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Distribution of the glacial water resources of New Zealand

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Abstract

A detailed inventory of the glaciers of New Zealand found a total of 3144 glaciers of over 1 ha in area covering a total area of 1158 km^2. The estimated ice volume of 53.29 km^3 is distributed from Mt. Ruapehu at 39° 15' S to southern Fiordland at 45° 57' S. Glacier mean elevations rise by 500 m west to east across the Southern Alps, and descend by 1000 m from Mt. Ruapehu in the north to southern Fiordland in the south. Intensity of glacierisation is a function of the height of the mountain ranges above the regional snowline. The glaciers contain a small but significant water resource in storage that accumulates or is released as the climate varies. The amount of water is most significant to those catchments containing the few larger glaciers. Fluctuations of the glaciers record enhanced signals of climate variation and change. A 50% reduction in glacier volume over 50 years would provide an additional flow from storage of 8 cumecs to the Waitaki River and 1 cumec to the Clutha River.

Introduction

Glacier ice currently covers 10% of the earth's surface, or some 15 million km^2. Although this resource contains 75% of the world's fresh water, most of it is locked away in the massive ice sheets of Greenland and Antarctica. The remaining 3-4 percent is found spread over an area of 550,000 km^2 as mountain glaciers and ice caps. Of this total, 50% is found in North America, 44% in Eurasia, 5% in South America and 1% in New Zealand (UNEP, 1992).

The first assessment of the extent of New Zealand glaciers was published by Mercer (1967) in a Southern Hemisphere Glacier Atlas. The publication contains a map showing glaciers between Arthur's Pass and Milford Sound and those on Mt. Ruapehu, but gives no estimates of total glacier numbers, areas or volumes. In a later estimate of perennial snow and ice water resources, Anderton (1973) identified 527 glaciers occupying a total area of 810±40 km^2 and containing an estimated 63±4 km^3 of ice.

In the late 1970s, the then Ministry of Works, Water and Soil Division began a detailed inventory of the glaciers of New Zealand in accordance with the methods of the IHD programme (UNESCO, 1970). This detailed inventory (Chinn, 1991) indicated 3144 glaciers in New Zealand, covering an area of 1158 km^2 and containing an estimated 53.29 km^3 of ice. The purpose of this paper is to present a summary of the results of this inventory, the role of glaciers in the quantity of water stored as perennial snow and ice in the New Zealand mountain ranges and its availability as a water resource.

Distribution of the glaciers

New Zealand has a comparatively large number of individual glaciers because the majority of the mountain peaks of the Southern Alps barely reach to above the regional snowline. This topography favours a large number of individual small cirque glaciers and glacierettes on separate peaks. The glaciers of the Southern Alps are distributed from the Inland Kaikoura Range at 42° 01' S in the north, to southern Fiordland at 45° 57' S in the south. Between Arthur's and Lewis Passes, none of the summits reach the regional snowline and there are no glaciers, while north of Lewis Pass there are only a few scattered small glaciers. The largest glaciers are to be found in the central Southern Alps, where summit heights reach to well above the regional snowline. Almost all of the main valleys in this region head with steep slopes against the Main Divide, with a few notable exceptions. Between the Wanganui and Rangitata Rivers, the Garden of Eden and Garden of Allah plateaux hold low-elevation icefields close to the regional snowline. Adjacent to Mt. Cook, the Franz Josef and Fox Glaciers spill from large snowfields on the only two Westland valley heads not incised deeply back to the Main Divide. Further southward, the Bonar Glacier and Olivine Ice Plateau are high-level valley glaciers. In the Landsborough Valley, the McCardell and Dechen Glaciers flow radially from the summit of Mt. Dechen in what may be termed an "ice cap", the only one in New Zealand. Few of the mountains of central to southern Fiordland intercept the snowline and here again, as in the northern Alps, the few glaciers are widely dispersed.

The North Island has extensive areas of low mountain and hill country that barely rises above the present tree limit. Three of the highest volcanic cones reach close to the permanent snowline, but only Mount Ruapehu at 39° 15' S, with a summit reaching 2,752 m, supports inventoried glaciers (Fig. 1). The summit plateau has the only crater glacier in New Zealand. Although the summit volcanic cone of Mt. Egmont rises above the regional snowline and has ice bodies near the minimum size for inclusion in the inventory, insufficient data was available to verify that this ice is permanent, so no glaciers for this peak are included in the inventory.

The wide distribution of the glaciers present contrasts with a common perception of a limited distribution of a few tens of glaciers centred around Mount Cook and Franz Josef, with smaller glaciers and "permanent snowfields" scattered between Arthur's Pass and the Darran Mountains of Fiordland. This perception has been largely due to inadequate information available as to what constitutes a glacier (see definition, below). Also, the distinction between perennial snow and seasonal snow has been confused, leading to the majority of the small glaciers being dismissed as seasonal snow patches, and many mountain glaciers have been dismissed as "snowfields", when any permanent snowfield has to be a glacier by definition.

Climate

New Zealand has a humid maritime climate, with the Southern Alps lying across the path of prevailing westerly winds, a situation which creates steep eastward precipitation gradients with a strong föhn effect in westerly conditions. Mean annual precipitation rises rapidly from 3000 mm along the narrow western coastal plains to a maximum of over 10,000 mm in areas immediately west of the Main Divide. From this maximum, precipitation diminishes approximately exponentially to about 1,000 mm in the eastern ranges (Chinn, 1979; Griffiths and McSaveney, 1983; Henderson and Thompson, 1999). The drier the climate, the colder the temperatures have to be to maintain a glacier, consequently glacier mean elevations rise from 1500 m in the west to colder elevations over 2000 m on eastern glaciers. The easternmost ranges extend into semi-arid climates and here, where there is a low ratio of snowfall to debris supply, many groups of classical rock glaciers, both active and fossil, are to be found. Although westerly winds prevail, easterly and, more especially, southerly winds are important sources of snow to the east of the main divide. Precipitation is evenly distributed throughout the year.

Recent studies have demonstrated that despite the very steep west-east precipitation gradients, there are no differences in response to climate between the glaciers to the west of the Main Divide from those to the east (Chinn, 1996, 1999). The annual equilibrium line altitudes (ELAs) or end-of-summer snowlines, which provide a good surrogate for glacier mass balance changes (Chinn, 1995) have been analysed for trend surface variations over the past 20 years (Lamont *et al.*, 1999; Chinn and Salinger, 1999). When compared from year to year, and with different circulation patterns, the annual shifts in ELA's show that all of the glaciers throughout the entire southern Alps behave in a similar manner, with no significant differences in surrogate annual mass balance changes either across or along the Main Divide. Thus the notion that the "western" glaciers behave differently from the "eastern" glaciers that is frequently mentioned in literature is unfounded. This false impression arises from the many simplistic comparisons made between only two groups of glaciers that are of different types and have very different responses to climate. Frontal changes at the steep and exceptionally responsive Franz Josef and Fox Glaciers, which provide enhanced responses to climate within 5 to 8 years, have repeatedly been compared with the large, low-gradient valley glaciers of the Mount Cook area, which have slow, subdued response times in the order of 100 years.

Recent glacier fluctuations

Since the end of the 19th century, the end of the "Little Ice Age", a 500-year cool period, New Zealand glaciers have generally undergone a hesitating, fluctuating recession, accompanying a small measured increase in temperatures between the 1860's and 1940's. Recession was slow at first, but gained momentum in the 1910–1930 period. It was not until after the 1940's, when temperatures rose sharply by about 0.5°C, that accelerating retreat became of concern to both alpinists and the tourist industry alike. Precipitation changes have not been so pronounced. During the warm 1950's glacial retreat was particularly pronounced. Since then the smaller cirque and alpine glaciers, and a few of the large glaciers with fast response times, have regained equilibrium with the present climate and have ceased receding. However, the trunks of a few of the large, low-gradient valley glaciers, which have response times of decades, continue to lower and withdraw.

Over the last century New Zealand glaciers have shortened by an average of 38%, with length changes showing a large variability in individual response, ranging from 0 to 6.6 km, with a mean recession rate of 13.3 m/a (Chinn, 1996). Associated with this retreat there has been a loss of 23% to 32% of glacierised area, which is similar to the European Alps loss of 30–40% (Haeberli, 1994), making the 1990's extent of glacier ice probably less than at any time during the past 5000 years.

Recession of the glacier fronts has been accompanied by an upward shift in mean elevation for all glaciers of 94 m (Chinn, 1996). Assuming precipitation has remained constant, this shift is approximately equivalent to an 0.65°C climate warming over the last century. Cirque and alpine glaciers have lost nearly half of their "Little Ice Age" lengths, while the valley glaciers have lost only a quarter of their original length. This difference is largely due to the significantly longer response times of the larger, low-gradient glaciers. The short response times of decades for the cirque and steep alpine glaciers have allowed these glaciers to complete their readjustment to the new climate of this century, whereas the large valley glaciers, which have response times of over a century, have yet to complete this adjustment. Some of the large debris-mantled glaciers such as the Murchison, Balfour and La Perouse, after a century of surface lowering, still essentially retain their "Little Ice Age" outlines. The large proportions of debris cover on these valley glaciers have also reduced their response to warming. Some of these large valley glaciers have entered a period of rapid retreat by accelerating proglacial lake growth, as an inevitable size readjustment to achieve equilibrium with the present climate. The significance and processes of the growth of ice-contact lakes has been addressed by Kirkbride (1993), Warren and Kirkbride (1998), Kirkbride and Warren (1999), Hochstein *et al.* (1995) and Purdie and Fitzharris (1999).

Basic glacier measurements

Mean elevations

The mean altitudes of the glaciers provide a value for the altitude of the regional snowline. A mountain has to rise above this altitude to support a glacier. The first attempt at assessing the regional distribution of present and past New Zealand glacier snowlines was made by Willett (1950), and the glaciation limit (the altitudes of the highest peaks without glaciers and the lowest peaks with glaciers) by Porter (1975). In this study, the mean elevations of the glaciers are used to give values for the regional snowline altitude. This approximation becomes increasingly more accurate the smaller the glacier. The mean elevation of small cirque glaciers closely approximates the altitude of the equilibrium snowline, defined as the end-of-summer snowline position, which when maintained over a number of years, will maintain the glacier at the same size.

Glacier mass balance

Glacier mass balance, the measured net annual gain or loss of snow and ice at the glacier surface, is the most informative measurement of glacier change. Mass balance values provide a direct, undelayed measurement of the climate of the past year without the signal being distorted and delayed with the passage of ice through the glacier system. Only one significant series of mass balance measurements have been made in New Zealand. These studies were made at the Ivory Glacier, a small cirque glacier in the Waitaha catchment, Westland, from 1969 to 1975 as part of an IHD Programme of representative basin studies (Anderton and Chinn, 1973, 1978). Annual mass balance was consistently negative during the study period. The runoff pattern was dominated by rain. The annual mean precipitation was 9630 mm for the period 1971–75. Snow represented about 25% of annual precipitation. Melt contributed 21% of runoff, including 9% contributed by loss of glacier volume. (Anderton and Chinn, 1973, 1978; Hay and Fitzharris, 1988).

Mass balance measurements are very labour intensive and costly, as they entail the installation of an array of stakes over the entire glacier. These stakes have to be visited at regular intervals to measure the snow gains and ice losses throughout the entire glacier year. As a consequence few full mass balance studies are continued world-wide, and alternative methods of measuring a glacier's health are employed.

Glacier snowlines

One alternative method of measuring glacier changes is to use the position of the snowline at the end of summer as a surrogate for mass balance. High snowlines indicate less snow and a negative balance while low snowlines indicate a gain to the net snowpack and a positive balance. Each glacier has a unique position of the snowline for a zero balance, known as the equilibrium line altitude or ELA. If the snowline maintains this position over many years, the glacier will remain in equilibrium with no change to its size or length. The ELA is easily recorded by simply photographing its position across the glacier at the end of summer (Chinn, 1995).

Preliminary work on this inventory indicated that the glacier outlines depicted on existing 1-inch-to-1-mile maps were quite unreliable as they had been compiled from vertical aerial photographs taken at various times of the year, with very few taken at the end of summer. Consequently these aerial photographs contained varying degrees of seasonal snow cover, making it impossible to accurately map the outlines of the smaller glaciers. To make an acceptably accurate inventory of the smaller glaciers, a programme was instigated to take oblique photographs of the glaciers at the end of summer from a small aircraft. The same flights would also record the frontal positions and the glacier ELAs and therefore record mass balance changes. Obviously it would be impractical to attempt to fly all of the 3144 glaciers in any one season, but by varying the flight path each year, it was expected that after a few year's flights, the majority of the glaciers would be photographed. This proved to be correct, and a photographic database for this inventory was compiled within a few years. However it was another 20 years of flights before the final glacier was captured on film. The first flight was made in 1977, followed by a very successful flight in 1978, and it is on this 1978 data that this inventory is based.

