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Lake Elterwater

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1 Introduction

Lake Elterwater is the largest surface water body in the Flaxbourne-Mirza-Waima (Ure) area and has high ecological significance. Despite this, little is currently known about the hydrology of the lake, and there are few empirical data.

Topographic surveys, both before and after the Kaikōura Earthquake, have identified that significant tilt of the lake occurred; with the southern end of the lake being elevated relative to the northern end. This has increased the potential for water storage within the lake and extended the duration over which the lake now contains water. Historically, Lake Elterwater has gone dry, often for extended periods. The increased water storage in the lake has significant ecological significance, particularly with respect to aquatic habitats.

This report summarises the hydrology of Lake Elterwater and the effect of the Kaikōura Earthquake on the potential for water storage within the lake. The report:

- Compiles and summarises the available information relating to the hydrology of Lake Elterwater and its wider catchment. This includes information from previous reports, climate data, and any other available material;
- Develops level/area/volume curves for the lake using both the pre- and post-earthquake topography from survey information; and
- Quantifies the effect of the Kaikōura Earthquake on the hydrology, dynamics, storage capacity and water balance of Lake Elterwater.

2 Background

Lake Elterwater is the largest surface water body in the Flaxbourne-Mirza-Waima (Ure) area and has high ecological significance. It is a highly dynamic system; unique in the sense that it functions as both a lake and wetland environment depending on conditions. The lake possesses a distinctive hydrological regime because of its seasonal fluctuation in water level combined with warm temperatures. During periods of limited precipitation the lake and wetland areas dry out, but they refill when the availability of water increases (DoC, 2019).

Uplift caused by the 2016 Kaikōura Earthquake raised the southern end of Lake Elterwater (where the natural lake outlet is located) by more than 250mm relative to the northern end of the lake. Consequently, the water depth has increased, particularly at the lake's nothern end, and the extent of wetland areas has also increased. The continuously evolving nature of Lake Elterwater's hydrological system requires active management to monitor the impact of these changes on wildlife (DoC, 2019).

Lake Elterwater hosts an abundance of wildlife, including many native flora and fauna species; some of which are 'threatened' (Wetlands NZ, 2017). Six indigenous bird species are chronically threatened, with another six ranked as 'at risk.' There are also numerous plant species that inhabit Lake Elterwater, including one which is ranked 'at risk' (DoC, 2019).

The continuously changing lake hydrology provides various aquatic habitats, and bird and plant life change in response to the dynamics of the wetland. These habitats include several different 'High Shore Communities,' such as those dominated by *Isolepis Cernua*, *Carex Buchananii* and *Lilaeopsis novae-zealandiae*. There are also various ephemeral communities that respond to water levels in the lake. These communities include Three-Squared Sedgeland, Willow-Weed Herbfield, Ranunculus Herbfield, Bachelor's Button Herbfield, and areas of cropland (Wetlands NZ, 2017).

Lake Elterwater has existing 'Wildlife Refuge' status (DoC, 2019) which prohibits gamebird shooting. A 'Wildlife Refuge Gazette Notice' (1957) also prohibits the use of boats on the lake. The lake is also listed as a 'Significant Wetland' in the Marlborough Environment Plan, which provides a range of resource management restrictions (DoC, 2019). Eels are harvested from the lake, as under its Wildlife Refuge status there is no restriction on eel harvesting. Commercial eel harvesting is managed by the Ministry of Primary Industries.

Lake Elterwater therefore functions as a lake during high water levels, and as an ephemeral wetland during low water levels (Wetlands NZ, 2017).

3 Physical Setting

3.1 Geology

The majority of the Lake Elterwater catchment is underlain by Starborough Formation siltstone/mudstone (which has low porosity and permeability) and river gravels (Figure 3-1). Consequently, any rainfall which does not runoff is likely to remain within the soil and regolith. There is no significant groundwater in the catchment. This conclusion is supported by the nature of any runoff which is directly related to rainfall, both its intensity and cumulative amount. There is only very limited continuity of flow once rainfall ceases.

