/natural_resources/water-physical-stock-account-1995-2005.aspx

timescales, and are suitable for more detailed temporal accounting. These detailed measurements reflect the rapid changes in water stocks and flows over time, as new rainfall enters the system throughout the year, is stored (e.g. in soil, lakes, groundwater) and then progressively leaves the system (e.g. evaporation, river flow).

2.3 Spatial accounting regions

The accounts are presented at two levels of spatial detail: national and regional. The 16 areas administered by regional councils and unitary authorities define the regional boundaries. The names of these 16 regions (and their land areas) are listed in Table 2, and the regions are mapped and labelled in Figure 1. The region boundaries used in this study are the same as those used in the second edition of the water accounts (Henderson et al, 2007). The region boundaries will need to be updated for future accounts, to recognise recent changes such as those around the new Auckland Council that occurred in late 2010, after the last date covered by these accounts.

Table 2: Names and land areas for regional accounting.

Region Name	Region Area (km^2)
Auckland	4,476
Bay of Plenty	12,108
Canterbury	45,039
Gisborne	8,335
Hawke's Bay	14,051
Manawatu-Wanganui	22,167
Marlborough	10,124
Nelson	412
Northland	11,840
Otago	31,710
Southland	31,093
Taranaki	7,069
Tasman	9,516
Waikato	24,195
Wellington	7,984
West Coast	23,238
New Zealand	263,357

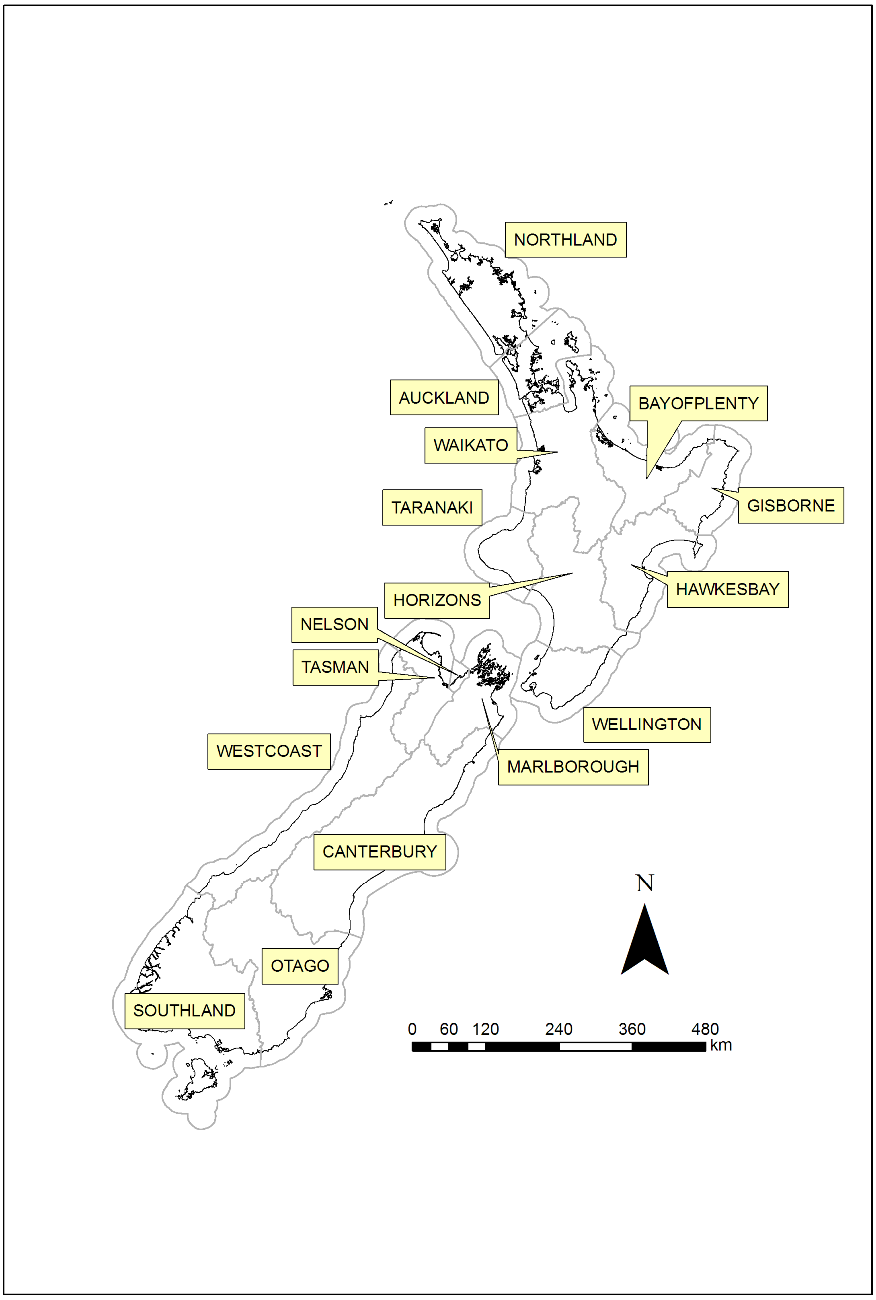


Figure 1: Boundaries for regional accounting.

3. Measurements

The major challenge in preparing water accounts is obtaining good spatial coverage. Water continually moves from place to place within New Zealand. Much of that water movement is not measured. Eight types of measurement are needed to cover the 11 account components in Table 1: rainfall (for component 1), actual evaporation (3), river flow (2,6,7), electricity generation (4, 5), lake level/volume (4, 5, 8), soil moisture (9), snow depth (10) and ice volume (11). These measurements are discussed below.

3.1 Precipitation

The accepted standard method for precipitation measurement is by raingauge, recorded either automatically or manually. Considerable care goes into the measurement of rain at measurement sites, and the technique has a long history. Typical measurement uncertainty is 10%, with a tendency for most gauges to catch less rain than actually falls, especially at windy sites. On average, the standard 300-mm diameter raingauges used in New Zealand catch about 7% less than the rainfall on the ground. Rainfall data were not adjusted for this effect before being used to create the rainfall product used in this study, because the adjustment depends on wind-speed, which is not known at most rainfall measurement sites. Snow, hail and sleet are not measured separately on a routine basis, but there are a few sites where snow accumulation is measured. Raingauges are located throughout New Zealand, but are extremely sparse in the alpine locations where rainfall is greatest and changes most rapidly. As a result, considerable effort is needed to reliably estimate rainfall in places where it is not measured, and there are few independent checking techniques to validate those estimates. Measurement of river flow in high-rainfall areas is a very useful technique to provide checks on rainfall estimates over areas of 10-1000 km^2, since most of the rain that falls in high-rainfall areas leaves as river flow.

3.2 Actual evapotranspiration

There are no routine measurements of actual evapotranspiration, the water vapour that moves from soil and plants to the atmosphere. Evaporation from open pans is measured at a few dozen sites in New Zealand, but this is not the same as actual evapotranspiration, which is significantly affected by plant type and by soil moisture conditions. Potential evapotranspiration is an estimate of the amount of water that would be evaporated if plenty of water were available. Potential evapotranspiration for a reference vegetation type (short grass) is calculated for a few dozen sites around New Zealand, using measurements of temperature, wind speed and solar radiation.

3.3 Inflows from rivers, outflows to other regions, outflows to sea from surface water

River flow is measured by monitoring the water level, and maintaining a calibration curve, which relates water level to river flow. The calibration curve depends on sample measurements of the discharge and water level of the river, which are made by visiting the site with meters to measure the velocity of the water throughout a cross-section of the river. As with raingauges, the technology for measurement at monitoring sites is well developed and has a long history. River flow measurements are made at several hundred locations throughout New Zealand, and again, specialist techniques are needed to estimate river flow in sites without measurements.

3.4 Abstraction by hydro-generation companies, discharges by hydro-generation companies

Hydro-generation companies in New Zealand abstract water from rivers, lakes and reservoirs, pass it through electricity generation facilities, and discharge the water to rivers reservoirs or the ocean. Electricity is generated by having falling water pass through turbines: the amount of power depends on how much water is passing through the turbine each second, and how far it falls. The flow of water through a power station is estimated by monitoring the difference between the water levels upstream and downstream of the turbines, the amount of power being generated and the number of generating machines that are operating. When this information is combined with a calibration curve representing the efficiency of the machines (how efficiently they convert falling water into electricity for various headwater/tailwater levels), the flow of water through the turbine can be calculated. These quantities are routinely measured at power stations.

3.5 Net change in lakes and dams

Water levels in lakes and reservoirs are monitored in a few dozen places, mostly for hydro-electricity reservoirs and major lakes. Changes in lake level can be multiplied by lake area to calculate change in lake volume. However, the volume of water stored at any given time can only be calculated if the bed of the lake has been surveyed in detail. Thus changes in volume are much easier to estimate than total volumes. There are more than 50,000 lakes in New Zealand, most of which are small and unmonitored, but because the monitored lakes are so large, the monitored lake level data covers approximately 80% of the lake area in New Zealand.

3.6 Net change in soil moisture

Soil moisture can be measured with a probe inserted in the ground that is connected to a recording device. This technology was developed relatively recently, so that until 2000, when a network of 40 sites was developed by NIWA, there were no nationwide measurements of soil moisture. Data had previously been collected for studies at a few research sites, but not for routine hydrological monitoring. Once again, the estimation at unmonitored sites is challenging, because of place-to-place variations in soil moisture caused by variations in climate, vegetation type, and soil type.

3.7 Net change in ice and snow

Water stored as ice is measured indirectly in New Zealand, through annual monitoring of the areas and altitudes of 49 index glaciers. Further details are given in a specialist report (Willsman & Salinger 2007), and the brief summary in section 4.11. Snow is directly measured at very few sites, so accumulation and melt are modelled. Details are given in section 4.12.

4. Methodology

This report includes 11 components of the stock accounts; these are listed and defined in Table 4, and the methodology used for each component is noted briefly. The methodology was chosen to suit the available data and techniques at the time the accounts were prepared.

Given the challenges noted above in obtaining complete spatial coverage, most of the available measurements have been used to assist in the development of models, which provide more complete spatial coverage. The remainder of this section provides an outline of the methodology used for each component of the accounts.

4.1 Overview of methodology

Before introducing the details of each component, we first note a few points that are common to the development of all components. Three methods were used to develop the components described in Table 3: direct calculation from measurements, spatial mapping, and simulation modelling. As noted in the previous section, comprehensive water measurements are not made in New Zealand, but many valuable data are available. The choice of method depends on the availability of suitable measured data, which are the preferred information source.

Table 3: Surface water components of New Zealand's National Water Accounts

Component Name	Description	Methodology
Precipitation	The total volume of rain/hail/snow/sleet during an accounting period, before evapotranspiration is taken into account.	Spatial mapping
Inflows from rivers	The volume of water that enters each region from rivers outside that region (regional accounts only).	Hydrological modelling
Evapotranspiration	The total volume of water lost by evapotranspiration during an accounting period (*actual* evapotranspiration, as opposed to *potential*).	Hydrological modelling
Abstraction by hydro-generation companies	The total volume of water abstracted from surfacewater by hydrogeneration companies during an accounting period.	Measurement
Discharges by hydro-generation companies	The total of water discharged by hydrogeneration companies during an accounting period.	Measurement
Outflows to sea	The total volume of water that flows to the sea during an accounting period, before any abstractions are removed (does not include any river flow to other regions).	Hydrological modelling
Outflows to other regions	The total quantity of surfacewater that leaves a region and flows to another region during an accounting period (regional accounts only).	Hydrological modelling
Net change in lakes and dams	The change in volumes of lakes and reservoirs during an accounting period.	Measurement
Net change in soil moisture	The change in volume of water stored in land and soil during an accounting period.	Hydrological modelling
Net change in ice	The change in quantity of water stored in ice during an accounting period.	Spatial mapping
Net change in snow	The change in quantity of water stored in snow during an accounting period.	Hydrological modelling

Where the measurements provide virtually complete spatial coverage or no suitable spatial modelling technique is available, the account data are prepared by collating, classifying and summarising the data obtained from those who hold it: at present this approach is used for Abstraction by hydro-generation companies, Discharges by hydro-generation companies, and Net change in lakes and reservoirs.

The account data for both precipitation and ice are developed using spatial mapping methods, which “fill in the gaps” between the measurement locations, using available knowledge of what controls the place-to-place variation.

The account data for actual evapotranspiration, the various river flow components, and the change in soil moisture are calculated by a hydrological model called Topnet (see Appendix 1 for details, and also Clark et al (2008), Bandaragoda et al. (2004) and Ibbitt et al. (2001)). The decision to use a hydrological model was motivated by the need to prepare accounts for evapotranspiration and soil moisture, for which the available measurements are quite unsuitable for national and regional accounting. Having taken the decision to use such a model, and noting the previously-expressed longer-term need of the Ministry for the Environment for more detailed river flow information, we decided to use the hydrological model for river flows as well. Regional accounts for the annual river flow data could also have been derived from measurements, with some form of extrapolation to each complete region based on the best available annual rainfall data.

The account values for outflows to sea and regional outflow volumes are calculated by assuming that no abstraction takes place. Abstractions need to be estimated and deducted from these flow volumes to obtain estimated actual outflows. In contrast, the account data for changes in lake storage do include the effects of abstraction.