The regional snowline

The results of the 1978 snowline flight were used to map the regional trend surface of the glacier snowline elevations throughout the Southern Alps

(Chinn and Whitehouse, 1980). The trend surface of snowline altitudes was found to be strongly up-warped towards the east, following the precipitation gradient. In the central Southern Alps it rises from 1600 m west of the main divide to 2200 m on the easternmost glaciers. This surface also follows the expected lowering with increasing latitude, from 2500 m on Mt. Ruapehu at 39°17' S, 1850 m at Arthur's Pass at 43° S, to 1500 m in southern Fiordland at 45°56' S. The study also found that the snowlines for glaciers with northern aspects were some 300 to 320 m higher than those for south-facing glaciers.

Ongoing snowline monitoring

Ongoing aerial flights use the end-of-summer snowline positions, or equilibrium line altitude (ELA) as defined by Meier (1962) as a surrogate for mass balance. The surveys currently cover some 48 selected index glaciers distributed along east-west transects throughout the Southern Alps. Since the first 1977 flight there have been only three years when no flights were made. The data collected have shown that the trend of glacier recession over the last 100 years has reversed, with the glaciers showing inferred positive balances in most years since 1978. Currently, all except a few glacier fronts are thickening and advancing.

The world glacier inventory

The need for a worldwide inventory of existing perennial ice and snow masses was first considered during the International Hydrological Decade (IHD) in 1965-74. The International Commission on Snow and Ice (ICSI) of the International Association of Scientific Hydrology (IASH) was requested by the coordinating council of IHD to prepare guidance material for the compilation of glacier inventory data. Hence, in 1970, a working group of ICSI produced a UNESCO/IASH Technical Paper titled "Guide for the Compilation and Assemblage of Data for a World Inventory of Perennial Snow and Ice Masses".

In 1976 a Temporary Technical Secretariat (TTS) was established in the Swiss Federal Institute of Technology (ETH), Zürich to carry out the necessary international co-ordination of the national inventory compilation and ultimately to produce a World Glacier Inventory (WGI). Although the original rationale for producing a world glacier inventory was to contribute information about water in frozen form to the world water balance studies within IHD, it gradually became clear that such an inventory could also serve as a basis for long-term monitoring of glacier behaviour in different climatic regions and be useful in studies of long-term climatic changes. (Gwynne, 1989).

A workshop on the Glacier Inventory was held in 1978, at Riederalp, Switzerland, when participants from all countries involved in compiling inventories, including New Zealand, met to discuss methods and progress (IASH – AIHS, 1980). This meeting coordinated the techniques and standards for the inventories and gave an incentive for each participating country to complete the work. It was emphasised that the TTS would definitely be temporary and that the project would be terminated in the near future to prevent refining and upgrading of the existing inventories from continuing endlessly.

In 1983 it was decided that the World Glacier Inventory should be concluded as soon as possible after 1985. The remaining activities of the TTS were merged with the Permanent Service on Glacier Fluctuations (PSFG), which had continued since 1950, to form a single service called the World Glacier Monitoring Service (WGMS) and a summary of the world glacier inventory was published (Haeberli *et. al.*, 1989). The operation of the new service started at the ETH in 1986 as part of Global Environment Monitoring System (GEMS), with financial support from UNEP, UNESCO, FAGS/ICSU and ETH. This new service ensures a continuation of cooperation and archiving of glaciological monitoring data.

The New Zealand glacier inventory

In 1971 the Water and Soil Division of the Ministry of Works and Development was contacted with the initial suggestion that New Zealand should become involved in compiling a national inventory of its glaciers. The Glaciology Section, Water and Soil Division of the Ministry of Works and Development, began preliminary work on the project following the 1978 Riederalp meeting.

With the data available from oblique aerial photography, the inventory was methodically compiled from the early 1980's. In 1987 the Department of Survey and Land Information made inquiries as to whether the inventory data might be used in their compiling of a new 1:50,000 scale mapping series. An agreement was made for the purchase of the glacier outline data of a completed inventory, and this financial impetus saw the completion of the project. The digitised outlines were used in publishing the NZMS 260 map series at 1:50,000 scale.

Definition of a glacier

The multitudes of small snow patches and glacierettes throughout the New Zealand Southern Alps made it necessary to have a working definition of a glacier. Most publications tend to avoid defining a glacier, mainly because of the complications of combining the descriptive and generic aspects of glaciers. The few available definitions are frequently inappropriate, e.g. one dictionary definition of a glacier reads "a slow moving river of ice such as is found in hollows and on the slopes of lofty mountains". In the Dictionary of Geological Terms, American Geological Institute (1962), a glacier is "a mass of ice with definite lateral limits, with motion in a definite direction, and originating from the compacting of snow by pressure". This definition may also be applied to a truckload of compressed snow being carried along a road. A useful definition should be directed at what a glacier is rather than its appearance, thus:

> "a glacier is the accumulation of many years of the snow surplus remaining above the snowline at the end of summer, which, metamorphosed into ice, flows slowly down slope until melt at lower altitude equals the supply".

A definition useful to the inventory also requires a limiting size and persistence with respect to climate. The WGI TTS recommended that 1 ha should be the minimum size for a glacier to be inventoried. The areas of ice bodies of this size vary markedly from year to year, depending on annual mass balance, and if they disappear in some negative balance years, then they become perennial snow patches, and are therefore not glaciers. The definition adopted for mapping the New Zealand inventory took into account both the size and persistence of the snow and ice body:

> *"Those ice bodies of 1 ha or greater in area which have remained in existence during the most negative balance years over the past two decades".*

On this definition, decisions were made, based on persistence, as to whether small ice bodies were included or excluded. Since the completion of the inventory, a few small glaciers mapped from vertical aerial photographs have, on later information gained on the aerial flights, been found to be non-existent or too small to be regarded as glaciers. These have been deleted from the inventory.

Date of the Inventory

Glaciers respond to climatic changes, and as climate change monitoring is one of the foremost reasons for compiling the inventory, a baseline time has to be established against which to compare changes to the glaciers. The 1978 set of oblique aerial photographs gave the best coverage of the early glacier flights, and this inventory has, wherever possible, been mapped for autumn 1978. One exception is the North Island glaciers on Mount Ruapehu, where no suitable photographs were available until a glacier flight was made in 1988. Ruapehu is inventoried for 1988; for all other areas, the N.Z. Glacier Inventory is as for 1978.

Glacier numbering system

The New Zealand glacier inventory was compiled using "Instructions for compilation and assemblage of data for a World Glacier Inventory" (Müller *et al.*, 1977), issued by the TTS. Fortuitously, in New Zealand, every river and stream entering the sea had been assigned a catchment number by Soil Conservation and Rivers Control Council (1956) for hydrological purposes. These three-digit numbers are ordered clockwise around each island, and the use of this classification provided no problems of compatibility with the WGI system. Existing river numbers were therefore used instead of river basin order as suggested by the TTS. The larger catchments were subdivided into sub-basins, using letters, also applied clockwise within the catchment. Within each defined basin the glaciers are numbered consecutively and clockwise around the basin. A departure from this numbering protocol was made for the Ruapehu volcano, where a total of 18 glaciers are numbered clockwise around the mountain through the three separate drainage catchments involved (Fig. 1).

Parameters measured for each glacier

From the glacier outlines drawn on 1-inch-to-1-mile maps, data for each glacier was recorded directly on to a form supplied by the WGI, which had provision for a maximum of 42 pieces of data when accuracy estimates are included. The base data includes about 20 common attributes measured for each glacier.

Identification information includes; Glacier Number, Name (if any), Drainage Basin, first-, second- and third-order rivers, and number of drainage basins (unlike rivers, glaciers may drain into two or more separate catchments).

The *position* of each glacier is defined by Latitude, Longitude and Map reference.

From the glacier outlines the following *dimension* measurements were made: Total area; Debris-covered area; Thickness estimate; Volume estimate; and the associated *linear measurements*: Mean width; Total length and Length of exposed (clean) ice. Four elevations are taken for each glacier: Maximum, Minimum, Mean and Minimum for exposed ice. *Aspects* for both the accumulation and ablation areas are noted. Finally the glacier is classified into *type* according to size, morphology and frontal characteristics, with types of moraines.

Glacier outlines were subjectively drawn on 1:63,360 scale maps from both oblique and vertical aerial photographs. Accuracy of draughting the outlines is about ±100 m (1.5 mm on the NZMS 1 map). Subsequent digitising has not introduced any significant further error. Errors in area

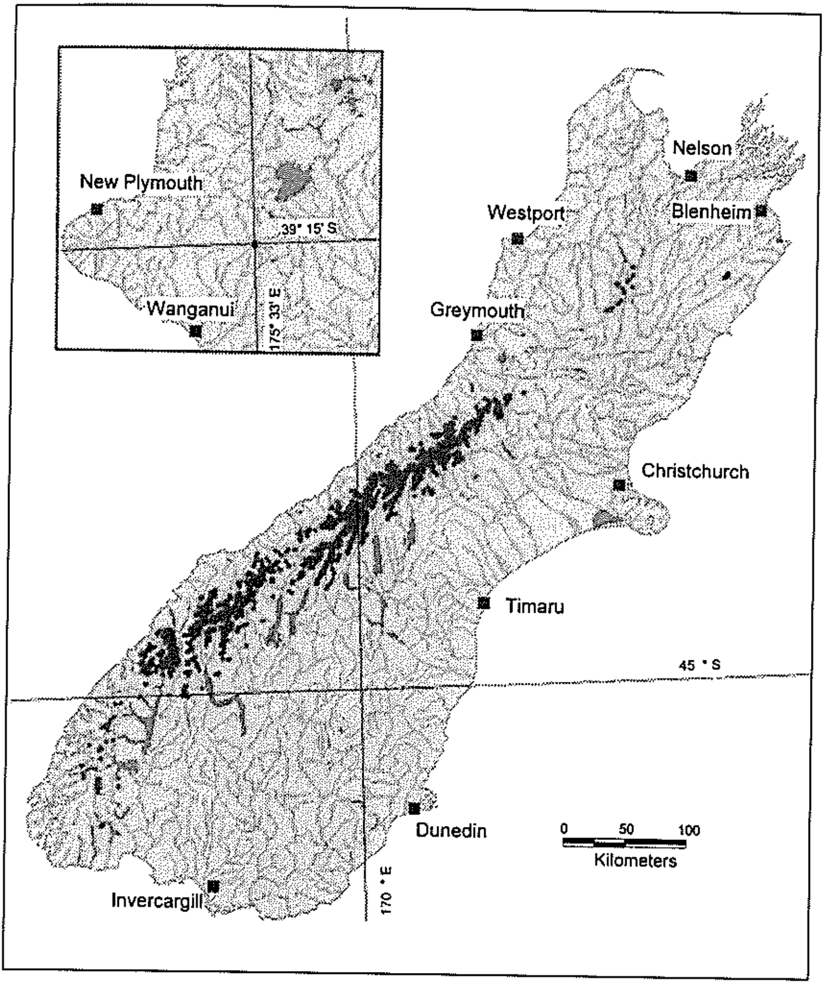

Figure 1 – Distribution of the glaciers of New Zealand plotted as a filled circle for each individual glacier centroid (not as glacier outlines) in relation to rivers and lakes. Mt. Ruapehu inset.

measurement will diminish from an estimated ± 25% for glaciers under 5 ha to less than ±5% for the large glaciers.

Ice volumes for each glacier were computed from the measured area and estimated mean depth. Mean ice depths are rarely measured and are the least accurate of the inventoried values, as they have been determined from area/mean-depth relationships. These relationships have been derived from a meagre number of world-wide ice thickness measurements that have been used to compile the relationship, supplied by the WGMS:

$$D = 5.2 + 15.4 \sqrt{A} \qquad (1)$$

where D is mean ice thickness (m) and A is total glacier area in km^2.

The smaller the glacier, the proportionally larger the depth estimate and an error of ±50% is assigned to the small glaciers. Volume errors therefore lie between ±50% for the smaller glaciers to about ±15% for the larger glaciers.