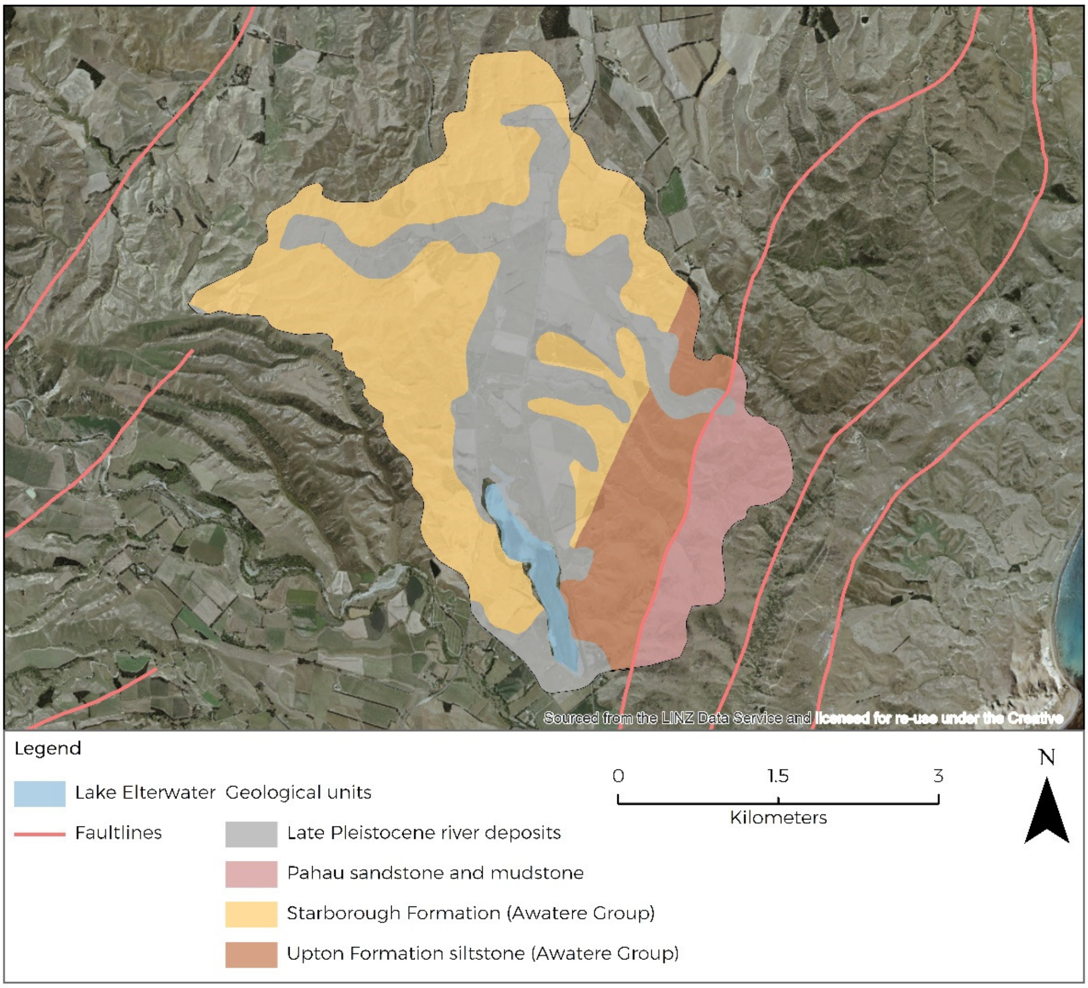

Figure 3-1: Geology of the Lake Elterwater catchment.

The Starborough Formation (Awatere Group) extends into both the northern and south-western areas of the catchment and comprises poorly-bedded sandstone and sandy siltstone. The main rock group is siltstone, with sandstone and siltstone as sub-rocks (GNS, 2006).