The Topnet model tracks the day-to-day movement of water through the hydrological cycle: it uses daily information on rainfall and air temperature to “drive” the model from the atmosphere, and information on topography, soil type, and vegetation type to calculate the movement of water near, on and just below the ground. The model subdivides New Zealand into many thousands of small areas, and for each one of these it calculates each day how much water is being added as rainfall, how much leaves as evapotranspiration, how much leaves as river flow, and how much the storage of water in the soil and shallow groundwater changes by. More details of the model are given in Appendix 1. This approach to water balance modelling is internationally accepted, and widely used in situations where insufficient measured flow and storage data are available. Topnet does not currently model any losses from catchments to deep groundwater storages, nor return flows from deep groundwater systems to rivers, although the former could potentially be included in future accounts.

The hydrological modelling is spatially structured at two levels. New Zealand as a whole is subdivided into 15 areas for hydrological modelling. The areas were defined using the region coding used in the NZREACH field of the River Environment Classification (Snelder et al. 2004).

Figure 2 shows the subdivision of New Zealand into these hydrological models, and the names of the models are shown in **Table 4**. The modelling regions do not exactly follow the reporting areas, and we have ensured that each element of each model is assigned to the correct reporting region. Some small coastal areas of each region are not explicitly included in the model because very small streams drain them. The unmodelled percentage of each region varied across the country, depending on how much coastline a region had; overall, 1.5% of the land area of New Zealand was unmodelled, but this term is considered small enough to be negligible, given the other uncertainties in the project.

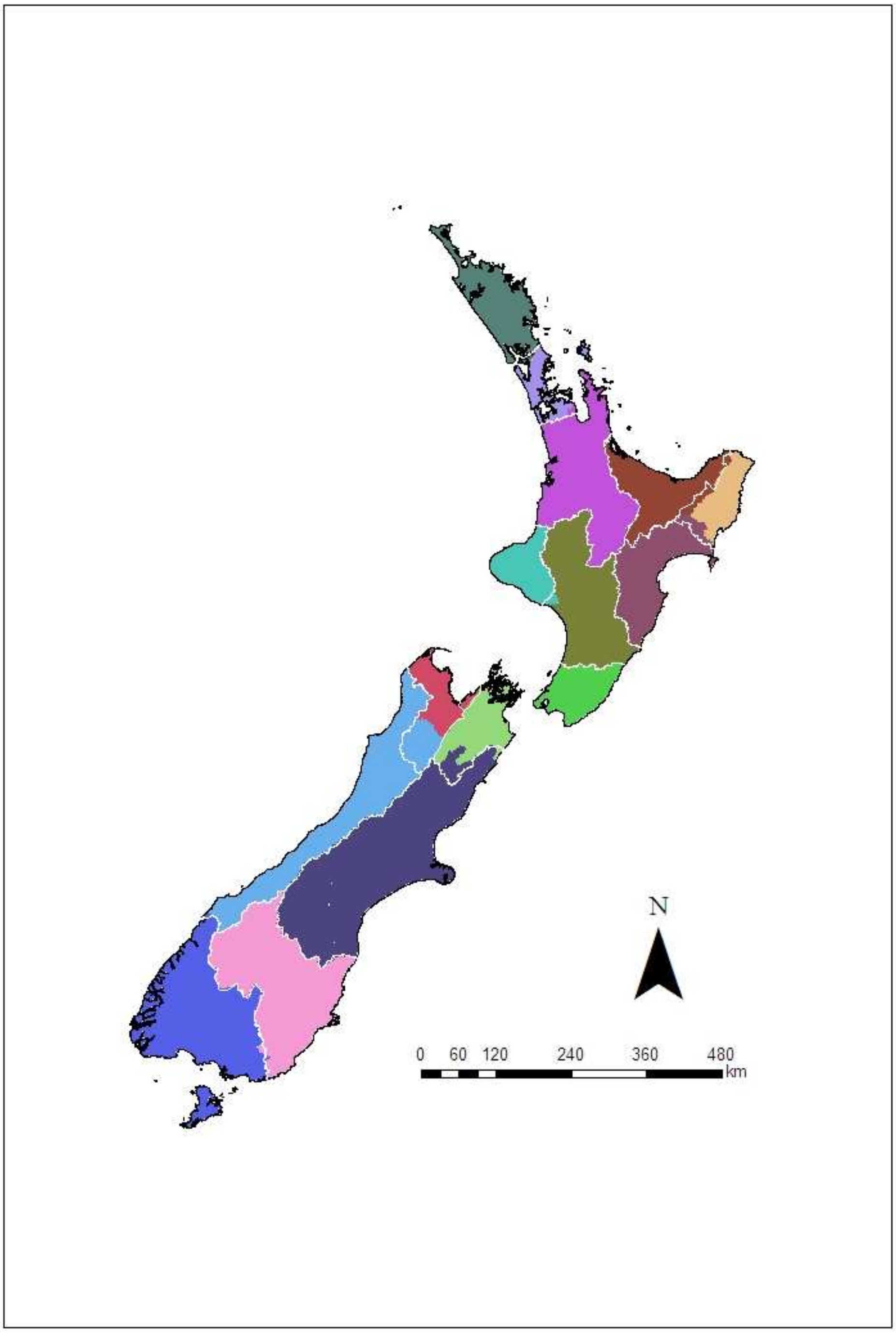


Figure 2: Model areas for the 15 hydrological models, with regional council and unitary authority boundaries overlaid in white.

Table 4: The hydrological modelling areas

Model number	Model name
1	Northland
2	Auckland
3	Waikato
4	Bay of Plenty
5	Gisborne
6	Taranaki
7	Manawatu
8	Hawke's Bay
9	Wellington
10	Tasman
11	Marlborough
12	West Coast
13	Canterbury
14	Otago
15	Southland

The Topnet models were not calibrated to measured river flow data, because a recent evaluation of the rainfall information (Tait et al. 2006) has shown that this source of bias has been largely eliminated at the regional scale. A successful validation plot for the "taranaki" model is shown in Figure 3. It is clear that the model captures the day-to-day catchment response acceptably well, although it has a number of imperfections. The quality is judged entirely adequate for the purposes of creating annual account values. It is quite possible that the model is biased in some regions: detailed evaluation of this would require further work.

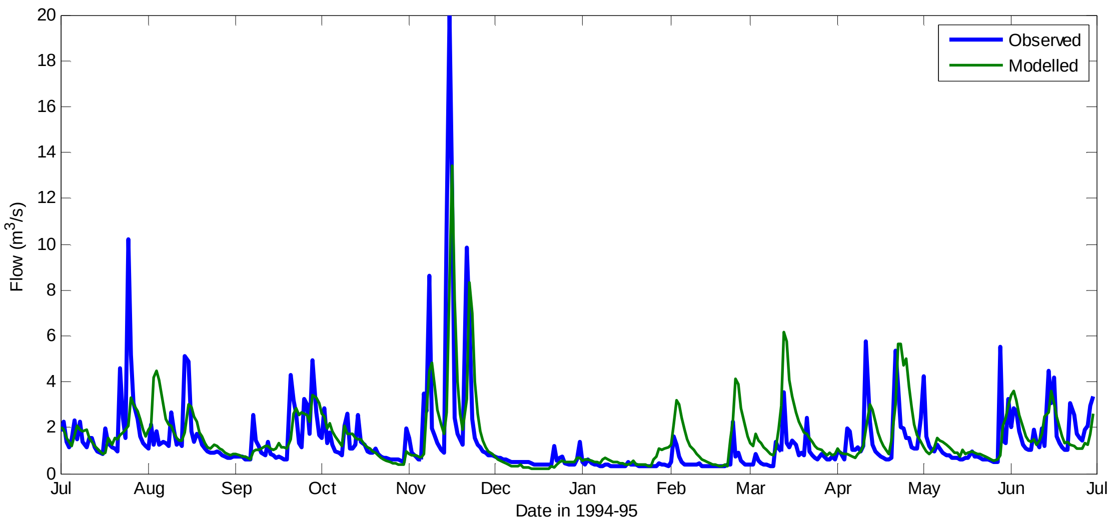


Figure 3: Topnet model validation for 1994-95 on Punehu Stream at Pihama in Taranaki (thick line is measurement, thin line is model). Using an un-calibrated Topnet model, the modelled mean flow is 15% larger than the measured mean flow, over the period 1995-2010.

For each account component, we provide below:

1. A description of the method and approach used to derive the data. The level of detail provided here is intended to give a broad understanding of the method
2. A detailed example of how one specific cell in the stock table is derived
3. A description of the coverage of the data i.e., to what extent are the final data dependent on modelling versus actual data
4. Identification for each component of any data estimates that may be weak.

4.2 Precipitation

From the daily measurements of rainfall at rain gauges, a detailed nation-wide rainfall data set was developed by a recent update of a spatial interpolation model (Tait et al. 2006). The rainfall data set has rainfall values every day from 1960-2010, over all of New Zealand on a regular grid with spacing of 0.05 degrees (approximately 5 km). This rainfall information was also used as input for the hydrological model, and the snow model.

The annual precipitation values for the accounts were obtained from summary files produced by the hydrological model (the model provides a link between the locations of the rainfall grid points and the model catchments, and makes reporting easier and more consistent than directly overlaying the region boundaries on the rainfall data set).

The precipitation volume for Taranaki for the period 1 July 1994 - 30 June 1995 is 19,188 million m^3 (equivalent to 2714 mm of rain over the region). The account value was obtained by adding all the annual precipitation values from all hydrological model catchments that are within the Taranaki region. The annual value for each model catchment is the sum of the daily rainfall values for the catchment, and each daily value for each catchment is a weighted average of the grid point values in and around the catchment on that day. The selection and weighting of grid points for each catchment is done automatically, based on the distance from the grid point to the catchment. The raw information used for precipitation is a list of daily values at all grid points that are within the Taranaki region.

The account values for precipitation are based on a recent update of the interpolated rainfall data developed using the validated method of Tait et al. (2006), because the available raingauge data on their own are not suitable for calculating regional or national totals. The precipitation data are by far the largest component of the accounts, and are the most uncertain in absolute terms, although the uncertainties are significantly less than the 25% reported in Woods and Henderson (2003).

4.3 Inflows from rivers

Most of the New Zealand regions shown in Figure 1 are bounded by catchment boundaries. This means that rivers usually do not cross the region boundaries, and so most regions have no river inflows (or outflows to other regions). However, there are some exceptions to this. We have documented them, and identified the transfers. They are listed in Table 5. The account values are obtained by separately identifying the catchments that produce river flow that is transferred to another region.

Table 5: River flows from one accounting region to another

From this region	To this region	Name of river(s)
Gisborne	Bay of Plenty	Motu, Waioeka (and others)
Gisborne	Hawkes Bay	Wairoa (and others)
Manawatu-Wanganui	Waikato (by diversion)	Whanganui (and others)
Marlborough	Canterbury	Clarence
Nelson	Tasman	Wairoa
Otago	Canterbury	Waitaki (south bank)
Otago	Southland	Mokoreta
Southland	Otago	Kaiwera Stream
Tasman	West Coast	Buller
Auckland	Waikato	Mangatawhiri (and others)

4.4 Evapotranspiration

The Topnet hydrological model calculates daily evapotranspiration using a model, and reports both daily values and annual summaries for each catchment. Regional and national accounts are obtained by accumulating the annual values over all catchments in a region. Evapotranspiration is calculated each day for each catchment using data for latitude, air temperature, and vegetation type and modelled soil moisture content. Evapotranspiration is larger for places with higher air temperatures, latitudes closer to the equator, taller vegetation types, and in wetter soils. See the section on the hydrological model for more details.

4.5 Abstraction for hydro-generation companies

The flow of water through turbines is known as the “machine flow”, and is what is reported in these accounts. It does not include any water that passes through the power station without making electricity, such as “spill flow”. The total volume of machine flow for each year of accounts for each hydroelectric power station in New Zealand was obtained by summing the flows that are calculated every hour. A list of the hydroelectric power stations in New Zealand was generated through our contacts in the electricity industry. We then requested the annual information from each company, and this was supplied to us by most companies (see Acknowledgements). Where all data were not available, the largest stations were generally provided. By using the nominal generation capacity of each power station, we estimate that the figures in these accounts represent 93% to 96% of the total abstraction and discharge for hydro-generation each year. The remaining 4% to 7% is from between 24 and 35 of 71 hydro power stations, many of them too small to have systematic records.

Water flows are typically reported by hydro generators as the average flow for the year, in litres/second, for each power station. These values are multiplied by the average number of seconds in a year (365.25*24*3600) and divided by 1000 to give the number of cubic metres per year for each power station. The power station volumes are then accumulated by region to produce the account values for each year. All the water that is abstracted for hydroelectricity generation is also discharged.

New Zealand has several chains of power stations (e.g., along the Waikato River), where the same water passes through several power stations. By adding the flows through all power stations in these accounts, the same water is counted as being abstracted and discharged several times in these accounts (obviously, the economic value of the water increases if it is used several times, and the accounts reflect this). This is an important distinction for the hydro-electricity industry, and we recommend that the accounts include a note to this effect. The term “abstraction” or “diversion” is sometimes used in the hydro-electricity industry to refer to a volume of water that is removed from a river and then used several times.