Summary of all New Zealand glacial data

Glacial regions

In the first attempt to document the glaciers of New Zealand, Mercer (1967) published a map effectively showing the glaciers as mapped in the existing territorial map series. He grouped the glaciers into five regions: Arthur's Pass to Mount Cook National Park; Mount Cook and Westland National Parks; Mount Cook National Park to Haast Pass; Haast Pass to Fiordland National Park and Fiordland National Park. Anderton (1973) in a more comprehensive inventory, also recognised five regions based on local areas of concentrated glaciation and named them after the dominant mountain peak in each region: Mt Whitcombe; Mt Cook; Mt Aspiring; Olivine and Barrier Ranges and Mt Tutoko. Gellatly *et al.* (1988) effectively expanded the classification of Anderton into eight regions: North Island; Nelson and Kaikouras; Arthur's Pass and North Canterbury; Mid Canterbury; Mt. Cook; Mt. Aspiring; Westland and Fiordland. Each of these classifications give useful geographic distributions, but they do not examine glacier distribution and behaviour with respect to climate. This paper uses a regional classification similar to the above, but allows logical comparisons across and along the Main Divide and the North Island in terms of climatic and topographic zones. The resultant five broad groups based on geographic areas and climatic zones are: Mount Ruapehu; northern South Island; eastern Alps; western Alps and Fiordland.

Individual glacier distribution

The distribution of the 3144 inventoried individual glaciers of New Zealand is presented in Figure 1, plotted as single points at the centroid of each individual glacier and *not* as glacier outlines. The majority of the small glaciers would not be visible at the scale of Figure 1 if they were drawn to scale.

A total of 18 glaciers were recognised in the North Island, all on Mt. Ruapehu. In the northern South Island, the Nelson Lakes glaciers and the glaciers of the Inland Kaikoura Range, although grouped together because they are so few in number, climatically fall into two separate groups. The Nelson Lakes glaciers are maritime Main Divide glaciers, while the 9 glaciers of the Inland Kaikoura Range are in an arid zone and contain some of the finest examples of active rock glaciers in New Zealand (Fig. 2). Peaks between Nelson Lakes and Lewis Pass, where 35 glaciers have been identified, barely intercept the snowline, and southward, between Lewis Pass and the headwaters of the Taramakau and Waimakariri Rivers, none of the mountains intercept the permanent snowline.

The area between Arthur's Pass and Hollyford Valley contains the bulk of the ice and has been separated into eastern and western regions. South of Hollyford Valley, in the lower subdued topography of Fiordland, the usual east-west gradient of glacier mid-elevations is not apparent because of a more uniform, but high, distribution of precipitation. The southernmost glacier lies on Caroline Peak above Lake Hauroko (Fig. 3).

Density of glaciation

The visually obvious changes in the amount of ice cover or degree of glacierisation of the various river basins cannot be expressed as a percentage of basin area because this value depends on where one arbitrarily places the position of the bottom of the catchment. However, distance along the Main Divide is independent of catchment areas, and Figure 4 presents a plot of intensity of glacierisation as ha per km southward along the Divide, together with topographic heights. The greatest areas of ice cover logically occur on the highest ranges in the South Canterbury, Mt. Cook and Mt. Aspiring areas.

Glacier areas

The glaciers show an enormous variation in size (area) from 1 ha to nearly 10,000 ha for the Tasman Glacier. A plot of the size of the 55 glaciers over 300 ha in area (Fig. 5) arranged in descending order of area, shows a relatively uniform distribution except for the Tasman Glacier, which is over twice the area of the next largest glacier, the Murchison.

Figure 2 – A superb example of an active rock glacier on Mt. Alarm, Inland Kaikoura Range. Glacier No. 621/1.

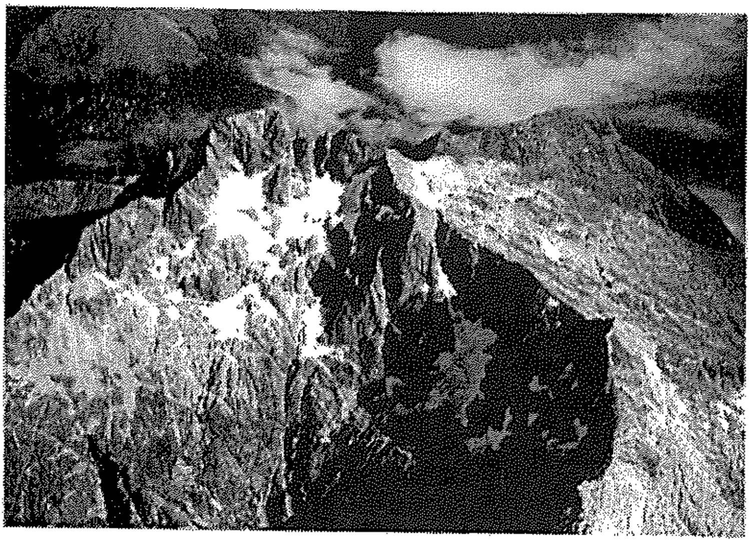

Figure 3 – The southernmost glaciers (803/1 and 2) on Caroline Peak, above Lake Hauroko in southern Fiordland.

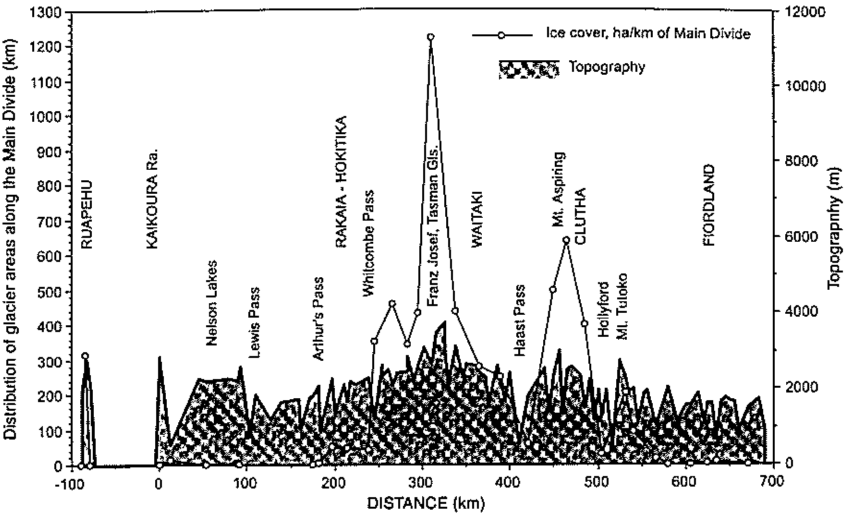

Figure 4 – Intensity of glacierisation along the length of the Main Divide expressed as ha per km of distance along the Main Divide. Associated maximum and minimum topographic heights are also plotted in profile. Position of Mt. Ruapehu not to scale.

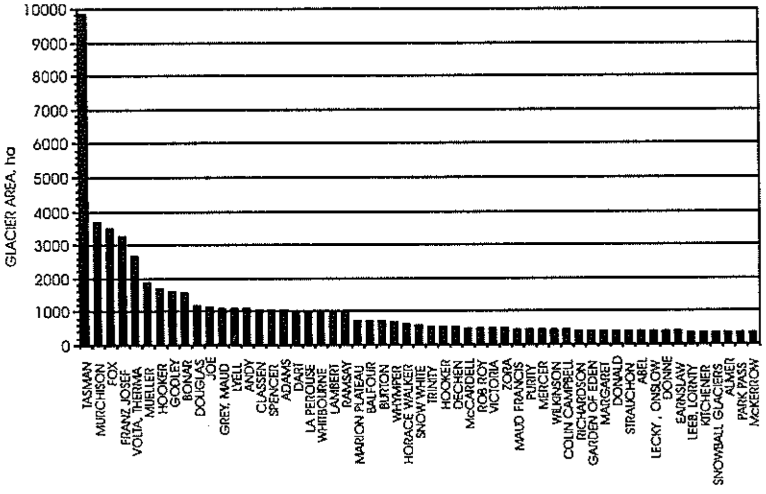

Figure 5 – The largest glaciers over 300 ha, arranged in descending order of area.

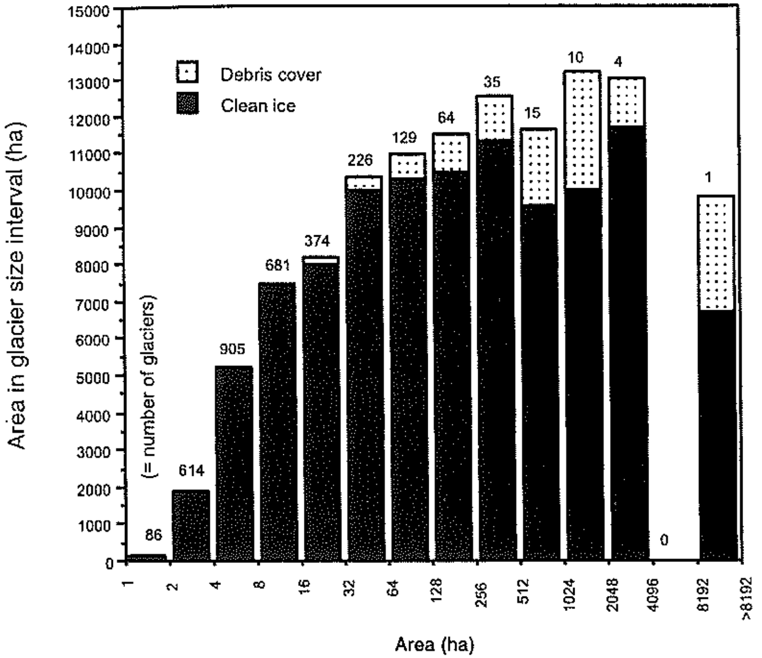

Figure 6 – Distribution of glacier areas for all New Zealand glaciers. Count of all glaciers in exponential size intervals of 2^n ha plotted as the sum of both clean ice and debris-covered ice within each area interval.

The nation-wide distribution of glaciers in size interval classes was examined by counting the number of glaciers in area intervals. Because of the large range in glacier areas and volumes, a linear scale is inappropriate, and the convention used by the World Glacier Monitoring Service is used (Haeberli *et al.*, 1989). Here both areas and volumes are plotted exponentially at intervals of 2^n or twice the previous value. Figure 6 presents the frequency of occurrence in each of the class intervals, together with the proportion of debris-covered ice. The number above each bar gives the number of glaciers counted in each interval (also shown in the frequency plot of Figure 7). The modal size for the glaciers of New Zealand is in the 4 to 8 ha interval, although the greatest area by far is covered by the few larger glaciers. The Tasman glacier stands alone in the >8192 ha category.

Debris cover

The larger New Zealand glaciers are renowned for their extensive areas of debris cover or surface moraine on the lower trunks. It has frequently been

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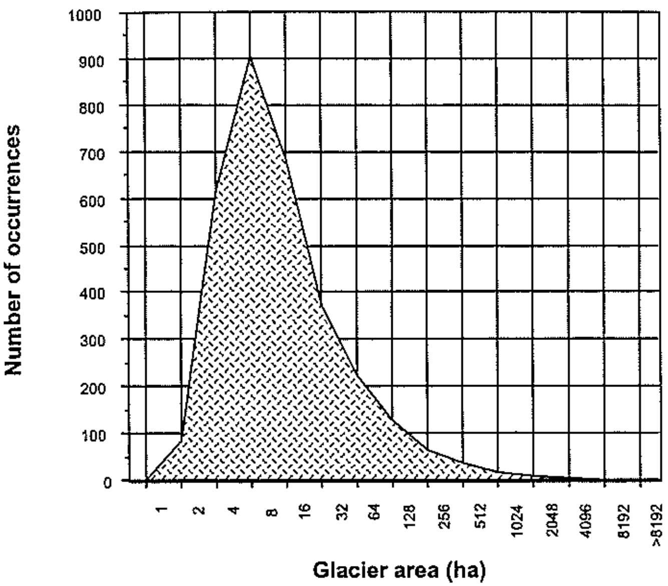


Figure 7 – Frequency distribution of all New Zealand glacier areas, showing a modal value at 4 - 8 ha.

stated that this occurs predominantly on glaciers to the east of the Main Divide (e.g. Harper, 1893, p. 37). However this study demonstrates that debris cover is firstly a function of glacier size and is not dependent on which side of the Alps the glacier is located. A plot of percent of debris cover with size (Fig. 8) demonstrates that the proportion of debris cover increases systematically with glacier size. The outlying point to the right of the curve includes both the unusually clean Franz Josef and Fox glaciers, discussed below.