The second most extensive lithology within the catchment is Late Pleistocene alluvial deposits, which cover the central and lower areas of the catchment. These deposits consist of poorly to moderately sorted gravel, with minor sand or silt underlying terraces. The main rock group is gravel, while sand and silt comprise the sub-rock group (GNS, 2006). .

There are two further geological units, located at the south-eastern area of the Lake Elterwater catchment. The first is a fairly uniform layer of Upton Formation Siltstone (Awatere Group). This unit comprises poorly-sorted and poorly-bedded channelised greywacke conglomerate, with lenses of sandstone and sandy siltstone (GNS, 2006). The overlying Late Miocene to Late Pliocene Starborough Formation is generally poorly exposed and consists of poorly-bedded brownish-grey fossiliferous sandstone and sandy siltstone.

The London Fault bounds the Upton Formation to the east. To the west of the fault is the Pahau Formation (Awatere Group). This unit is made up of thick and poorly-bedded sandstone, well-bedded commonly-graded sandstone and mudstone with minor volcanic rocks. Pahau sandstone is generally slightly lighter in colour and has a more “sugary” appearance than the low-grade Rakaia terrane sandstone. Pahau terrane rocks also differ in that they locally contain more carbonaceous matter, conglomerate bands and volcanic rocks. The main rock group comprises sandstone and sub-rock group mudstone, basalt and limestone (GNS, 2006).

All known groundwater in the catchment is restricted to the shallow gravel in localised areas, creating small reservoirs in terms of the volume of water they hold. This gravel depends on river recharge and do not store enough water to support irrigation (Davidson & Wilson, 2011).

3.2 Soils

Most of the bedrock of the Lake Elterwater catchment is overlain by pallic soils (Figure 3-2). Pallic soils have pale coloured subsoils (because of the low iron oxide content) with a weak structure and high bulk density.

These soils mostly occur in locations that have dry summers and wet winters. In many areas, the surface horizons become waterlogged in winter, resulting in rapid runoff during rainfall because of slow drainage.

The characteristics of these pallic soils means that they have low permeability and low porosity. Consequently, they have a limited ability to store soil moisture. Therefore, any rainfall, particularly rainfall of higher intensity, will runoff rather than be stored within the soil profile. Runoff from catchments containing these soils is therefore relatively rapid following the onset of rainfall; once the limited pore space within the profile has been saturated. For example, runoff from slopes on the eastern side of the Lake Elterwater catchment, at Thistle Hill, generally commences once the soil moisture content reaches approximately 40%.

Gley soils are present around the margins of Lake Elterwater. These soils tend to occur where there are high water tables; they are strongly affected by waterlogging and have been biochemically reduced. Waterlogging occurs during winter and spring, with some soils remaining wet all year; especially during wetter than average conditions.