So for example, suppose there are three power stations in Region B, which are supplied by a diversion of one million cubic metres per year from a river in Region A (**Figure 4**). The water is taken out of region A, and piped into region B, where it passes through three power stations connected by rivers or canals (in this simple example we will ignore any other water in region B). This hypothetical water transfer would be counted in these accounts as river outflow from Region A, river inflow to Region B, and also as being abstracted and discharged three times in Region B. This is summarised in **Table 6**. Within the hydro-electricity industry, this would be referred to as a diversion of one million cubic metres from Region A to Region B.

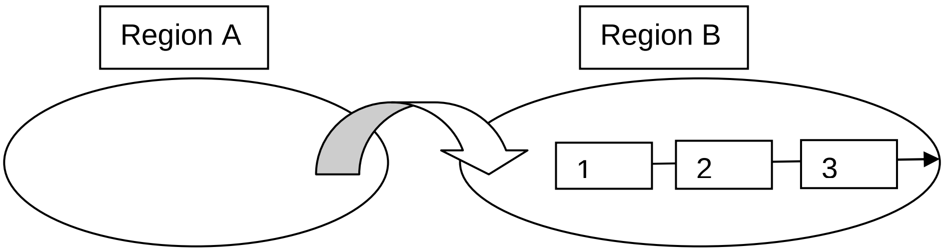


Figure 4: Accounting for abstraction of hydro-generation flows from one region to another in a hypothetical example.

Table 6: A summary of abstractions and discharges for a hypothetical example involving inter-basin transfer of water for hydrogeneration

	Region A	Region B	Total
Outflows to other Regions	1,000,000	0	**1,000,000**
Inflows from Rivers	0	1,000,000	**1,000,000**
Abstraction for hydrogeneration	0	3,000,000	**3,000,000**
Discharge by hydrogeneration	0	3,000,000	**3,000,000**

4.6 Discharges from hydro-generation companies

This item is discussed under section 4.5 above. Discharge by hydrogeneration is equal to abstraction for hydrogeneration in every region.

4.7 Outflows to sea from surface water

The hydrological model calculates the river flow out of each catchment on each day, as the sum of surface runoff and flow into streams from shallow groundwater. The model routes that flow along a river network, linking up the flows from the various catchments in the model. Any water that enters the river network continues being routed along the network until it reaches the sea. The time of travel within the river network is typically a few days, and considerably less for high flows, because flow velocities tend to increase with flow rate. Groundwater travels much more slowly by comparison. The river discharge to the sea from a region is the sum of modelled river discharges from catchments in the region, except those that flow to another region.

4.8 Outflows to other regions

Each individual inflow from another region (row 2 in Table 3) has a corresponding outflow. The river discharge to other regions from one region is the sum of modelled river discharges from catchments in the region that are known to drain to other regions. These catchments were identified by a GIS operation to overlay catchment boundaries on the region boundaries.

4.9 Net change in lakes and dams

Water levels are measured in most of the major lakes and reservoirs of New Zealand. The change in storage for each measured lake is the difference in level between the start and end of each accounting period, multiplied by the area of the lake. Changes in volumes were then accumulated by region and nationally. The information needed to calculate starting and ending volumes is available only for a small number of lakes, and so has not been included. However, this does not prevent us from calculating the net change in volume.

For example, over the 1995 accounting year, the water level in Lake Moeraki (near Haast in South Westland) rose from 1084 mm to 1197 mm (measured relative to local datum), a change of 0.113 m. The inter-annual changes in level are typically 0.1 to 0.8 metres. It is apparent from Figure 5 that lake level changes over a wide range during the year, and that most of the annual differences in level are simply a reflection of the rain events in the last few days or weeks.

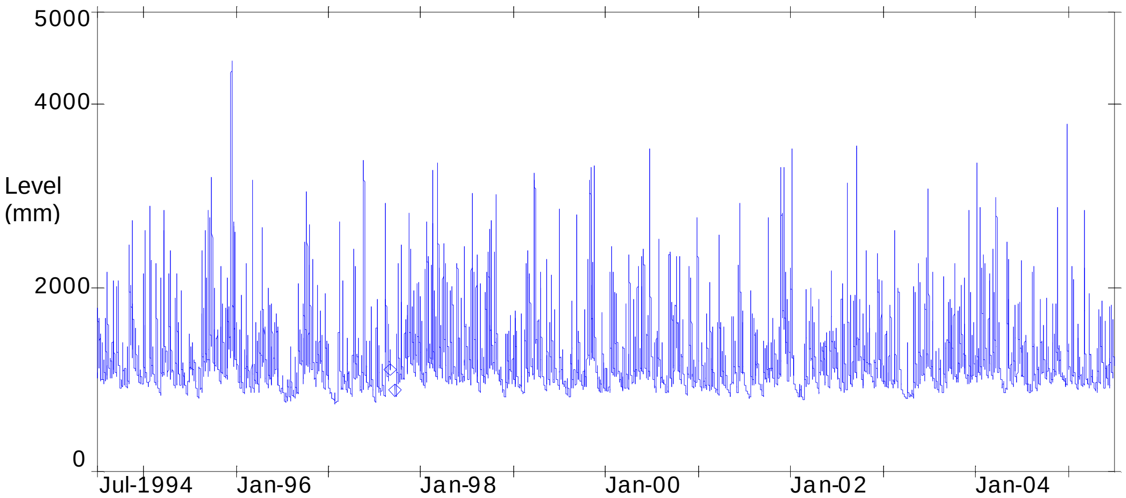


Figure 5: Lake level data for Lake Moeraki, measured every 15 minutes (levels are relative to a local datum). The rapid changes in level caused by rain events are large, in comparison to the differences between levels on 1 July each year.

The area of Lake Moeraki is 2.418 km^2, and this is assumed not to change significantly. The change in volume for the 1995 accounts is thus 0.273 million m^3. The calculated volume changes for each lake with data are added together to provide the regional and national accounts. Increases in storage during an accounting year have positive values, while decreases in storage are negative values.

There are three sources of uncertainty in this procedure for determining change in lake volume:

1. The area of the lake changes as the lake level rises and falls, but for some lakes we have assumed the area to be constant, because the relevant information is not available. This is estimated to cause an uncertainty of +/- 5% in volume.

2. There is uncertainty (i.e., a 95 % confidence limit) of +/-3 mm in the measured level of the lake at the start and end of the accounting period, due to limited instrument precision and to oscillations in the water level caused by wind.

3. Not all of New Zealand's lakes and reservoirs are included in the accounts, only those for which data are available. The lakes and reservoirs in the accounts cover 98.5% to 99.8% of all the monitored lake area in New Zealand. As noted earlier, 80% of the lake area is monitored: data for the other 0.2% to 1.6% of lake area that is monitored was not made available to NIWA for these accounts.

The information needed for a modelling approach for unmeasured lakes is not currently available. This component of the accounts could be refined in future by increasing the number of lakes with measurements (either by at-site instrumentation or remote sensing of water level), and by determining the change in lake area with level.

4.10 Net change in soil moisture

The hydrological model calculates the amount of water stored in the rooting zone (typically the top one metre of soil, depending on soil and vegetation type) at the end of each day of simulation. The modelled values are expressed as a depth, that is, a volume of water per unit land area (e.g. reported by the model in millimetres). Modelled differences in rooting zone storage between the start and end of a year are divided by 1000 to convert to metres, and multiplied by catchment area in m^2 to obtain the change in volume of rooting zone water for each year. The model also calculates for each catchment the depth to a shallow groundwater table at the end of each day (reported by the model in mm). A change in depth to water table can be converted to an equivalent volume per unit catchment area by multiplying by the drainable porosity of the soil.

The model reports the combined change over the year in water stored in the rooting zone and shallow groundwater, as a volume per unit land area for each catchment in the model (in millimetres). This value is divided by 1000 and multiplied by the area of the catchment, to obtain a change in water volume in m^3 for the year. Increases in storage during an accounting year have positive values, while decreases in storage are negative values.

Note that in contrast to the lake level data for Lake Moeraki, soil moisture can show pronounced seasonal patterns, and inter-annual differences may provide useful information on water balance. For example, Figure 6 shows a strong seasonal pattern in soil moisture at

Darfield in mid-Canterbury, with the maximum soil moisture in winter, but with some winters wetter than others.

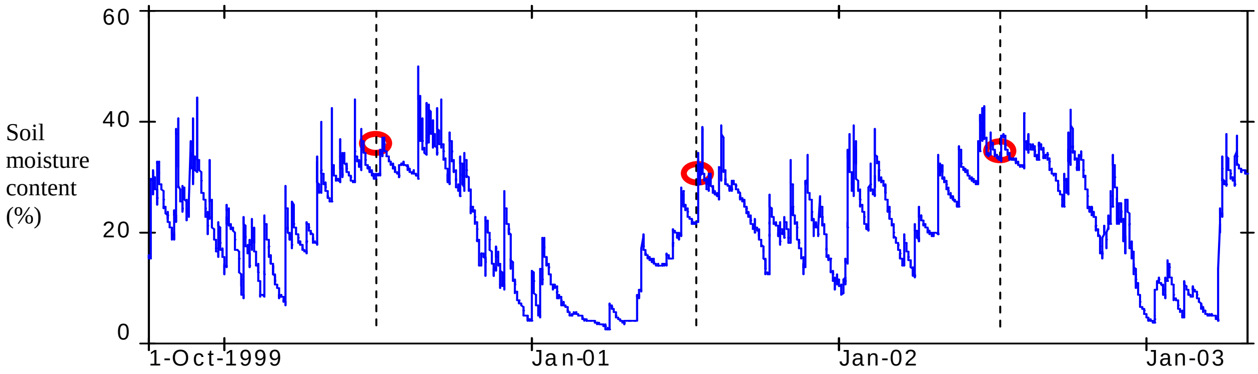


Figure 6: Measured variation in soil moisture conditions at Darfield in mid-Canterbury. The data from late 1999 to mid 2003 shows the relatively consistent seasonal cycle, with wet winters and dry summers. The first 4 months of 2001 were unusually dry, leading to lower than normal moisture values in mid-2001. (Balance date of 30 June is marked by vertical lines, with circles to mark soil moisture on those dates)

4.11 Net change in ice storage

Ice storage is measured indirectly in New Zealand, through annual monitoring of the areas and altitudes of 49 index glaciers. This permits the estimation of changes in mass of the index glaciers, and a spatial mapping technique is then used to extend this to the 3144 glaciers in the New Zealand glacier inventory. A detailed description of the methodology is given in Willsman (2011), and is briefly summarised here. The total volume of ice in New Zealand was estimated for a base year (1978), and then estimated annual changes in ice volume were added or subtracted from this base volume. The changes in annual ice volume are based mainly on annual glacier snow surveys of 49 index glaciers. For each of those glaciers, the elevations and areas were measured each year, and changes in volumes were calculated in detail for each of them, based on studies of glacier mass balance at two research sites.

The method derives an annual specific mass balance for each index glacier by dividing each volume by each index glacier area. This is then averaged for all the index glaciers to give a mean specific mass balance for the Southern Alps. The annual glacier volume variations are then calculated by applying the product of mean specific mass balance from the index glaciers and the area of all glaciers making allowance for the reduction in glacier area with the growth of proglacial lakes. Loss of ice to growth of proglacial lakes has been accounted for at seven glaciers in Canterbury. Satellite and ground based mapping (Delia Strong pers. comm.) combined with available and estimated bathymetry was used to determine this loss. As well, additional ice volume losses due to reduction in trunk volume are accounted separately for thirteen larger glaciers.

To permit regional accounting of changes in ice storage, the annual changes in ice storage were apportioned among the regions of New Zealand on the basis of the relative values of reference ice volumes from 1978 (Chinn 2001), and listed here in Table 7. The assignment of the glacier data to regions was made using river basin number (Chinn 2001). Increases in storage during an accounting year have positive values, while decreases in storage have negative values.

Table 7: Reference ice volumes for New Zealand glaciers in 1978 (Chinn 2001)

Region name	Regional glacier ice volume expressed as water equivalent (million m^3)	Regional glacier volume as fraction of NZ glacier volume
Auckland	0	0
Bay of Plenty	0	0
Canterbury	27532	0.51664
Gisborne	0	0
Hawkes Bay	0	0
Manawatu-Wanganui	44	0.00083
Marlborough	7	0.00013
Nelson	0	0
Northland	0	0
Otago	3400	0.06380
Southland	876	0.01643
Taranaki	0	0
Tasman	0	0
Waikato	12	0.00022
Wellington	0	0
West Coast	21420	0.40194

A glacier is a body of ice at least 1 ha in area, which has persisted over the last two decades (Chinn 2001). Snow-covered areas that melt away completely in warm summers are not glaciers. The glacier data reported here are for changes in glacier volume over a glacier accounting year, which ends at the end of summer (e.g. March or April). This is the only time when glaciers can be observed separately from temporary snow. By the end of the water accounting year at the end of June, some new snow will have fallen, but the amount of glacier ice does not change until the end of the following summer.

Another method for reporting the status of New Zealand glaciers is the position of the Equilibrium Line Altitude (ELA), a measure of the elevation of the snowline above sea level. Higher values of ELA correspond to smaller glaciers. However, the ELA is best understood as an indicative value, while the estimates of water volume stored as ice in this report are more accurate. The reason for this is that the ELA values for each year give equal weight to all index glaciers, whereas the methodology in this report weights each glacier according to its volume, which is more precise.