Extensive debris-mantled glaciers and rock glaciers are normally associated with arid climates where low precipitation totals permit the supply of debris to constitute a significant proportion of total accumulation. Prerequisites which favour the accumulation of an extensive debris mantle on a glacier tongue include:

(1) a high ratio of debris to snow accumulation;
(2) steep headwalls that permit rock falls and rock avalanches to feed directly on to the glacier surface;
(3) disconnected icefalls that expose the glacier bed, allowing basal debris to be physically mixed and brought to the surface;
(4) large low-gradient lower trunks with high ablation rates that permit steeply emerging and decelerating ice to bring basal debris to the surface.

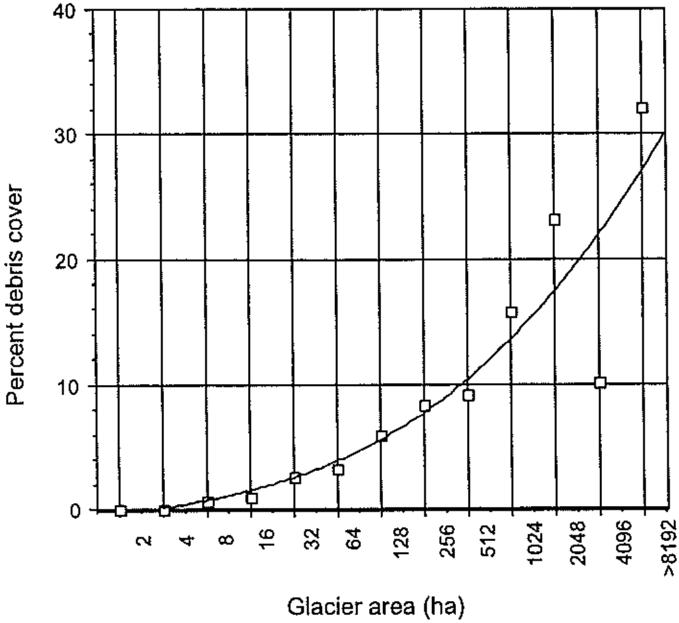


Figure 8 – Percent of debris cover versus glacier area for all glaciers.

The high precipitation on New Zealand's maritime glaciers precludes condition (1) except in the arid ranges well to the east. The exceptionally high tectonic and geomorphic activity of the Southern Alps provides ample opportunity for conditions (2) and (3). The occurrence of numerous large glaciers with low-gradient tongues fulfil condition (4). Both the Franz Josef and Fox Glaciers have névés on an unusually high, broad plateau minimising prerequisites (2) and (3), while their fast-flowing steep tongues rapidly clear debris. As a consequence, both of these glaciers are exceptionally clean of debris for large New Zealand glaciers.

Glacier volumes

Glacier volumes have been estimated by using the crude relationship of Equation 1. The large range of sizes makes it difficult to find an appropriate unit of measurement. Cubic metres lead to large and cumbersome numbers, while km^3 lead to long series of decimal zeros for the small glaciers. Millions of m^3 has been chosen as the most appropriate unit to give sensible-sized values and again a linear plotting scale is inappropriate and an exponential scale of 2^n has been used when plotting volumes. The frequency of occurrence

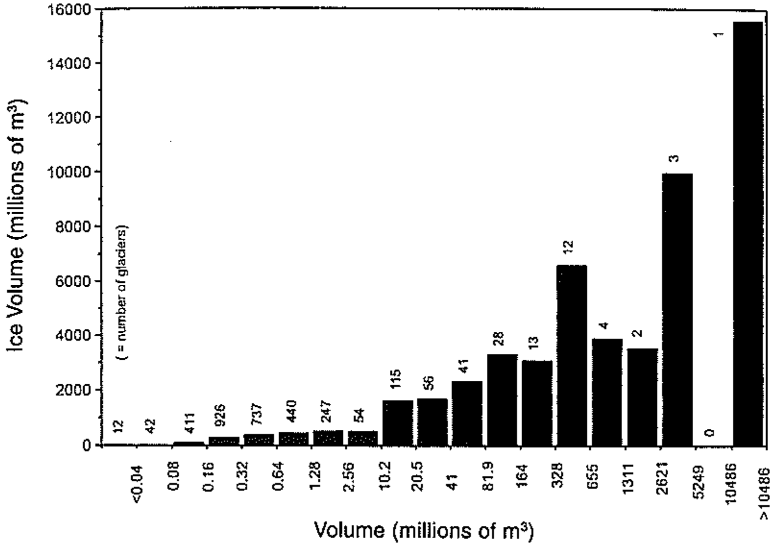


Figure 9 – Distribution of glacier volumes of all New Zealand glaciers by volume intervals using an exponential scale of 2^n million m³.

of individual glaciers volumes was examined by counting the number of glaciers in exponential class intervals plotted at 2^n millions of m³. Figure 9 shows the distribution of glacier volumes in each of the class intervals, where the numbers above the bars give the number of glaciers counted in each volume interval. From these numbers the modal volume for the glaciers of New Zealand (Fig. 10) is in the 0.16 to 0.32 Mm³ interval. Again the greatest volume by far is held by the few larger glaciers. This is demonstrated by Figure 11, which shows that nearly 50% of all of New Zealand's ice is contained in the 5 largest glaciers.

Glacier mean elevations

On small glaciers the mean elevation of the glacier approximates the regional snowline, and along the Southern Alps snowline elevations descend southward with increasing latitude, from 2500 m on Mt. Ruapehu to 1600 m in Fiordland. Across the Alps snowline elevations are strongly distorted in inverse proportion to total precipitation. Snowlines increase markedly from about 1600 m in the west to over 2200 m on far eastern glaciers (Chinn and Whitehouse, 1980). This data includes the noise introduced by a 300 to

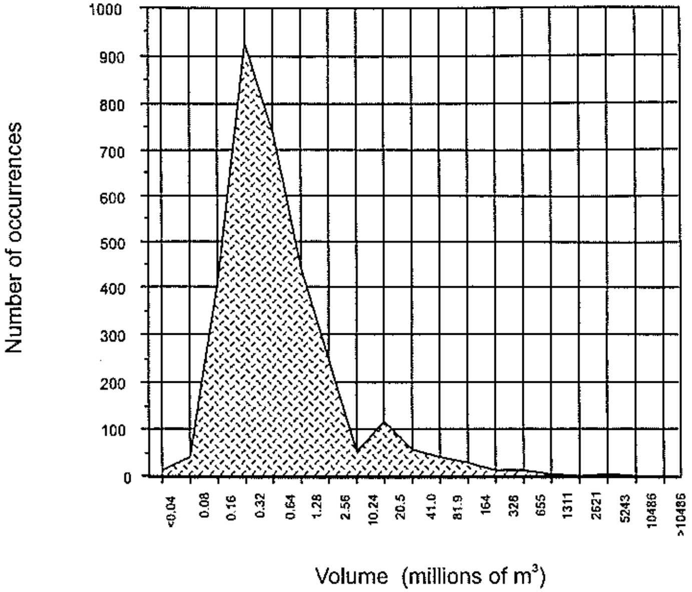
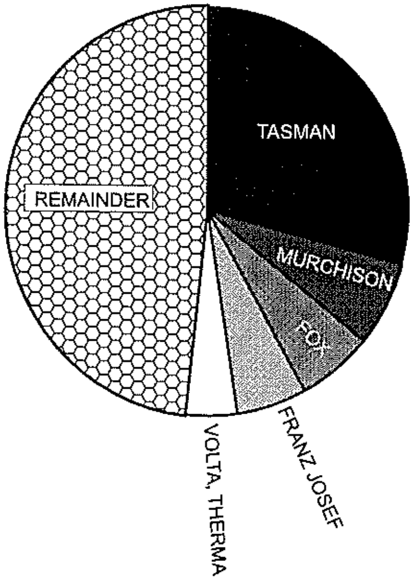


Figure 10 – Frequency distribution of all glacier volumes, showing a modal value at 0.16 - 0.32 million m³.

Figure 11 – Ice volumes held by the 5 largest glaciers as a % of New Zealand total ice volume.



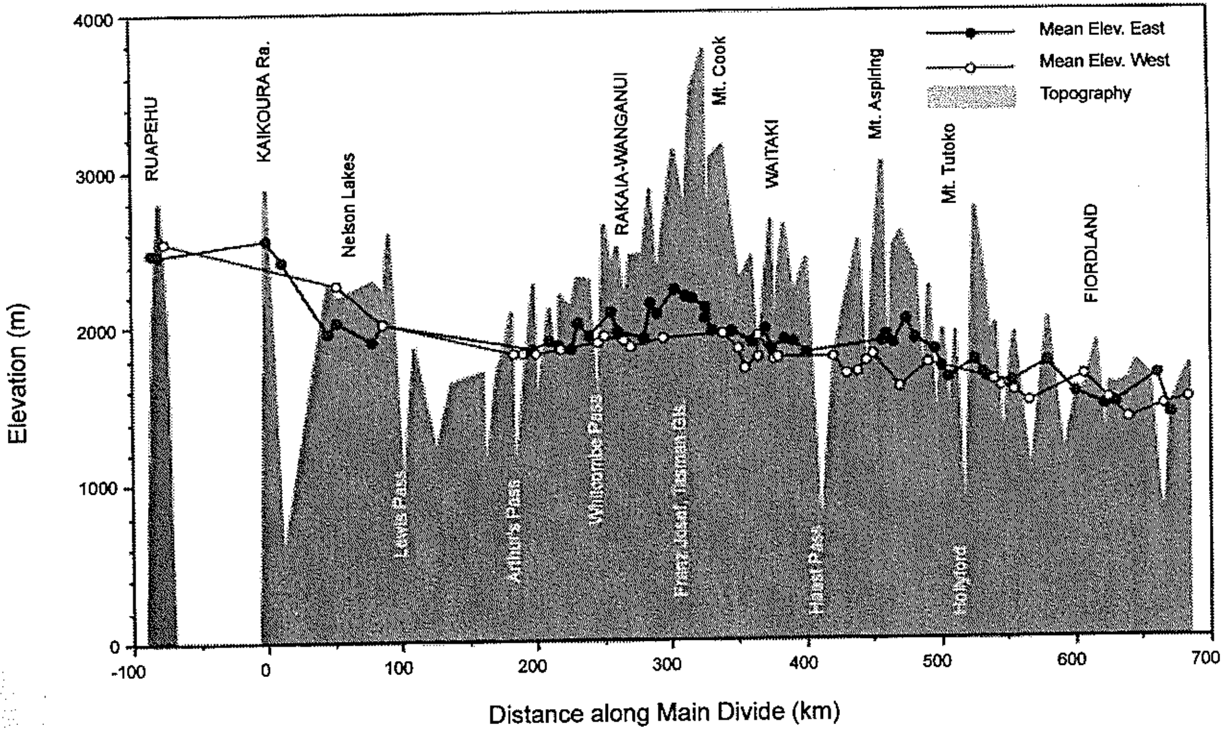


Figure 12 – Mean glacier elevations for each basin, plotted separately for eastern and western glaciers, over a topographic profile along the Main Divide. Position of Mt. Ruapehu not to scale.

320 m elevation difference between north- and south-facing glaciers. Figure 12 shows glacier mean elevations plotted on a background of the topographic profile, with Mt. Ruapehu arbitrarily positioned at -100 km. Values are the averages for all glaciers in each river basin, separated into those east and those west of the Main Divide.

Despite the steep west-east precipitation and snowline gradients, the overall average difference between eastern and western glaciers for the entire Southern Alps is only 65 m, from 1778 to 1842 m, mainly because most of the glaciers lie on or close to the Main Divide. Peak elevations on the eastern trace occur where there are a large number of glaciers in far eastern arid ranges. The apparent absence of consistent east and west differences in the Nelson Lake and Fiordland regions arises from the small number of glaciers being influenced by variable aspects. A simple curve fitted to all of the mean elevation data shows that the regional snowline over New Zealand descends with increasing latitude, at a slope of -1.09 m/km.

Glacier aspects

Chinn and Whitehouse (1980) ascertained that there was a mean difference of 300 m to 320 m between north-facing and south-facing glaciers. There will thus be a tendency for more small glaciers to occur on south-facing slopes while equivalent north-facing slopes will only carry seasonal snow. Figure 13 verifies this and shows that over the entire country south-facing glaciers do indeed predominate, with the lowest numbers in the NW to NE quadrant.