It is clear from this data that the glaciers of Canterbury, West Coast, Otago and Southland comprise almost all the ice storage in New Zealand. It will become apparent later in this report that for all the other regions of New Zealand, the recent annual changes in ice storage are an extremely small fraction of the annual water accounts.

4.12 Net change in snow storage

We calculated the net change in snow using a component of the Topnet model. The development and testing of this approach is described in Clark et al (2009). It is generally similar to the SnowSim model, developed by Chris Garr, Brendon McAlevey, Prof. Blair Fitzharris and others at Otago University. Both are temperature index models which include factors to simulate the effects of snow ageing and rain on snow events. Differences between the models are described in Clark et al (2009), along with a rationale for adopting the Topnet model.

Snow water equivalent was accumulated (or ablated) within every Topnet model catchment. Positive snow water equivalent remaining at the end of the snow season was allowed to accumulate, providing for the possibility of over-year storage. However, the Topnet model used here does not account for glacier processes; that research is still in development.

Figure 7 shows a sample map of modelled snow on 1 October 1995. The Topnet model produced a map of snow water equivalent for each day in the period 1995-2010. The change in snow storage for each accounting year at each grid point was calculated as the difference between snow maps on 30 June in each successive year, multiplied by the catchment area associated with each catchment.

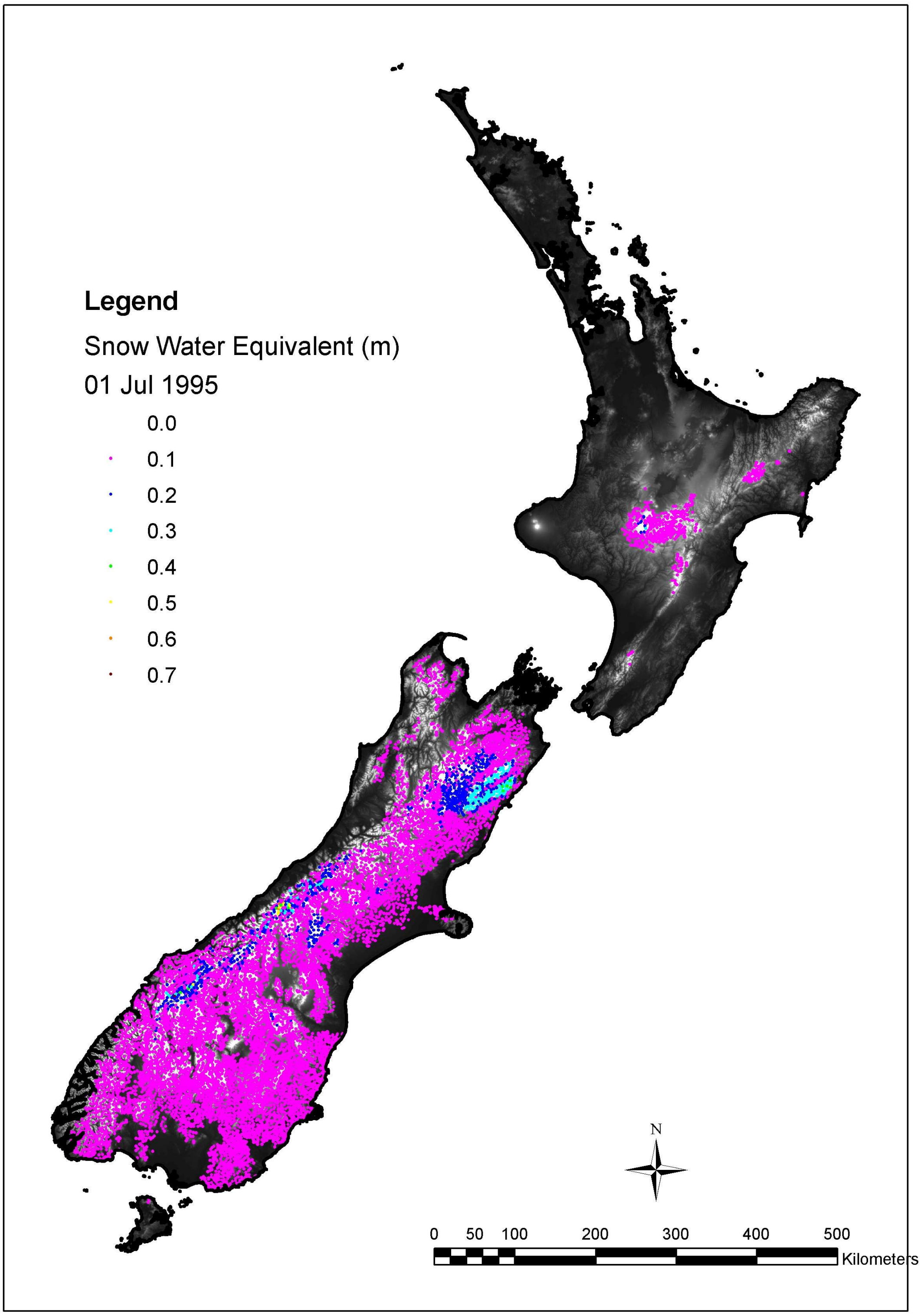


Figure 7: Snow storage on 1 July 1995, as modelled by Topnet

5. Results

The water accounts in this report comprise eleven component values (measured in m^3), for 16 regions plus the whole of New Zealand, for each of sixteen years, making a total of 2992 numbers. The account numbers for water are very large when expressed in cubic metres per year. For example the total rainfall over New Zealand for 1995 is approximately 684,986,000,000 cubic metres of water. To make this report easier to read, we use millions of cubic metres in most figures and tables (the raw data supplied electronically to Statistics New Zealand are in cubic metres, as requested). That 1995 volume of rain (684,986 million cubic metres) is the equivalent of 2.601 metres of rain for every square metre of land in New Zealand, and would be enough to fill Lake Taupo ten times over.

Even one million cubic metres is still a large volume of water: it would fill 290 Olympic-sized swimming pools, each 50 by 23 by 3 metres. Since there are 31,557,600 seconds in an average year, one million cubic metres of water a year represents a flow rate of 31 litres of water a second, enough to fill three ten litre buckets of water every second for a year.

The water account components for each year, for all regions, were provided to Statistics New Zealand in spreadsheet form, and will be summarised on their web site when the accounts are published there. The same information is also presented as year-to-year variations in the Discussion section, to enable comparison with observed trends in other systems related to water. It should be noted that the accounts in these tables only balance when the lake and ice volumes are not included. If one of the other components is to be adjusted in order to obtain a precise balance, it is recommended that the outflow to sea component be adjusted.

5.1 National Perspective

The large volume of information generated for this report can be usefully summarised in several ways. The average overall water balance for New Zealand for the period 1995-2010 is shown in Figure 8 and Figure 9.

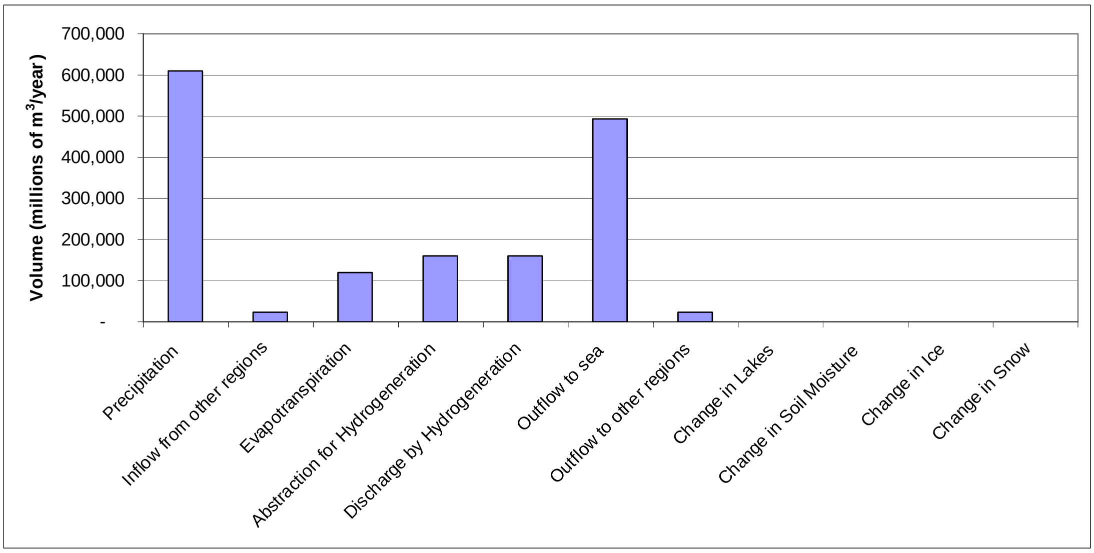


Figure 8: The water balance components in this report, for New Zealand (average of 1995-2010), using a linear scale. Note that some components are too small to see at this scale.

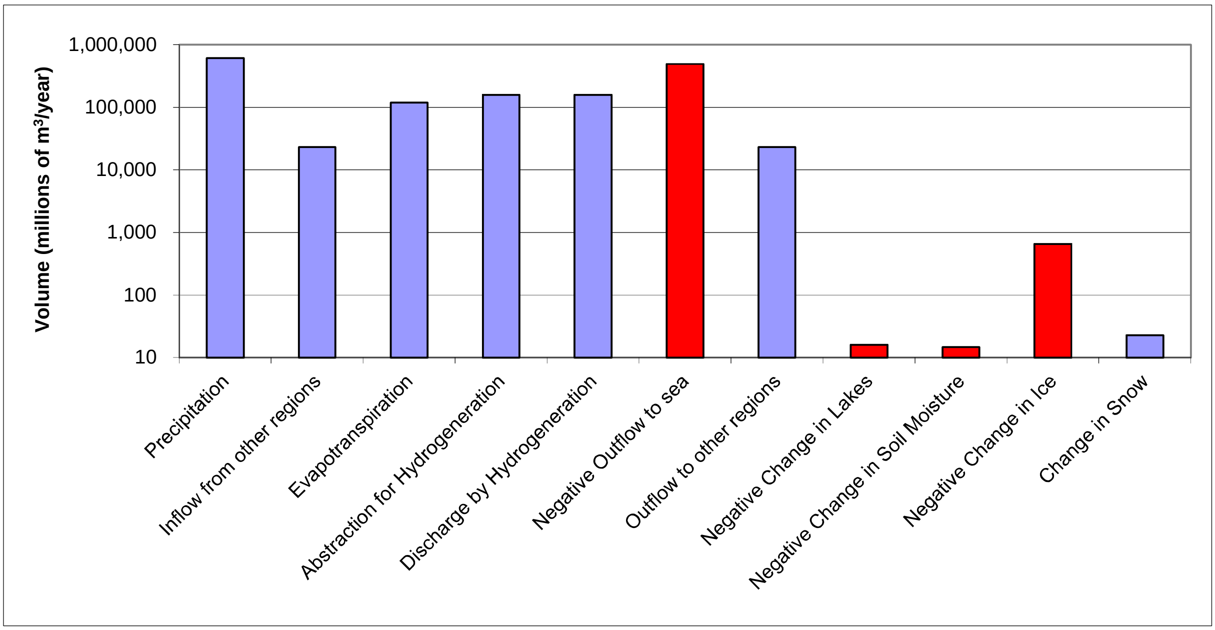


Figure 9: The same data as Figure 8 plotted to logarithmic scales, with the negative balances reversed for plotting purposes (and coloured red). Note the vertical axis starts at 10 million m^3.

It is clear from Figure 8 and Figure 9 that

- Precipitation is the dominant input component;
- Outflow to sea and actual evapotranspiration together can explain the fate of most precipitation, with outflow considerably larger than evapotranspiration;
- The use of water for hydrogeneration is a significant component of the national accounts (note this is a non-consumptive use, and that the water has been counted each time it is used for hydrogeneration); and
- Inter-region flows and the various net changes in storage are relatively small at the annual-national scale.

5.2 Regional Perspective

Comparing the regions of New Zealand (Figure 10), we see that the regional accounts vary greatly in magnitude through the country. Regions with smaller areas (e.g., Nelson, Auckland, and Gisborne) tend to have smaller volumes in the accounts, simply because they have less land with which to catch the rain, which is the ultimate source of almost all the water in the accounts. However, the effect of regional climate variations is also important, independent of a region’s land area. Thus West Coast has the largest rainfall volume, although it has only the fifth largest land area, and Otago, with its extensive dry areas, has only the fifth largest precipitation volume, although it is the second-largest region.

Hydroelectric power generation effects are large in Canterbury, Otago, Southland and Waikato, and relatively insignificant elsewhere.

Year-to-year changes in the water stored in soil moisture (which includes shallow groundwater), lakes, ice, snow are very small in comparison with the other fluxes. The year-to-year changes in deep groundwater (White & Reeves 2002) are also small in comparison with the other fluxes.