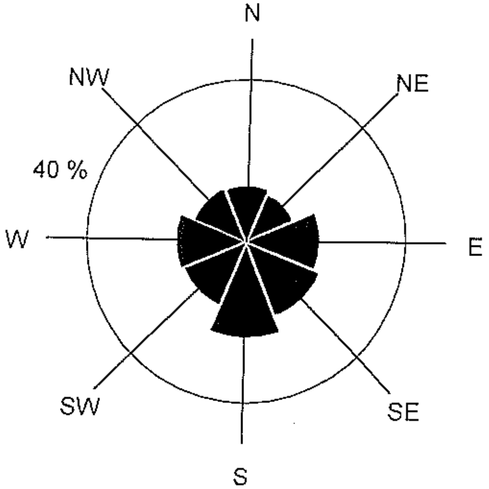


Figure 13 – Frequency distribution of aspects for New Zealand glaciers.

Summary of regional data

Tables, maps and plots for the regional summaries are arranged by region in the Appendices.

Ruapehu Region (Appendix I)

The glaciers of Ruapehu are unique in New Zealand because they are to a large extent influenced by volcanic activity. Intermittent ash showers have introduced layers of debris which, when at the glacier surface, either accelerate or inhibit melt, depending on thickness. Beneath the glaciers, geothermal heat accelerates basal melt. There are 6 named glaciers on Mt. Ruapehu including the only crater glacier in the country. The inventory noted another 12 ice bodies of sufficient size to be included here.

Figures 1 and the map of Appendix I a show the location of Mt. Ruapehu and the river catchments associated with the glaciers. Summary data for the region are tabled in Appendix I b, with the distribution of glacier areas given in Appendix I c. Here the influence of the volcano is apparent as extensive debris cover, as much as might be expected in a very arid climate. The distribution of volumes (Appendix I d) shows that most of the ice is contained in three of the largest glaciers: the Whangaehu, Mangatoetoenui and Summit Plateau Glaciers. The glaciers are fairly evenly oriented to all aspects (Appendix I e).

Northern South Island Region (Appendix II)

The map of Appendix II a shows the locations of these two sets of climatically distinct groups of glaciers in this region. The properties of the two groups are given separately in the table of Appendix II b. Most of the eight glaciers on the arid eastern Inland Kaikoura Range, between the Awatere and Clarence Rivers, are heavily debris-covered "rock glaciers" providing all of the debris cover plotted in Appendix II c. The remaining 35 small glaciers and glacierettes are high-precipitation maritime glaciers positioned close to, or on the Main Divide south of the Nelson Lakes. In contrast to other regions, the 18 glaciers of the modal volume (Appendix II d) also contain the most ice. Their aspects (Appendix II e) are strongly oriented between south and north-east.

Eastern Alps Region (Appendix III)

This region includes all of those glaciers east of the Main Divide from Arthur's Pass to the Hollyford Valley, and also includes the largest glaciers with the greatest area and volume of all of the regions (Appendix III d). Melt water from the glaciers of this region drain into the main hydro-electric power schemes of the Clutha and Waitaki Rivers, and also feed into rivers tapped for irrigation in Canterbury. The distribution of the glacier centroids is shown in Appendix III a, where only those glaciers to the east of the Main Divide are shown. Glacier basin names and numbers of those catchments that head at the Main Divide are placed to the west.

The distribution of glacier areas (Appendix III c) is uneven, with the most area dominated by a few of the largest glaciers, although the modal size is 4 - 8 ha. Debris cover also increases systematically with glacier size. The volume distribution is even more uneven (Appendix III d), with the plot dominated by the ice of the Tasman glacier. Aspects (Appendix III e) favour the south-east quadrant.

Fiordland Region (Appendix IV)

The chosen northern boundary of this region is that of the Hollyford River catchment (Appendix IV a), although topographically and climatically the Hollyford River itself may more accurately separate the character of Fiordland from that of the Southern Alps to the north. The glaciers of the Darran Range, to the west of Hollyford valley, dominate this region both in size and number. The remaining mountains of Fiordland barely intercept the snowline. In contrast with the ranges to the north, Fiordland glacier mean elevations do not show the strong up-warping to the east found elsewhere in the Southern Alps and this indicates a smaller precipitation gradient across the region.

Glacier size distribution is comparatively uneven (Appendix IV c) although the modal size is again 4 to 8 ha. The glaciers carry a very limited debris cover in this very humid climate. Glacier volumes show a skewed distribution with a modal volume at 0.16 - 0.32 million m^3 (Appendix IV d) and southern aspects dominate (Appendix IV e).

Westland Region (Appendix V)

The narrow coastal plain of Westland favours many small separate river catchments (given in Appendix V a). Each filled circle of this map represents a single glacier centroid, where only those glaciers draining to the west are plotted. The Westland glaciers are distributed consistently along the Alps, and include the Franz Josef and Fox glaciers, the best known, but perhaps the most un-representative of the New Zealand glaciers. They both occupy a high plateau feeding the only two valleys of Westland that are not incised back to the Main Divide; they descend to the lowest altitudes of all glaciers; and they have as short a response time to climate fluctuations as any glacier in New Zealand.

The size distribution of Westland glaciers is evenly skewed to the right (Appendix V c) but with a less uniform relationship between debris cover and size than is found in the Eastern Alps. The volume distribution is dominated by the two largest, the Franz Josef and Fox Glaciers (Appendix V d) but with the same modal value as the other regions of 0.16–0.32 million m^3. Constrained by north-west facing flanks of the Southern Alps, the glacier aspects are dominantly west facing (Appendix V e).

Glaciers and climate

Glacier changes occur in response to both winter snow accumulation and summer melt losses. These volume changes are stored in the glacier system to be delivered to the terminus as a distorted climate signal after the many years of the glacier's response time. The common use of the terminus position as an indicator of glacier response to climate is therefore only applicable over long periods of decades or more. Measurements of annual mass (volume) changes provide a far better indicator of the climate signal seen in glaciers. In New Zealand, recent studies have used the elevation of the end-of-summer snowline as a surrogate for direct mass balance measurements (Chinn, 1995).

Over 20 years of data obtained during this programme, coupled with modelled atmospheric pressure fields of the Southern Hemisphere, have been used to examine the responses of the glaciers to atmospheric circulation. Fitzharris *et al.* (1997) found that atmospheric patterns exert a strong control on glacier changes, with S-SW flow anomalies associated with positive glacier balances and N-NE anomalies favouring negative balances. Atmospheric circulation patterns also exert a strong control on elevation and slope of the annual snowline trend surface (Lamont *et al.*, 1999). The annual snowline trend surface across the Southern Alps, however, has been found to vary little with these phases and variations are even smaller along the Main Divide (Fitzharris *et al.*, 2001) These findings indicate that the entire Southern Alps behaves uniformly as single climate zone with respect to glaciers.

Glacier changes and south-west Pacific circulation patterns are linked to El Niño-Southern Oscillation (ENSO) events, with glacial advance associated with a higher frequency of El Niño events with anomalous south-west flow and higher precipitation (Hooker and Fitzharris, 1999). Annual glacier changes have also been related to both circulation and sea surfaces temperatures (Clare *et al.*, 2001). The numerous oscillations of the Southern Hemisphere circulation patterns (Clare *et al.*, 2001) indicate that there are numerous teleconnections throughout the south-west Pacific. Tyson *et al.* (1997) found a distinctive 18-20 year period of an out-of-phase relationship between advances of the Franz Josef Glacier and extended dry spells in South Africa. Numerous cyclic teleconnections have also been shown by Fitzharris *et al.* (in press), with negative glacier balances associated with negative values of the Interdecadal Pacific Oscillation (IPO) and La Niña events, and positive gains to the glaciers with a positive IPO and El Niño events.

Coincidentally, the 1977 inception of the programme of annual glacier snowline surveys commenced at the time of a change in the IPO, when glacier balances changed to positive after a long period of recession. Advances of the most responsive glaciers began a few years later around 1983. In the same period, from 1978 to 2000, the Clutha River showed a 15% increase step in mean flow (McKerchar and Pearson, 1997; McKerchar pers. comm.) that is synchronous with the IPO, the glacier balance trends and enhanced westerly winds.

Water resources of glaciers

Glacier ice constitutes a significant water resource held in New Zealand mountains. Fluctuations in the volumes of glaciers directly affect downstream hydrology and thus New Zealand's essential hydro-electric industry. The main impacts will be from changes in water storage held as ice. Recent scenarios of climate warming suggest that glaciers may have a measurable effect on river discharges. Scenarios of 1.5°C and 3°C warming were investigated (Ministry for the Environment, 1990) and it was reported that these warming trends would reduce the volume of perennial snow and ice by 25% and 50% respectively (Chinn, 1990). By applying these ice losses over a 50-year period to the main hydro-electric generating rivers of the Waitaki and Clutha, and to the larger Canterbury rivers, the additional contributions to daily mean discharge from diminishing ice storage (ignoring the 0.9 conversion for the density of ice) were calculated (Table 1). For the majority of the rivers, the increase in flow would be insignificant, however for the Clutha it would be significant (0.5 to 1 cumec increase) and for the Waitaki there would be an important 8 cumec increase in flow.

Comparative estimates of the contribution to the Waitaki River system from depletion of ice storage are available for the Tasman Glacier. The Tasman Glacier catchment contains a significant 65% of the ice area of the Waitaki catchment. From surveys on the lower Tasman Glacier, Skinner (1964) calculated that discharge from downwasting alone over the 72-year period from 1890 to 1962 contributed a discharge of 1.43 cumec (51 cusec) to the Tasman River. Since the development of the pro-glacial Tasman Lake, the rate of ice loss has increased dramatically and in a recent study, Purdie and Fitzharris (1999) found that recession of the Tasman Glacier now discharges 4.3 cumecs into the system, of which 0.7 cumecs is supplied by direct calving of ice into the lake.

Table 1 – Discharge to main eastern rivers from ice storage over a 50 year period for two climate warming scenarios. Scenario 1 is for a 1.5°C temperature rise, leading to a 120m rise in snowline and 25% loss of present ice volume. Scenario 2 is for a 3°C temperature rise, a 230m rise in snowline and 50% loss of present ice volume.

Basin Number	River	Scenario 1 25% ice reduction 50 yr meltwater runoff (cumecs)	Scenario 2 50% ice reduction 50 yr meltwater runoff (cumecs)
664	Waimakariri	0.009	0.018
	RAKAIA		
685B	Cameron	0.011	0.022
685C	Rakaia	0.216	0.433
685D	Mathias	0.008	0.016
685E	Wilberforce	0.010	0.019
685F	Avoca	0.001	0.002
	Entire Rakaia	0.246	0.493
	RANGITATA		
693B	Havelock	0.026	0.051
693C	Clyde	0.047	0.094
693D	Lawrence	0.008	0.015
	Entire Rangitata	0.080	0.161
	WAITAKI		
711B	Ahuriri	0.009	0.019
711C	Ohau	0.0004	0.0008
711D	Huxley	0.009	0.018
711E	Hopkins	0.057	0.115
711F	Dobson	0.016	0.033
711G	Ben Ohau	0.007	0.015
711H	Hooker-Mueller	0.421	0.842
711I	Tasman	2.477	4.953
711J	Murchison	0.609	1.217
711K	Jollie	0.004	0.009
711L	Cass	0.013	0.025
711M	Godley	0.388	0.777
711N	Macaulay	0.009	0.018
	Entire Waitaki	4.021	8.042
	CLUTHA		
752B	Humboldts	0.020	0.040
752C	Dart	0.278	0.556
752D	Rees	0.053	0.106
752E	Shotover	0.006	0.012
752F	West Matukituki	0.071	0.143
752G	East Matukituki	0.041	0.081
752H	Wanaka	0.0007	0.001
752I	Wilkin	0.029	0.057
752J	Makarora	0.011	0.021
752K	Hunter	0.031	0.062
	Entire Clutha	0.540	1.079

The hydrology downstream of glaciated areas is also very dependent on glacier behaviour, which, in addition to water discharge, affects potential hazards from glacier floods and sediment discharge, with its implications for river aggradation and erosion. The tourist industry also needs predictions of future glacier behaviour, because of both their scenic value and potential hazards near glacier termini. Changes in ice volumes are of international interest to compute and predict the contribution of temperate glaciers to sea level change. Information on glacier fluctuations will also be of interest to the world-wide scientific community working in the various fields of climate change.