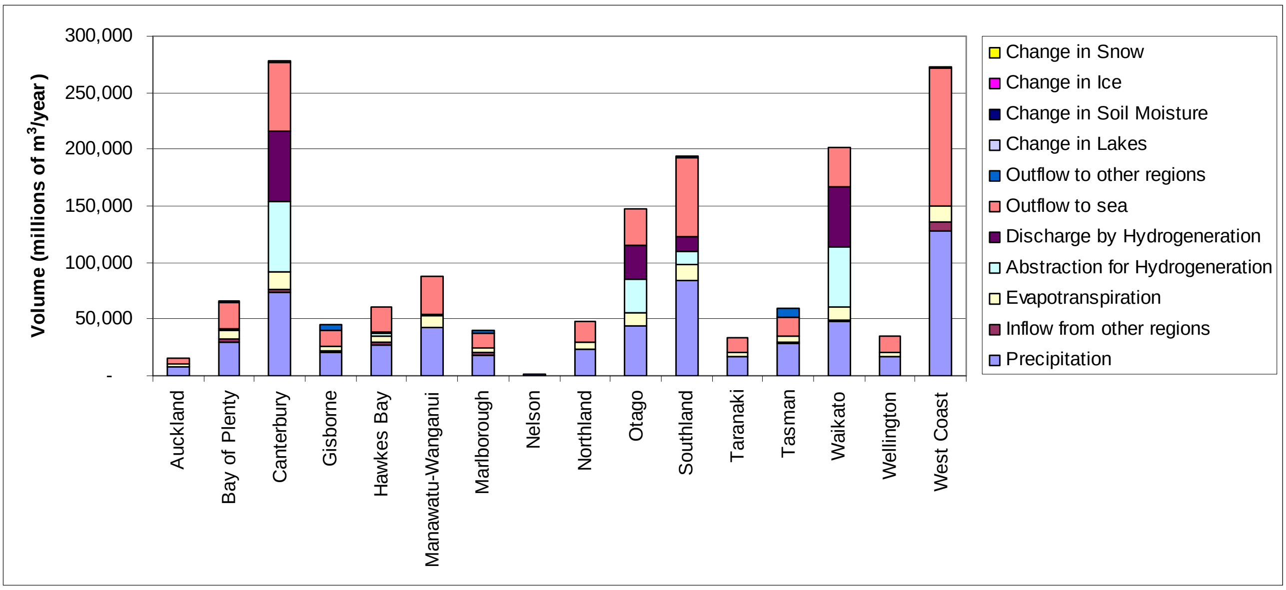


Figure 10: The relative sizes of regional water account components (average of 1995-2010).

5.3 Year-to-year variability

The year-to-year variations of water account components (e.g. precipitation, abstraction for hydrogeneration, outflow to the seas, and change in lake storage) have significant impacts for New Zealand and for each region, for example on hydrogeneration and agricultural production. Figure 11 shows the national account values for each year for each component. Year-to-year variations are a significant fraction of the total available resource. We return to this point in the next section.

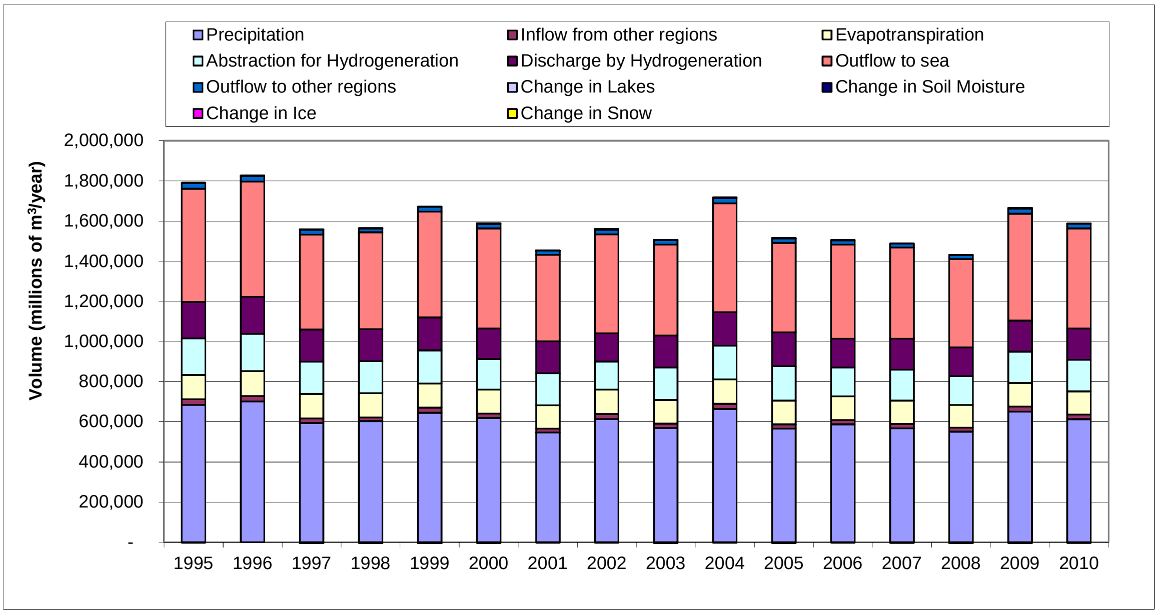


Figure 11: Year-to-year variations in components of the national water accounts.

The lower than average national values for precipitation and outflow to sea in 1997, 2001, 2003, 2005 and 2008 in Figure 11 are mainly caused by low precipitation in the South Island and Taranaki or central North Island. Consistent impacts of El Niño/Southern Oscillation (ENSO) events on precipitation are not necessarily visible at the national scale, because ENSO impacts vary by region (Gordon 1986,Salinger & Mullan 1999). A severe El Niño event occurred in 1997-98, and weak events in 2002-03, 2004-05 and 2006-07, while weak La Niña conditions occurred over late 1998-2000, 2007-08 and 2008-09. The tendency for lower than average national values since 2000 (7 of 11 years) may also reflect a change in phase of the Inter-decadal Pacific Oscillation (IPO) since that time.

6. Discussion

The accounts are given in terms of cubic metres of water for each year, as specified in our contract, making the numbers rather large. To assist in the interpretation of these numbers, and provide some “ground-truthing” of the account values, we have provided comparisons with several other measurements, and, where practical, related the volume values for regions to “per-unit-area” values, which may be more commonly experienced by the general public.

Precipitation - Rainfall statistics are commonly quoted in mm per year – as noted above, the precipitation volumes in the accounts can be converted to equivalent depths by dividing by the land area of a region. In Figure 12 the regional rainfall depths for each of the years is plotted against the measured rainfall at each of four towns and cities.

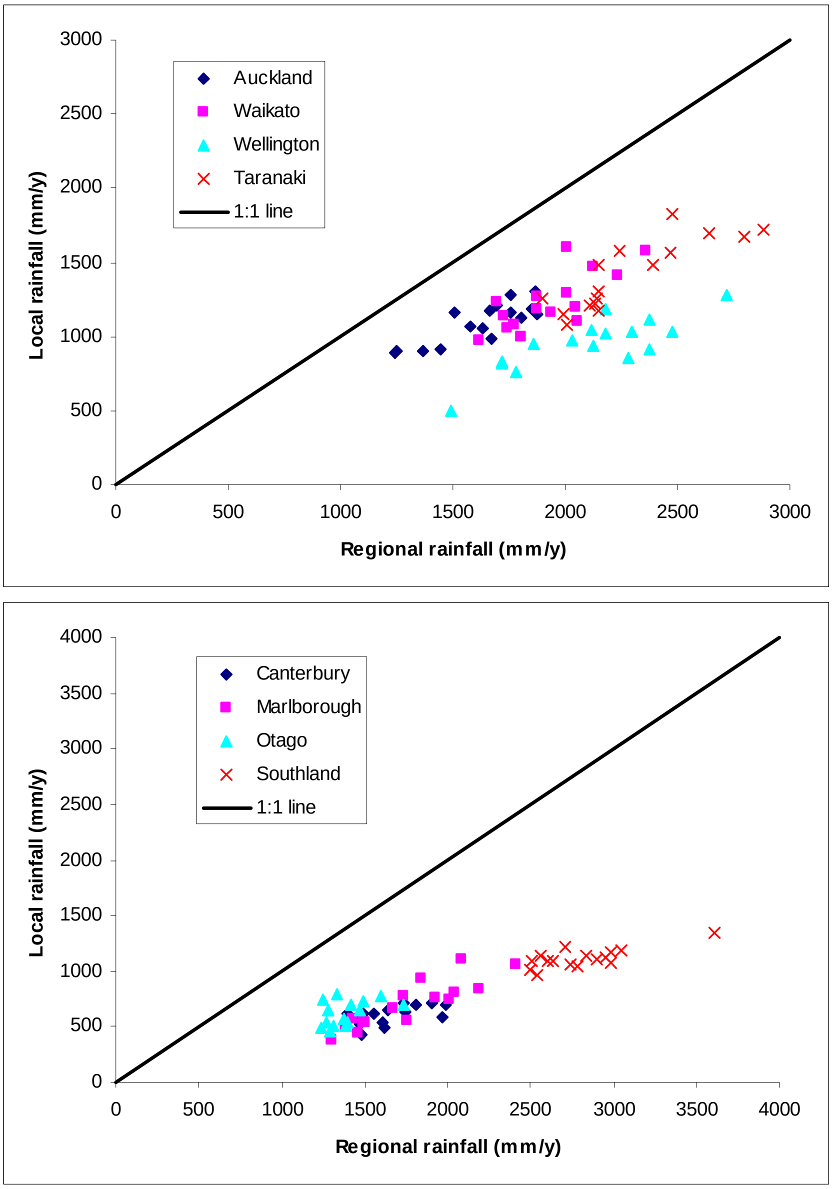


Figure 12: Comparisons of regional vs locally-measured rain (Auckland/Auckland City, Waikato/Hamilton, Wellington/Wellington City, Taranaki/New Plymouth, Canterbury/ Christchurch, Marlborough/Blenheim, Otago/Dunedin and Nelson/Nelson). Each point on the graph is an annual total for rainfall

The purpose of the plots is to check whether the year-to-year trends in the regional account values follow the locally measured trends. For each city/town, it can be seen that there is a strong tendency for the high values from the accounts to occur in the same year as the high measured values. However, the correspondence is not exact, because a single city is not always representative of the region's rain. For example, Christchurch is not necessarily a good indicator of Canterbury rain, because it is located in a dry part of the region.

Inflow from Rivers – The headwaters of the Buller River lie in the Tasman region, but the Buller flows to sea via the West Coast region. The Buller River flow measurement site at Longford monitors flow from about 35% of the region that flows from Tasman to West Coast. The annual water accounts values for West Coast inflow were converted to m^3/s by dividing by the number of seconds in a year, for comparison with the measured flow rates (Figure 13). The two flow series rise and fall together from year to year which shows that the model is indicating the time trend correctly. The river flow is approximately one third of the regional inflow estimate, indicating that the regional rainfall is well modelled.

Outflow to sea – The Buller at Te Kuha flow site monitors a significant fraction of the West Coast's outflow to sea, near the northern end of the region, and the Haast at Roaring Billy flow site monitors a large catchment near the southern end of the West Coast region. Figure 14 shows the comparison of the account and measured values; the account values again converted to m^3/s. Again the account values are fairly consistent with the measured year-to-year variability. The significant fall in the account value for 1997, and the rise in 1999, are matched in the Haast flow record, but not in the Buller flow record. This kind of variability is expected and illustrates the need to monitor flows in different parts of a region.

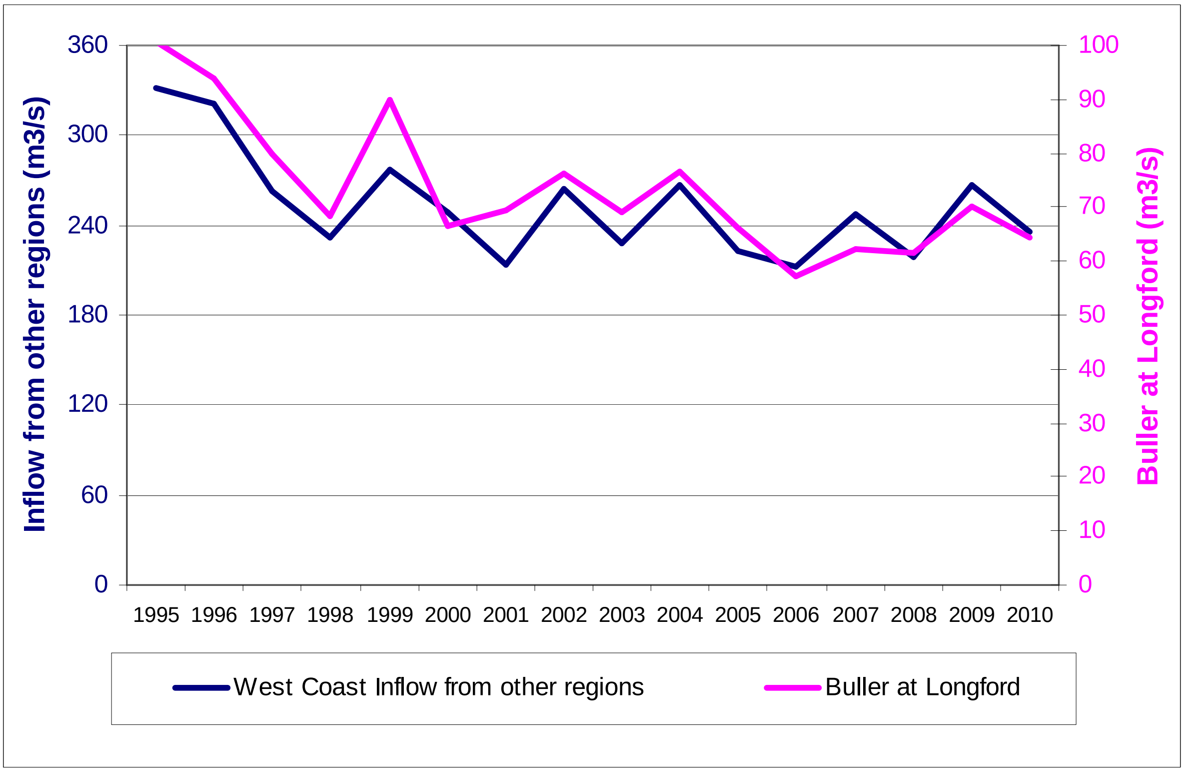
Evapotranspiration – measured values of actual evapotranspiration are not available for direct evaluation. The account values for New Zealand correspond to approximately 450 mm/y, which is less than the annual water balance results from New Zealand experimental catchments (typically 650 mm/y). This discrepancy needs further investigation, but that is outside the scope of the current project.

Lake level – The changes in level oscillate about zero change from year to year, with very small increases or decreases, in comparison to other water balance components (Figure 15).

Soil moisture – The national scale changes in soil moisture oscillate about zero, with a range of perhaps 10 mm either side of zero. As with the lakes, this is a relatively small component of the water balance (Figure 16).

Ice – The changes in ice storage are discussed in the report by (Willsman 2011).

Snow – The changes in snow volume from year to year are shown in Figure 17. According to Hendrikx et al (2009) "… 2000, 2004 and 2006 are widely considered to have been "good" snow years, while 1999 and 2003 were both "lean" snow years." The time series of annual changes in snow storage correlate reasonably well with that commentary.



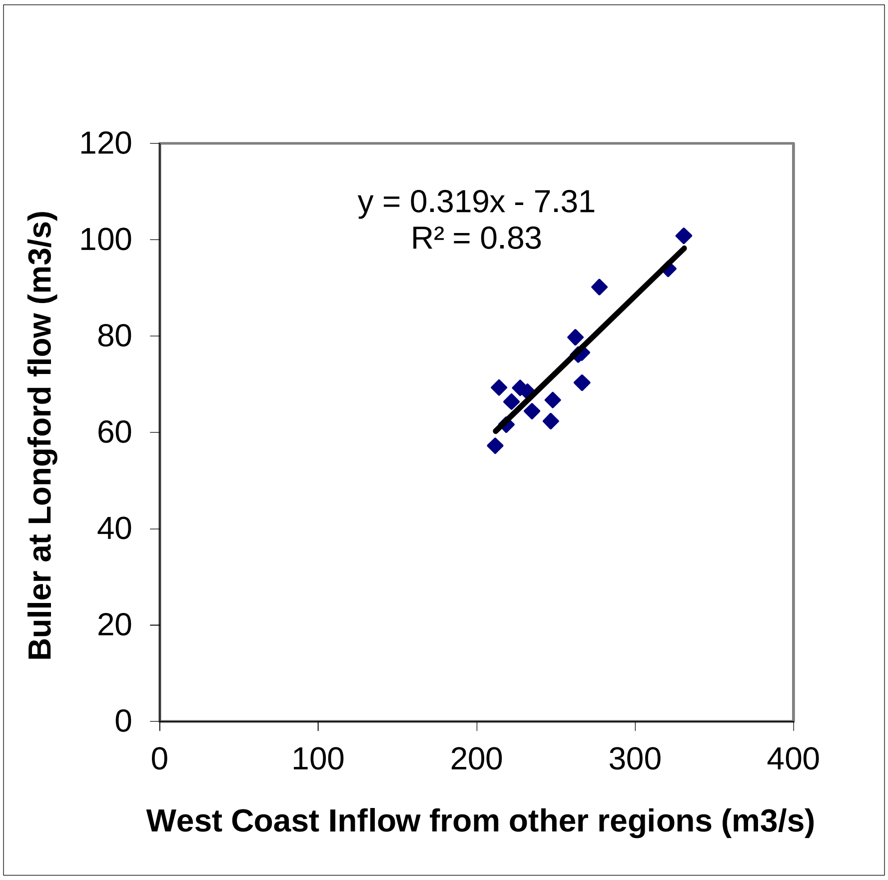
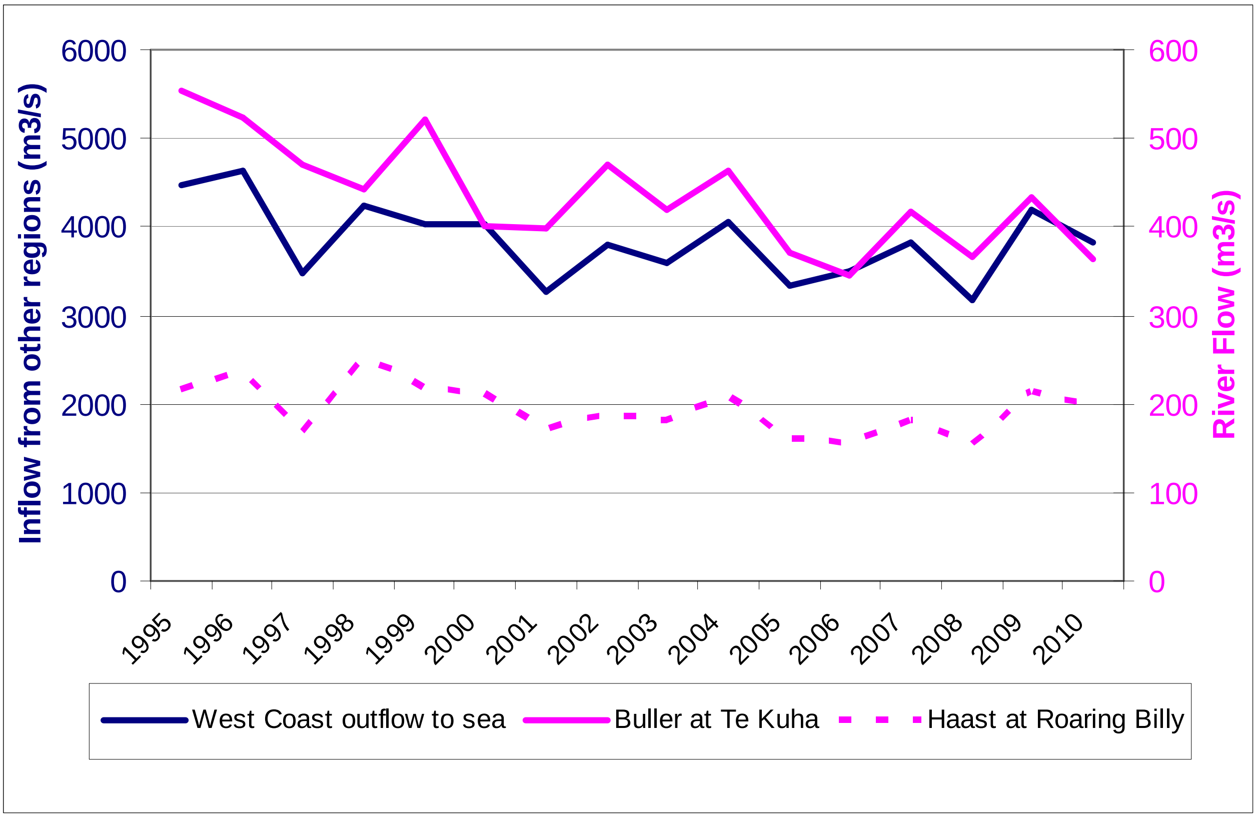


Figure 13: Checking the inflow from other regions for the West Coast region. Note the separate scales for inflow and river flow on the upper graph.



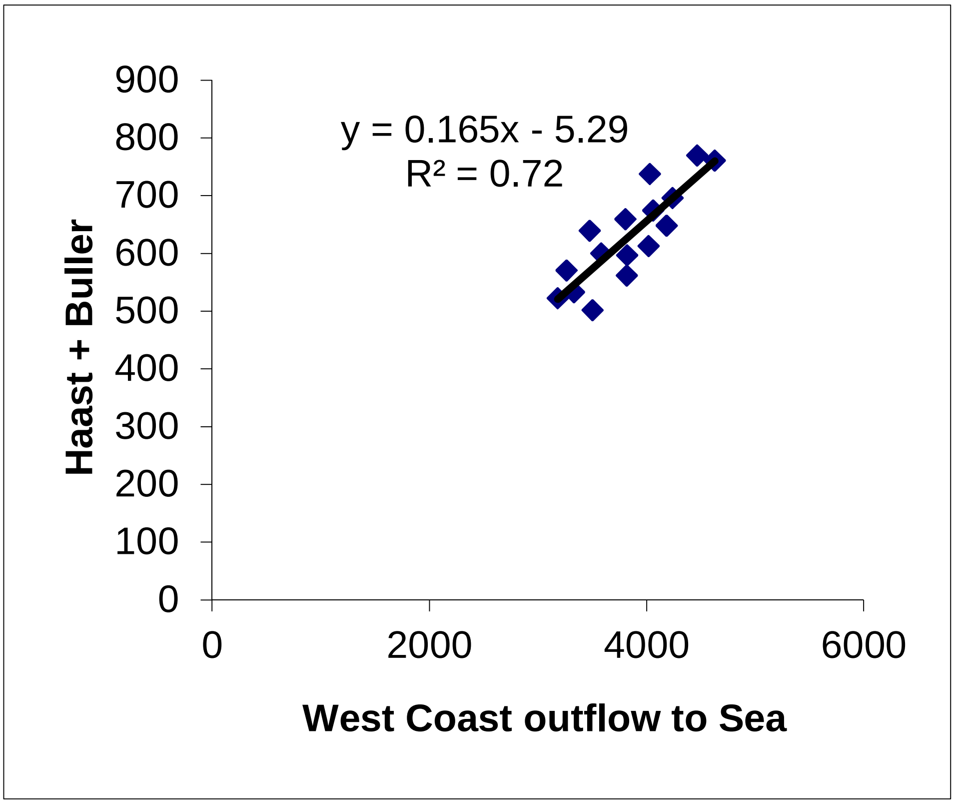


Figure 14: West Coast flows to sea from accounts, compared to measured flows from the Buller River at Te Kuha and Haast River at Roaring Billy. Note separate scales for outflows and river flows in upper graph.