Conclusion

The New Zealand glacier inventory of 1158 km^2 glaciers containing a total ice volume of 53.3km^3 provides a valuable addition of essential knowledge on alpine regions. The 3144 glaciers from Ruapehu to southern Fiordland provide a wide distribution of water resources held in a fluctuating storage. Mean elevations of the glaciers provide a measure of the regional snowline. This descends southward with latitude from 2500 m on Mt. Ruapehu to 1500 m in southern Fiordland, with an average gradient of 1 m per km. Superimposed on this trend is a strong west-east gradient caused by the west-east precipitation gradient, with mean glacier elevations rising from 1600 m in the west to 2200 m on eastern ranges. Glacier aspects are determined more by solar radiation than topography, with south-facing glaciers outnumbering those in the northern quadrant. Over the past two decades the recessional trend of the past century has reversed, with most glaciers currently expanding or in equilibrium with today's climate. Because of the differing response times of the glacier termini to climate change, from 5 to >100 years, some glaciers are advancing, others are still receding from earlier climate changes. An initial prediction of water resource behaviour under climate change scenarios has shown that a warming climate of 1.5°C and 3°C will provide flows from diminishing ice storage, of 4 to 8 cumecs for the Waitaki and 0.5 to 1 cumec for the Clutha respectively.

Acknowledgements

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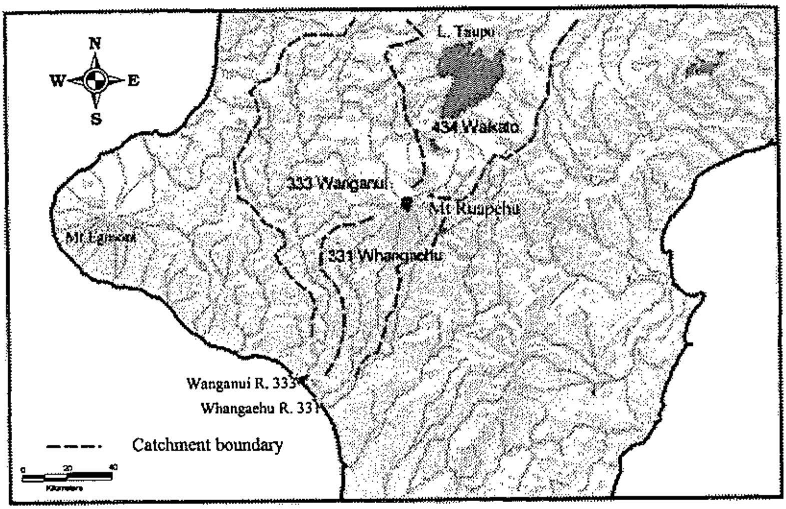
Appendices

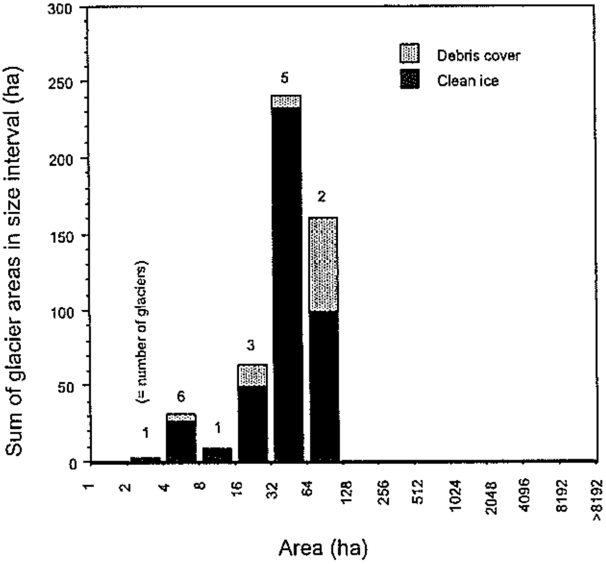
Appendix I a – Ruapehu Region map showing the three main river catchments fed by the glaciers.



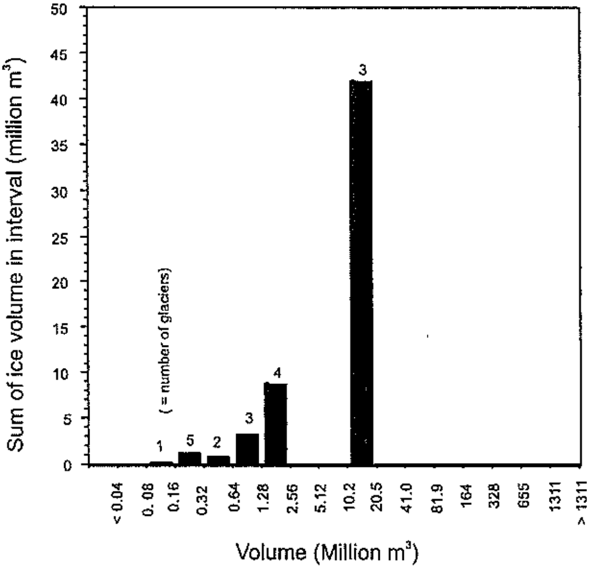
Appendix I b – Summary data for each of the glaciated catchments of Mt. Ruapehu. Shaded values calculated from individual glacier data.

River number	River basin	No. of glaciers	Ice area ha	Debris cover ha	Ice volume Mm³	Max. length km	Max. elevation m	Mean elevation m	Min. elevation m
434	Waikato	2	69	0	11.74	0.88	2673	2478	2295
331	Whangaehu	9	226.5	56.3	26.31	0.85	2608	2467	2250
333	Wanganui	7	171.2	32.8	18.10	0.80	2666	2544	2391
	Sum	18	506.7	89.1	56.15				
	Mean		28.15	4.95	3.12	0.83	2638	2498	2310
	Max		86.6	39.9	17.32	1.85	2760	2635	2590
	Min		2.2	0	0.11	0.23	2285	2225	2075

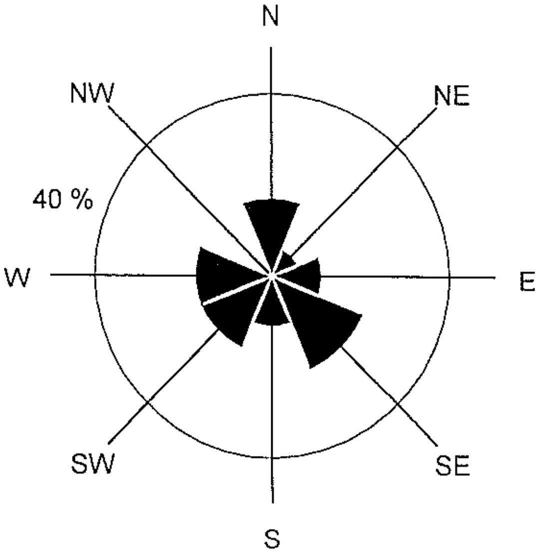
Appendix I c – Ruapehu Region, distribution of glacier areas.



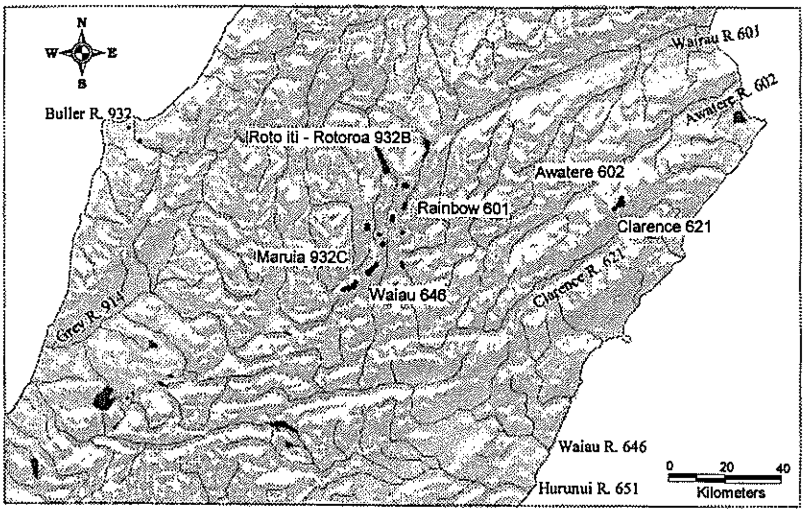
Appendix I d – Ruapehu Region, distribution of glacier volumes.



Appendix I e – Ruapehu Region, distribution of glacier aspects.



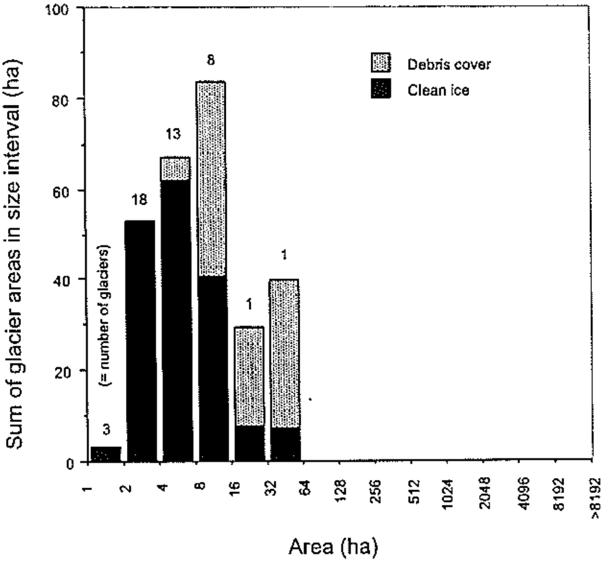
Appendix II a – Northern South Island Region map showing the two spatially and climatically distinct groups of glaciers.



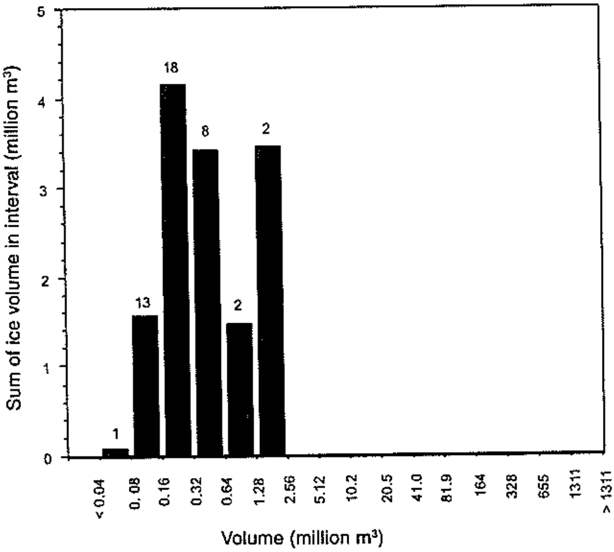
Appendix II b – Summary data for each of the glaciated basins of the Northern South Island Region. Shaded values calculated from individual glacier data.

River number	River basin	No. of glaciers	Ice area ha	Debris cover ha	Ice volume Mm³	Max. length km	Max. elevation m	Mean elevation m	Min. elevation m
602	Awatere	1	8.3	5.5	0.41	0.50	2680	2560	2440
621	Clarence	8	129	97.1	6.43	0.71	2568	2422	2277
	Sum	9	137.3	102.6	6.84				
	Mean		68.65	51.3	3.42	0.61	2624	2491	2358
	Max		129	97.1	6.43	0.71	2680	2560	2440
	Min		8.3	5.5	0.41	0.50	2568	2422	2277
601	Rainbow	1	3.6	0	0.18	0.15	2010	1970	1920
646	Waiau	18	83.8	0	4.15	0.23	1984	1913	1840
932B	Rotoiti-Rotoroa	13	50.1	0	2.49	0.24	2100	2033	1965
932C	Maruia	3	9.8	0	0.48	0.23	2080	2022	1960
	Sum	35	147.3	0	7.3				
	Mean		36.83	0	1.83	0.21	2044	1985	1921
	Max		83.8	0	4.15	0.24	2100	2033	1965
	Min		3.6	0	0.18	0.15	1984	1913	1840

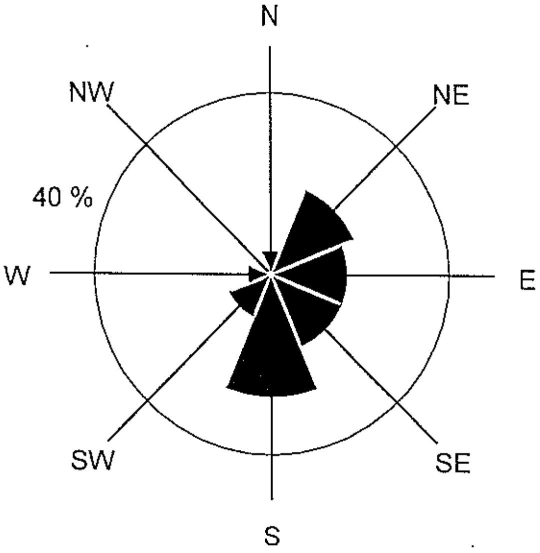
Appendix II c – Northern South Island Region, distribution of glacier areas. All of the debris cover occurs on the glaciers of the Kaikoura Range.