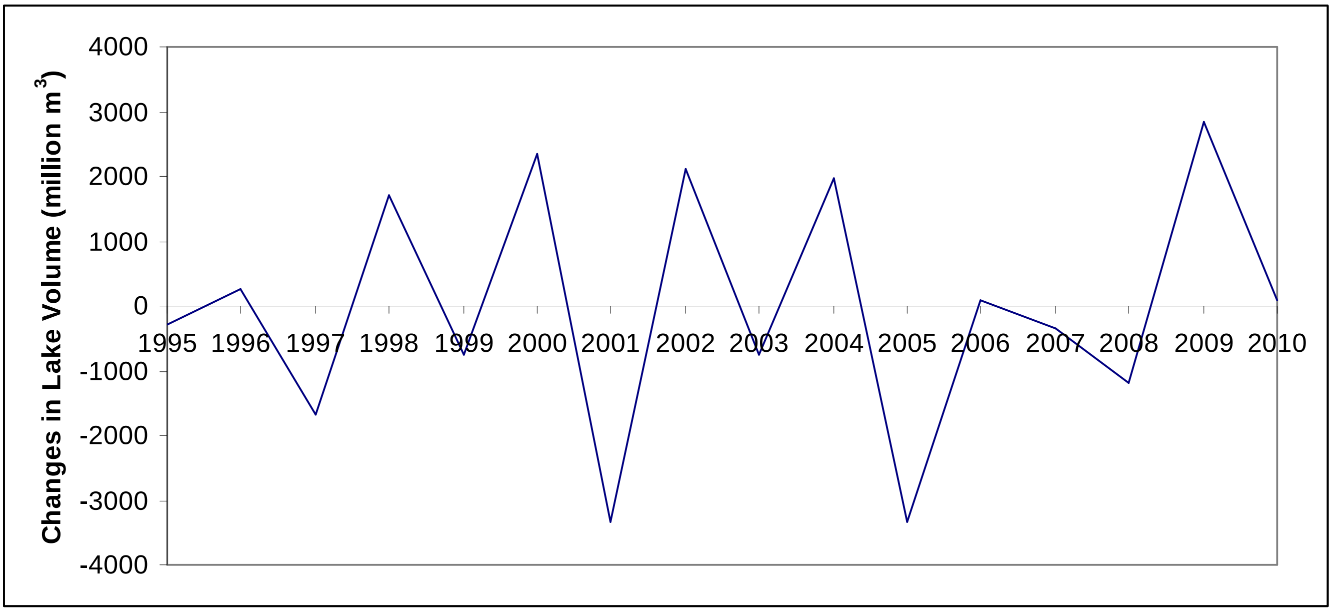


Figure 15: National changes in lake storage

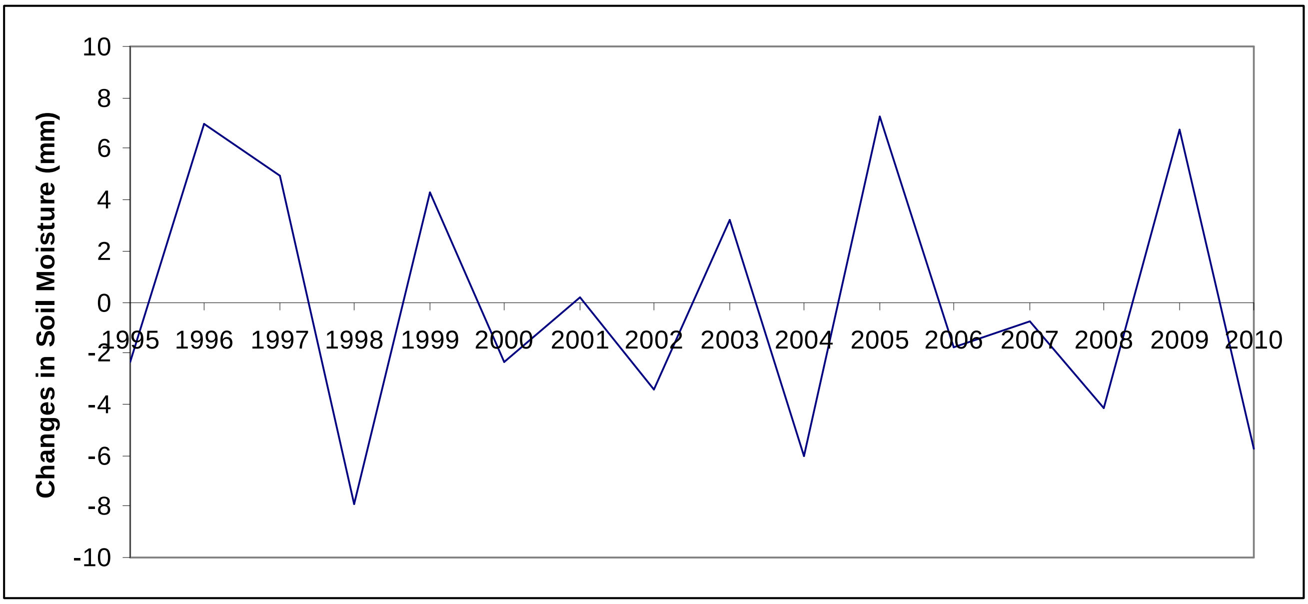


Figure 16: National Changes in soil moisture expressed in mm.

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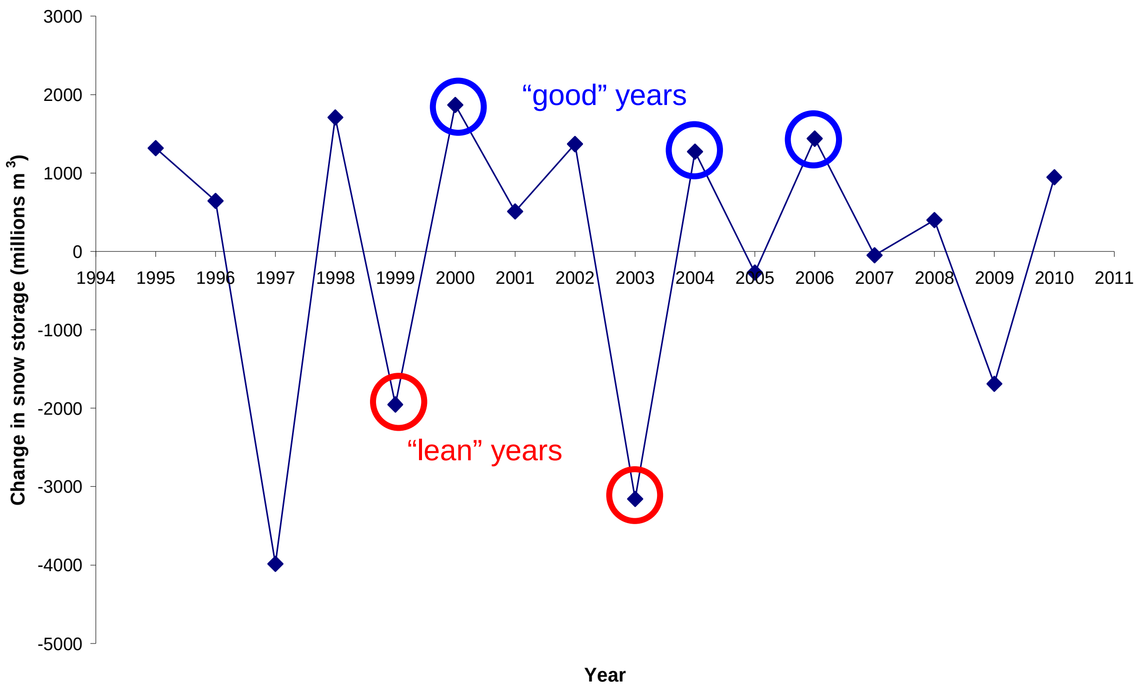

Figure 17: National changes in snow volume, annotated with commentary from Hendrikx et al (2009). .

Causes of Year-to-Year Changes - Year-to-year variations in river flows, evaporation, and abstraction/discharge for hydrogeneration are all affected by the substantial year-to-year variations in precipitation. Some of the larger inter-annual variations are associated with the ENSO phenomenon (El Niño/Southern Oscillation), when large pools of unusually warm or cool ocean water accumulate in the central Pacific, and these are associated with changes in the weather patterns. These ENSO events typically last 6-18 months, with El Niño events in the New Zealand region being characterised by stronger westerly and south-westerly winds than usual, while La Niña events have stronger northeasterly winds. Figure 18 shows these effects in the national accounts data, with the national year-to-year changes in the precipitation account being strongly reflected in the Outflow to sea account. There is a very muted response in the evapotranspiration account data, which increases slightly in high rainfall years because of the greater availability of water for evaporation. However, we consider that the evapotranspiration values are somewhat unrealistic, and further research is needed to improve them. This work will be included into future MSI-funded programme proposals.

There is also evidence of some longer-period persistence, so that for example the years 1945-77 were typically warmer and wetter in the east of New Zealand than the years 1978-1998. This multi-decadal change is associated with an ocean-atmosphere phenomenon called the Interdecadal Pacific Oscillation (IPO). At a simple level, it can be understood as periods where the balance between El Niño and La Niña events changes. There is evidence in Southern Alps-draining river flow records that we have returned to an extended period where conditions are more like those of the 1945-77 period. Thus the apparent downward trend in Figure 18 should not be interpreted as a trend. Studies of longer time series of river flow (McKerchar & Henderson 2003) have shown no evidence of long-term trends, and have instead detected shifts in mean value (in 1978, and possibly in 1999, though this latter shift remains speculative), associated with a change of phase in the IPO.

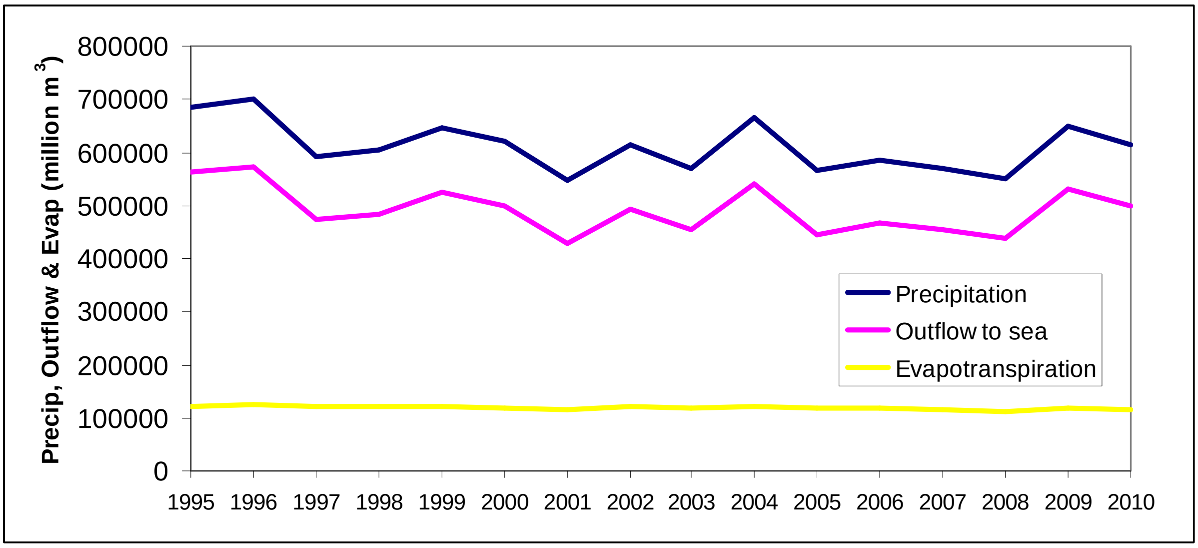

Figure 18: The responses of outflow to sea and evapotranspiration to inter-annual variations in rainfall at the national scale.

Estimates for the mean annual water balance of New Zealand published 35 years ago (Toebes 1972) are shown in Table 8. Although the uncertainties on the Toebes (1972) estimates are substantial, it provides the only fully independent estimate against which to assess the national-scale water accounts. The annual precipitation in Table 8 is similar to that obtained in these accounts (which average 611,000 million m^3/year – see Figure 8). This supports our contention that the rainfall data are now much improved over the previous national water accounts (Woods & Henderson 2003) – rainfall was identified there as being a significant source of uncertainty. The new accounts indicate less evaporation and more runoff than Toebes (1972). The evaporation in this latest set of accounts is now of similar uncertainty to that in the rainfall, and both require some more research.

Table 8: Mean annual water balance of New Zealand as published in Toebes (1972).

Component	Volume (millions of m^3)	Equivalent Depth (mm)
Precipitation	546,100	2059
Evaporation	158,800	599
Runoff	392,800	1481
Change in storage	5,500	21

6.1 Interpretation of Results for National Water Accounts

The data in this report are intended for use in combination with other water accounting information that was compiled independently (e.g., on groundwater, water use by irrigation). A reconciliation procedure will be needed to produce an overall set of balanced accounts. While the full reconciliation is outside the scope of this project, we note below a few points that may be useful in this process.

- The outflow volumes to sea in this report are estimates of total outflows to sea, including both surface and groundwater outflows. These outflows do not make any allowance for abstraction, or any change in groundwater storage.

- The Topnet model does not include deep groundwater systems, for which GNS (Geological and Nuclear Sciences) have previously compiled data on changes in groundwater storage. Some of the Topnet "outflow" actually flows into groundwater systems. This water pathway is known as groundwater recharge, and increases the groundwater storage. From there the water eventually flows out to sea (possibly via a river), or is pumped out for consumptive uses. The Topnet outflow volumes should be adjusted to account for changes in groundwater storage. If the groundwater storage increases during a year, then it is reasonable to reduce Topnet outflow volume by that amount, in order to balance the accounts. If the groundwater storage falls, then the outflow volume should be increased.

- Water is abstracted from rivers and groundwater for irrigation, domestic supply and many other purposes. Some of the water abstracted for irrigation is not ultimately transpired by plants, but instead flows to rivers or groundwater systems. The net abstraction is the total amount abstracted, less the amount that returns to rivers and groundwater. The outflow volumes in this report should be reduced by the net abstractions taken from rivers (total abstraction from rivers minus the amount of returned flow to rivers).

- For abstractions taken from groundwater, the adjustments required would depend on how the groundwater accounts were created. At this stage, NIWA has no detailed information on this. If the account entries for changes in groundwater storage are measured changes, and there are no recharge estimates in the accounts, then (net) abstractions from groundwater should be subtracted from the outflow volumes in this report.

7. Conclusions

A set of 11 surface water components for the first set of national and regional water accounts has been developed for New Zealand, for the period 1995-2010. The accounts capture the broad temporal and regional variability of water movement and storage. They show that precipitation, river flow to the sea, and evapotranspiration are the major components, and that abstraction/discharge by hydrogeneration is a substantial non-consumptive use.

Further development will be needed to improve on estimates of rainfall in high-rainfall areas of New Zealand and on actual evaporation throughout New Zealand, to improve the accuracy of the accounts. However, in their present form, they already provide detailed information on year-to-year trends around the nation.

8. Acknowledgements

We acknowledge the following sources of information used in the preparation of these accounts: they gave permission to use the data, and/or helped make it available:

8.1 Hydrogeneration data

Alpine Energy & ECS
Contact Energy Ltd
Genesis Power Ltd
King Country Energy
Meridian Energy
Mighty River Power
NIWA (Nationally Significant Database: Water Resources and Climate, funded by Foundation for Research Science and Technology contract C01X0910)
Opus International Consultants
Pioneer Generation
TrustPower

8.2 Lake level data

Auckland Regional Council
Alpine Energy & ECS
Contact Energy
Environment Bay of Plenty
Environment Canterbury
Environment Waikato
NIWA (Nationally Significant Database: Water Resources and Climate, funded by Foundation for Research Science and Technology contract C01X0910)
NZX
Genesis Energy
Meridian Energy
Mighty River Power
Opus International Consultants
Otago Regional Council
Pioneer Generation
TrustPower
Greater Wellington Regional Council

9. References

Bandaragoda, C.; Tarboton, D.G.; Woods, R.A. (2004). Application of TOPNET in the Distributed Model Intercomparison Project. *Journal of Hydrology 298(1-4)*: 178–201.

Clark M.P.; Rupp, D.E.; Woods, R.A.; Zheng, X.; Ibbitt, R.P.; Slater, A.G.; Schmidt, J.; Uddstrom, M. (2008). Hydrological data assimilation with the ensemble Kalman filter: Use of streamflow observations to update states in a distributed hydrologic model. *Advances in Water Resources 31(10)*: 1309-1324, doi:10.1016/j.advwatres.2008.06.005.

Clark, M.; Hreinsson, E.O.; Martenez, G.; Tait, A.; Slater, A.; Hendrikx, J.; Owens, I.; Gupta, H.; Schmidt, J.; Woods, R. Simulations of seasonal snow for the South Island, New Zealand. *Journal of Hydrology (NZ) 48(2)*: 41-58 .

Chinn, T.J. (2001). Distribution of the glacial water resources of New Zealand. *Journal of Hydrology (NZ) 40(2)*: 139-187.

Fitzharris, B.B.; Garr, C.E. (1995). Simulation of past variability in seasonal snow in the Southern Alps, New Zealand. *Annals of Glaciology 21*: 377-382.

Gordon, N.D. (1986). The Southern Oscillation and New Zealand weather. *Monthly Weather Review 114*: 371-387.

Hendrikx, J.; Clark, M.P.; Hreinsson, E.Ö.; Tait, A.B.; Woods, R.A.; Slater, A.G.; Mullan, A.B. (2009). “Simulations of seasonal snow in New Zealand: past and future.” Presented at the 9th International Conference on Southern Hemisphere Meteorology and Oceanography (9ICSHMO), Melbourne, Australia, 9-13 February 2009.

Ibbitt, R.P.; Henderson, R.D.; Copeland, J.; Wratt, D.S. (2001). Simulating mountain runoff with meso-scale weather model rainfall estimates: a New Zealand experience. *Journal of Hydrology 239*: 19-32.

Kerr, T. (2005). Snow storage modelling in the Lake Pukaki catchment, New Zealand: An investigation of enhancements to the Snowsim model. Unpublished MSc thesis. University of Canterbury, Christchurch. 151 p.

Maidment, D.R. (Ed.) (1993). Handbook of Hydrology. McGraw Hill.

McAlevey, B. (1998). A distributed seasonal snow model for New Zealand. Unpublished MSc thesis. University of Otago, Dunedin. 186 p.

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.

Salinger, M.J.; Mullan, A.B. (1999). New Zealand climate: temperature and precipitation variations and their links with atmospheric circulation 1930-1994. *International Journal of Climatology 19*: 1049-1071.

Snelder, T.; Biggs, B.J.; Weatherhead, M. (2004). New Zealand River Environment Classification User Guide. *No.* 161 p.

Tait, A. (submitted). Future projections of growing degree days and frost in New Zealand and some implications for grape growing. *Weather and Climate*.

Tait, A.; Henderson, R.D.; Turner, R.; Zheng, X. (2006). Spatial interpolation of daily rainfall for New Zealand. *International Journal of Climatology 26(14)*: 2097-2115.

Toebes, C. (1972). The Water Balance of New Zealand. *Journal of Hydrology (NZ) 11(2)*: 127-139.

White, P.A.; Reeves, R.R. (2002). The volume of groundwater in New Zealand: 1994 to 2001. Institute of Geological & Nuclear Sciences Client Report *No.* 2002/79. 39 p.

Willsman, A.; Salinger, J. (2007). Annual Glacier Volumes in New Zealand 1995 - 2005. NIWA Client Report *No.* AKL2007-014. 23 p.

Willsman, A.; (2011). Annual Glacier Volumes in New Zealand 1995 - 2010. NIWA Client Report *No.* CHC2011-050. 18 p.

Woods, R.A.; Henderson, R.D. (2003). Surface water components of New Zealand's National Water Accounts, 1995-2001. NIWA Client Report *No.* CHC2003-074. 50p.

Appendix 1. Introduction to Hydrological Modelling

A Topnet hydrological model of New Zealand was developed to assist with the following water account components: Inflows from rivers, Evapotranspiration, Outflows to sea from surface water, Outflows to other regions, and Net change in soil moisture. This methodology was chosen because there are many places in New Zealand where these components are not measured. The development of the hydrological model is also intended to have longer-term benefits for the Ministry for the Environment, to assist with issues of water allocation across New Zealand.

The 15 models (**Figure 2**) are based on the regions defined by the River Environment Classification (Snelder et al. 2004), which were defined as a convenient way to subdivide regions too large for modelling as a whole. Each of the 15 models contains several thousand small catchments; the average area of each catchment is approximately 8 km^2. A sample of these catchments is shown in Figure A1.1, for the part of the “waikato” model which covers the region around Lake Taupo. We have determined which regional boundary each catchment falls into, and then summarised the catchment results to the region level for the regional accounts. The national accounts are obtained by summarising the results from all regions.

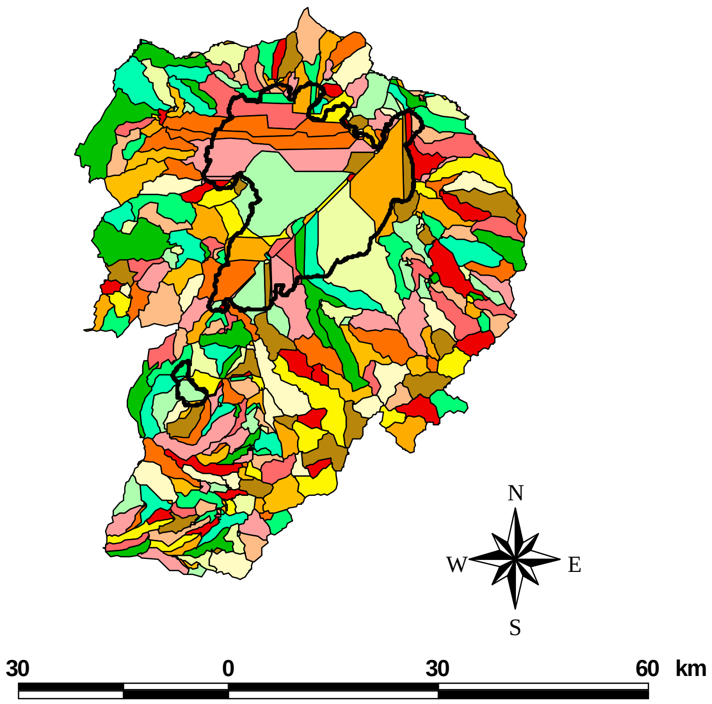

Figure A1.1: Modelled catchment boundaries within part of the “waikato” model. The shorelines of Lakes Taupo and Rotoaira are shown in black for reference. The colours distinguish neighbouring catchments from one another.

Raw daily results are generated for every single catchment in New Zealand: due to the size of these files, we have retained only the annual summary data. It currently takes about 48 hours computing time on a high-end PC to run all the models for 16 years, and this produces almost 100GB of model output: the running of these models is fully automated.

The hydrological model, called Topnet (see Clark et al (2008), (Bandaragoda et al. 2004) and (Ibbitt et al. 2001)), keeps daily accounts of the water balance for each of the catchments: that is, precipitation, evapotranspiration, discharge to rivers, change in soil water storage, and change in soil water storage (the model monitors this in two parts: root zone water, which can be evaporated, and groundwater, which can only be evaporated if it is close to the ground surface). The model does not include deep aquifers. The discharge to river from each catchment is passed into a model of the river network. Water is routed along the network, and joins up with water from other catchments. The water eventually flows out to sea: there are no losses modelled from the river into groundwater systems. Figure A1.2 summarises some of the basic concepts in the Topnet model.

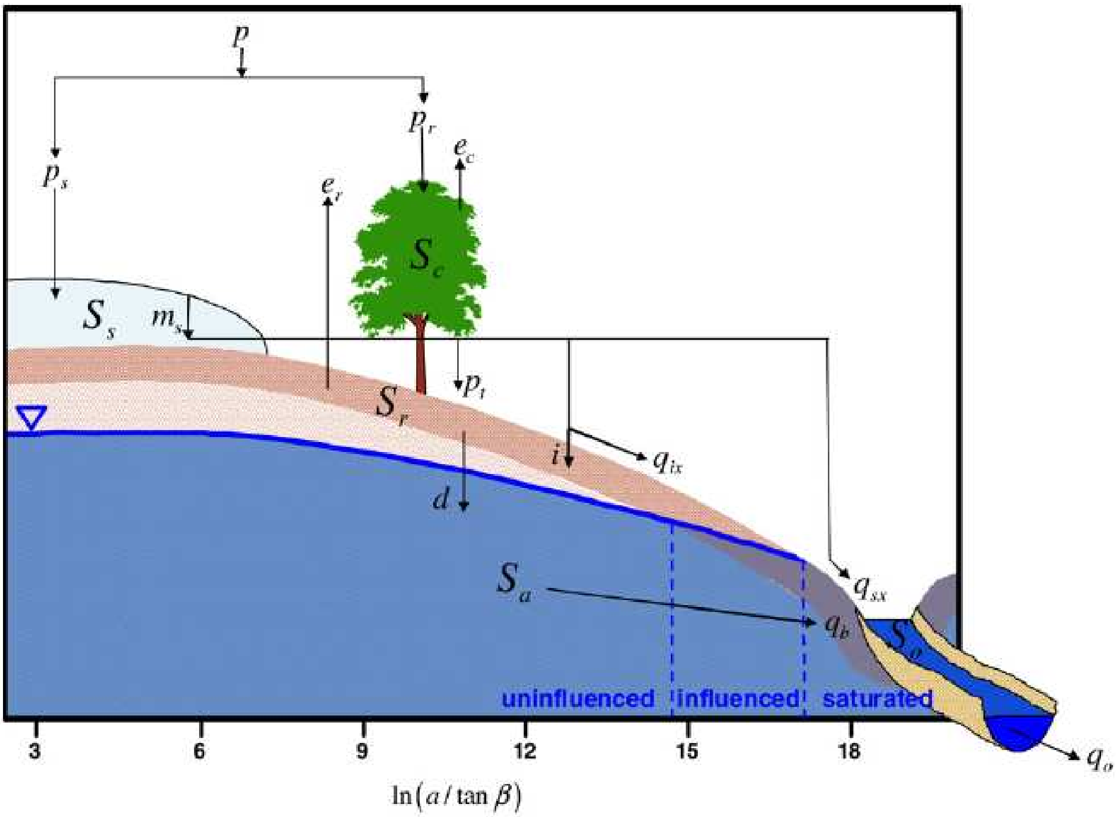

Figure A1.2: Runoff generation processes in each TopNet catchment. The topographic index ln(a/tanβ) increases towards the stream indicating areas of topographic convergence and areas where the water table intersects the soil zone. The symbols in the diagram are defined in Clark et al (2008).

The catchment precipitation is calculated from the precipitation at the grid points in and around the catchment.

All precipitation becomes either surface runoff or infiltration, according to infiltration calculations. If the groundwater storage levels are high, then more of the catchment is saturated to the surface, and so more area is generating surface runoff. The proportion of this “saturated area” surface runoff expands and contracts both seasonally and within storms. In addition, if the soil in the root zone is dry then more water can infiltrate. The model also takes account of the fact that as the groundwater levels rise closer to the surface, the soil which is near the saturated area is also getting wetter.

Evapotranspiration is calculated by first estimating a maximum possible value given the temperature and day-length on that day (the “potential evapotranspiration”, using the Priestley-Taylor approach, as implemented in Maidment (1993), and then adjusting for the increase in evaporation that is created by tall vegetation (e.g. forest). If the soil in the root zone is wet enough (water holding capacities are estimated from a soil database), then the actual value of evapotranspiration is the “potential evapotranspiration”, and if the soil moisture in the root zone is below “field capacity” then actual value is proportionately less than the potential value.

If the soil is wet (above field capacity) then water drains to the shallow groundwater system. The wetter the soil in the root zone, the faster it drains. Water that enters the groundwater zone increases the amount of water stored there. Water flows from the groundwater zone into streams. The more water there is in the groundwater system, the faster it flows into the streams. The flow in streams is routed through the river network using kinematic wave modelling (Figure A1.3)

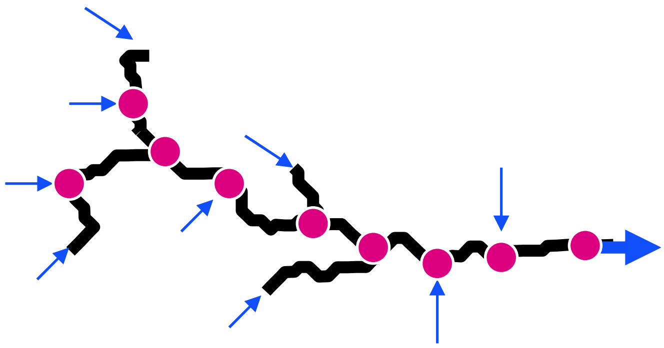

Figure A1.3: A typical river network in the Topnet model. Runoff from each of the catchments (blue arrows) enters the river network either at the head of small streams, or at node points within the river network.