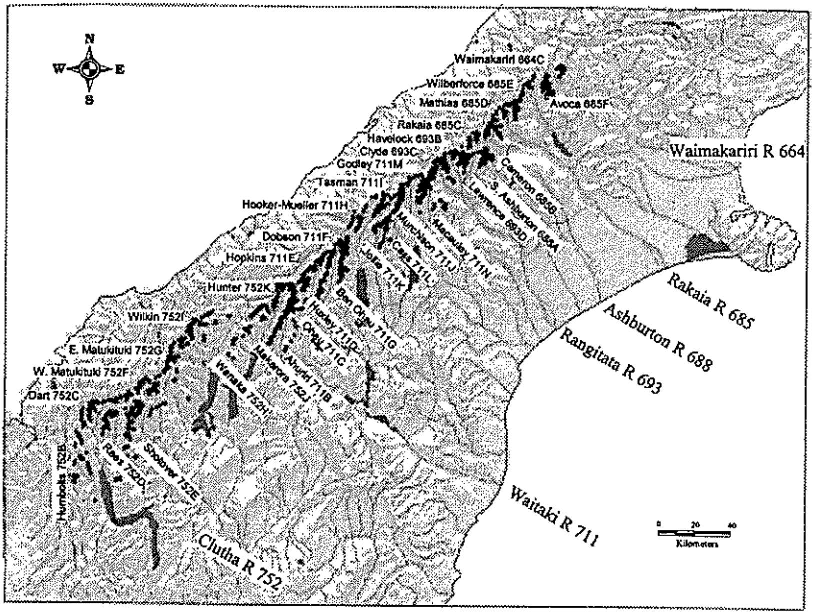
Appendix II d – Northern South Island Region, distribution of glacier volumes.



Appendix II e – Northern South Island Region, distribution of glacier aspects.



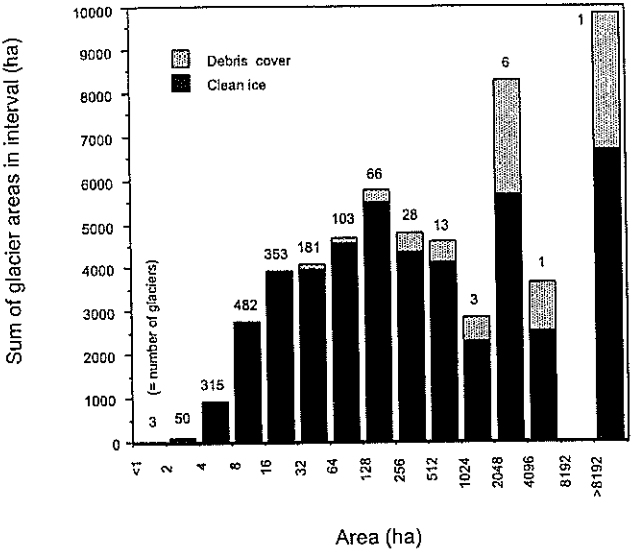
Appendix III a – Eastern Alps Region map with the inventoried glacier basins labelled. Centroids plotted for only those glaciers draining eastward of the Main Divide.



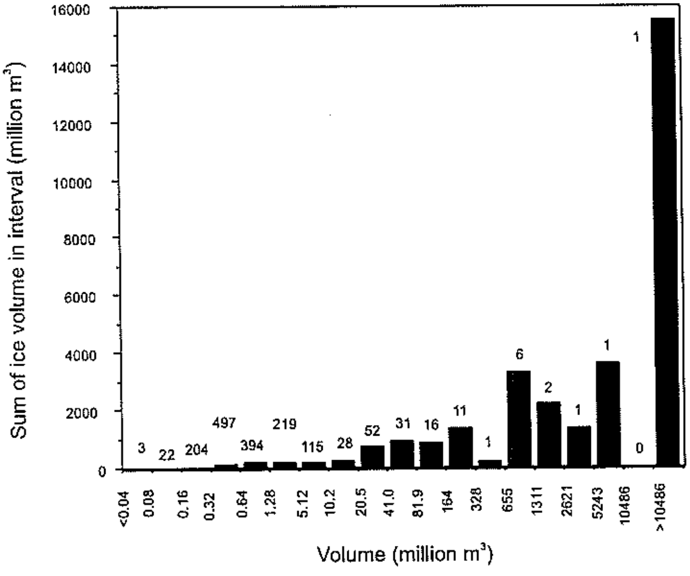
Appendix III b – Summary data for each of the glaciated basins of the Eastern Alps Region. Shaded values calculated from individual glacier data.

River number	River basin	No. of glaciers	Ice area ha	Debris cover ha	Ice volume Mm³	Max. length km	Max. elevation m	Mean elevation m	Min. elevation m
664C	Waimakariri	49	637	0	56.78	0.52	1975	1854	1733
685B	Cameron	10	359	21	70.45	0.88	2228	2026	1810
685C	Rakaia	89	3835	521	1364.6	0.73	2104	1941	1780
685B	Mathias	74	758	18	51.21	0.42	1975	1856	1721
685E	Wilberforce	67	887	6	62.16	0.47	2015	1878	1755
685F	Avoca	14	127	0	6.29	0.38	2023	1910	1807
688A	S. Ashburton	7	226	16	45.14	0.66	2245	2089	1933
693B	Havelock	75	1377	77	161.18	0.60	2092	1928	1759
693C	Clyde	67	1654	216	297.92	0.70	2135	1959	1765
693D	Lawrence	26	386	32	47.69	0.47	2235	2071	1908
711B	Ahuriri	39	446	17	60.01	0.42	2053	1891	1762
711C	Ohau	12	50	0	2.49	0.24	2069	1983	1911
711D	Huxley	47	659	8.8	58	0.49	2035	1851	1701
711E	Hopkins	65	1818	221	362.26	0.61	2064	1901	1705
711F	Dobson	72	910	35	103.37	0.44	2110	1969	1839
711G	Ben Ohau	55	759	91	46.18	0.58	2226	2055	1887
711H	Hooker-Mueller	26	4566	1273	2656	1.83	2268	1964	1656
711I	Tasman	39	10550	3166	15620	1.36	2351	2121	1893
711J	Murchison	43	4951	1136	3839	1.12	2436	2178	1966
711K	Jollie	25	305	16	27	0.51	2339	2191	2014
711L	Cass	28	466	13	80.08	0.49	2361	2225	2081
711M	Godley	77	5359	1236	2450	0.94	2275	2075	1866
711N	Macaulay	22	526	32	56.13	0.72	2317	2143	1963
752B	Humboldts	47	759	5	124.95	0.45	1979	1836	1712
752C	Dart	115	5715	527	1754	0.79	2104	1913	1700
752D	Rees	29	1346	7	334.85	0.65	2221	2041	1825
752E	Shotover	52	625	0	37.86	0.49	2080	1937	1802
752F	West Matukituki	43	1740	86	449.43	0.63	2088	1881	1662
752G	East Matukituki	30	1085	0	255.79	0.49	1939	1754	1531
752H	Wanaka	8	89	0	4.41	0.32	2011	1895	1803
752I	Wilkin	104	1275	109	180.87	0.34	1877	1758	1620
752J	Makarora	19	435	28	67.36	0.53	1969	1830	1627
752K	Hunter	129	1605	0	193.95	0.41	2053	1913	1777
	Sum	1604	56284	8910.9	30928				
	Mean		34.9	5.52	937	0.63	2129	1964	1796
	Max		9834	3166	15620	28.50	3765	2745	2680
	Min		50.3	0	2.49	0.05	1110	1005	730

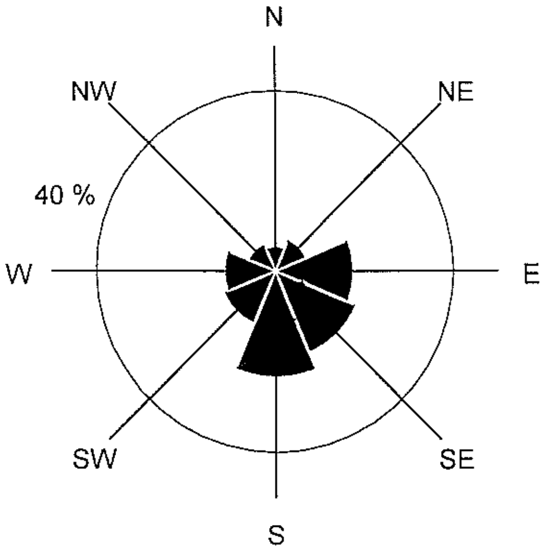
Appendix III c – Eastern Alps Region, distribution of glacier areas.



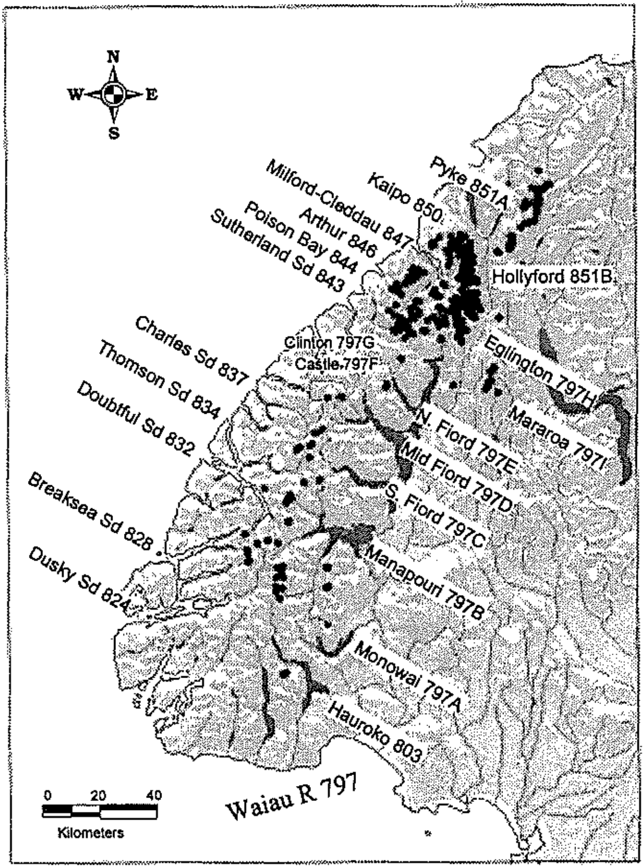
Appendix III d – Eastern Alps Region, distribution of glacier volumes.



Appendix III e – Eastern Alps Region, distribution of glacier aspects.



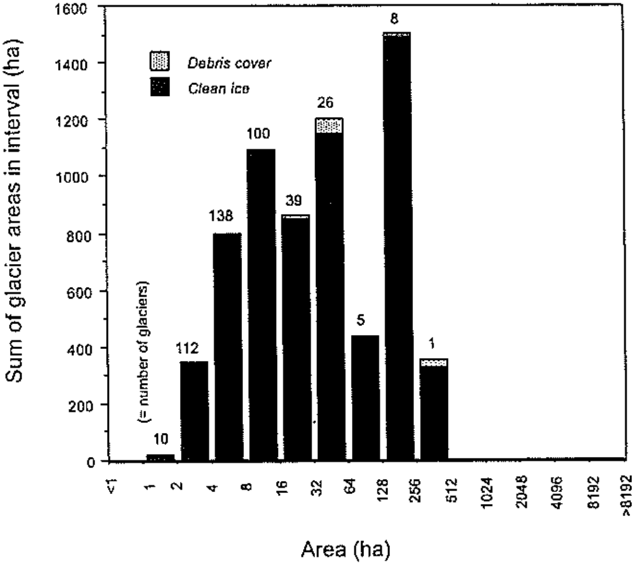
Appendix IV a – Fiordland Region map with glacier centroids plotted as filled circles and the inventoried glacier basins labelled.



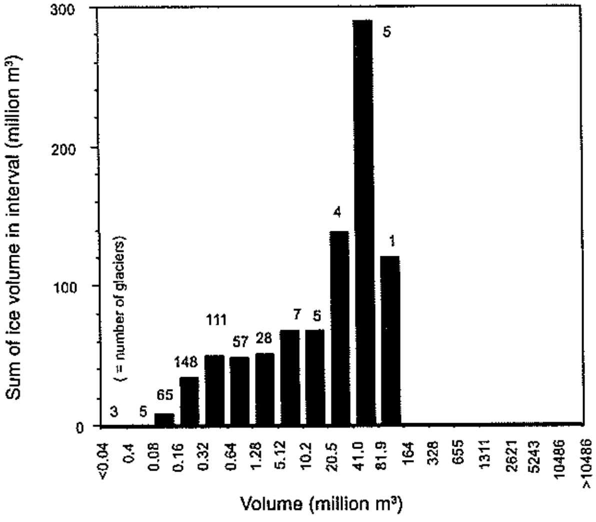
Appendix IV b – Summary data for each of the glaciated basins of the Fiordland Region. Shaded values calculated from individual glacier data.

River number	River basin	No. of glaciers	Ice area ha	Debris cover ha	Ice volume Mm³	Max. length km	Max. elevation m	Mean elevation m	Min. elevation m
797A	Monowai	2	10	0	0.48	0.18	1720	1668	1593
797B	Manapouri	21	106	0	5.25	0.23	1565	1486	1420
797C	South Fiord	5	34	0	1.69	0.32	1573	1482	1387
797D	Mid Fiord	4	37	0	1.86	0.30	1649	1559	1464
797E	North Fiord	3	19	0	0.96	0.23	1848	1753	1687
797F	Castle	16	186	0	14.73	0.33	1784	1636	1480
797G	Clinton	44	402	0	20.01	0.31	1788	1656	1528
797H	Eglington	13	121	14.8	6.01	0.30	1842	1680	1570
797I	Mararoa	13	82	0	4.03	0.31	1891	1767	1654
803	Hauroko	3	16	0	0.81	0.25	1575	1423	1290
824	Dusky Sd	5	19	0	0.92	0.24	1591	1516	1438
828	Breaksea Sd	1	9	0	0.42	0.30	1615	1480	1340
832	Doubtful Sd	8	63	0	2.93	3.09	1478	1396	1315
834	Thomas Sd	5	29	0	1.43	0.16	1582	1522	1439
837	Charles Sd	2	6	0	0.28	0.18	1730	1675	1600
843	Sutherland Sd	4	19	0	0.94	0.20	1630	1509	1434
844	Poison Bay	4	34	0	1.66	0.23	1691	1578	1466
846	Arthur	47	411	0	20.43	0.26	1698	1597	1492
847	Milford-Cleddau	53	1218	6.9	216.64	0.53	1846	1647	1413
851A	Pyke	62	1019	35.4	127.29	0.51	1902	1755	1608
851B	Hollyford	122	2759	40.9	446.46	0.46	1906	1730	1549
850	Kaipo	2	7	0	0.37	0.28	1738	1660	1555
	Sum	439	6603	98.00	875.6				
	Mean		23	0.33	39.80	0.42	1710	1596	1484
	Max		1218	35.4	446.46	3.60	2745	2195	2075
	Min		5.7	0	0.28	0.10	1250	1005	550

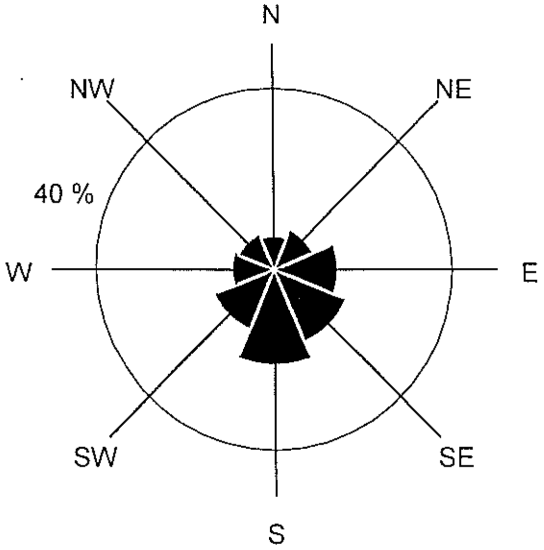
Appendix IV c – Fiordland Region, distribution of glacier areas.



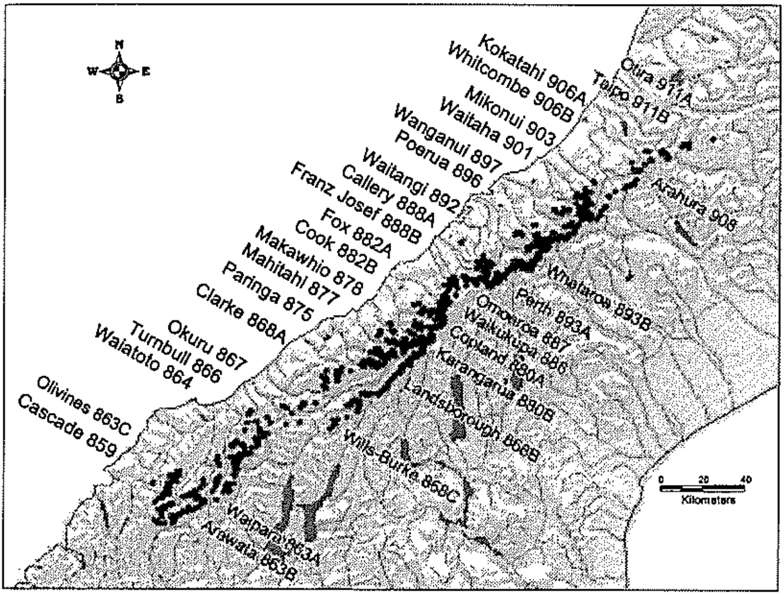
Appendix IV d – Fiordland Region, distribution of glacier volumes.



Appendix IV e – Fiordland Region, distribution of glacier aspects.



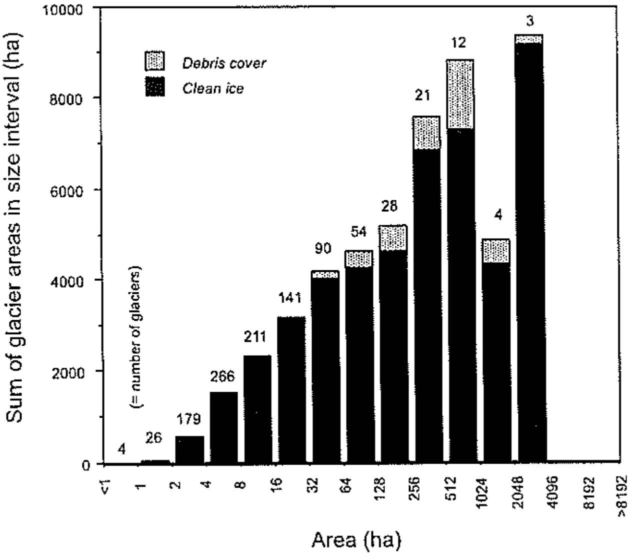
Appendix V a – Westland Region map with the inventoried glacier basins labelled. Centroids plotted for only those glaciers draining westward of the Main Divide.



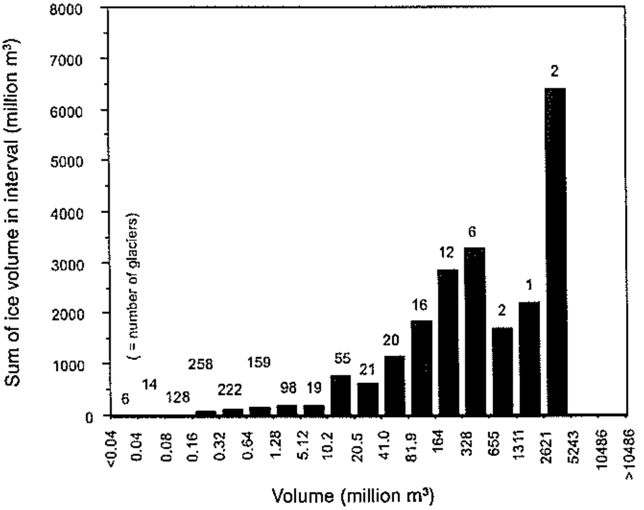
Appendix V b – Summary data for each of the glaciated basins of the Westland Region. Shaded values calculated from individual glacier data.

River number	River basin	No. of glaciers	Ice area ha	Debris cover ha	Ice volume Mm³	Max. length km	Max. elevation m	Mean elevation m	Min. elevation m
859	Cascade	14	310	11.2	38.99	0.55	1711	1602	1482
863A	Waipara	32	2389	121.7	1189.97	0.70	1952	1770	1583
863B	Arawata	59	4779	304.9	1742	1.03	1978	1766	1534
863C	Olivines	37	2111	23.5	845.09	0.69	1751	1606	1437
864	Waiatoto	82	4853	140.7	2718	0.56	1965	1811	1667
866	Turnbull	19	192	0	9.55	0.27	1796	1707	1625
867	Okuru	10	103	0	11.91	0.28	1774	1693	1579
868A	Clarke	42	1281	74.8	331.03	0.51	1943	1799	1627
868B	Landsborough	131	3906	392.9	874.91	0.65	2123	1934	1757
868C	Wills-Burke	34	587	0	112.16	0.39	1912	1796	1697
875	Paringa	21	1145	93.1	296.95	0.98	2045	1794	1501
877	Mahitahi	37	599	54.1	39.24	0.69	2018	1783	1574
878	Makawhio	22	264	9.5	13.14	0.42	1910	1728	1586
880A	Copland	51	1566	293.7	292.67	0.79	2215	1958	1703
880B	Karangarua	30	2329	342.7	998.45	0.98	2091	1849	1614
882A	Fox	11	4295	157	3569.96	2.49	2155	1832	1459
882B	Cook	17	2162	690.7	922.68	2.03	2437	1998	1663
886	Waikukupa	3	298	0	78.79	1.22	1945	1782	1515
887	Omoeroa	1	5	0	0.24	0.25	1950	1920	1845
888A	Callery	27	2735	414.8	1021	1.48	2211	1902	1539
888B	Franz Josef	9	3688	50.9	3137	1.94	2104	1820	1526
892	Waitangi	4	61	0	3.03	0.50	2000	1888	1788
893A	Perth	65	2610	164.4	578.67	0.88	2066	1869	1630
893A	Whataroa	81	2827	507.7	669.07	0.86	2163	1923	1661
896	Poerua	5	183	30.5	29.16	0.88	2151	1911	1664
897	Wanganui	78	4270	102.9	1493	0.84	2096	1908	1718
901	Waitaha	35	868	33.2	108	0.65	2098	1938	1800
903	Mikonui	4	13	0	0.64	0.24	1965	1898	1853
906A	Kokatahi	9	68	0	3.36	0.29	1869	1768	1669
906B	Whitcombe	48	1496	61.5	279.62	0.66	2015	1847	1680
908	Arahura	2	8	0	0.38	0.28	1883	1825	1768
911A	Otira	5	69	0	3.43	0.41	1944	1827	1713
911B	Taipo	14	96	0	4.75	0.33	1921	1824	1729
	Sum	1039	52164	4076	21417				
	Mean		50	3.92	43.74	0.78	2004	1826	1642
	Max		3469	381.9	3569.96	13.20	3500	2650	2315
	Min		4.90	0	0.24	0.05	1220	1160	305

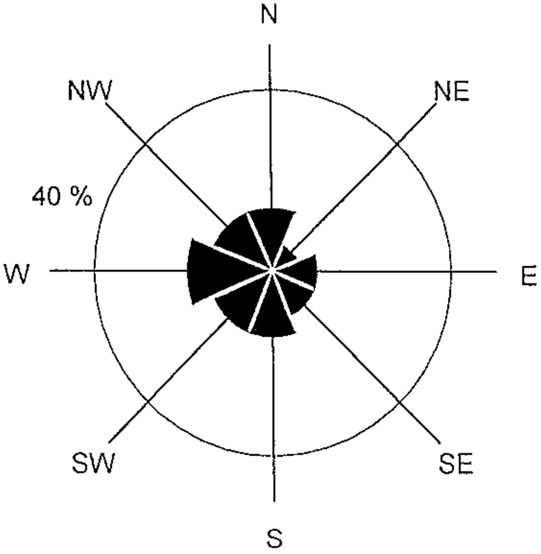
Appendix V c – Westland Region, distribution of glacier areas.



Appendix V d – Westland Region, distribution of glacier volumes.



Appendix V e – Westland Region, distribution of glacier aspects.



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