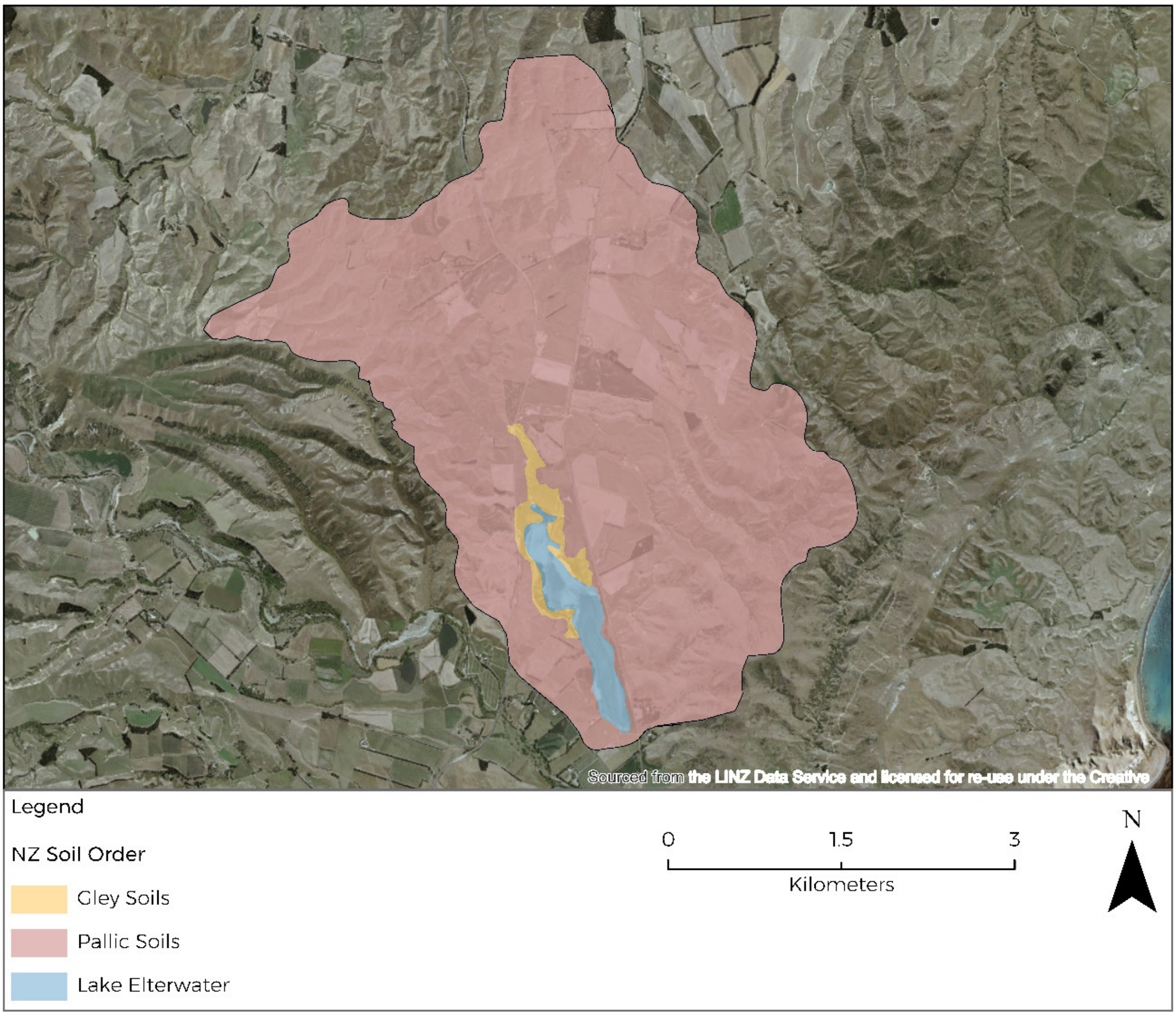

Figure 3-2: Soils overlying the bedrock in the Lake Elterwater catchment.

3.3 Kaikōura Earthquake

The 14 November 2016 Mw 7.8 Kaikōura Earthquake occurred in the north-east of the South Island, at the boundary between the Australian and Pacific tectonic plates. It initiated near Waiau in north Canterbury at 12:03. Rupture propagated south–west to north–east and terminated offshore in Cook Strait. Surface rupture occurred on at least fourteen faults, including displacements of >10m on the Kekerengu Fault (Clark *et al.*, 2017).

3.4 Summary

When combined with the climate, the soils and geology of the Lake Elterwater catchment explain why runoff is intermittent, and why the streams are ephemeral and generally flow only from May until September. This period of flow can either be longer or shorter than average depending on the rainfall pattern, antecedent conditions, and the passage of major rain-bearing weather systems. In some years there is no runoff or streamflow into Lake Elterwater.

4 Hydrology

4.1 Available data

There are limited climatic and hydrologic data available in the vicinity of the Lake Elterwater catchment. While this acts as a potential constraint on the level of precision of any analysis, the general trends and relationships identified from the available data are likely to be reliable.

NIWA has maintained two rain gauges in the wider area around the catchment. These are at Grassmere Salt Works and Ward, Chancet. The rainfall records from both sites are suffiicently long to allow robust estimates of the likely rainfall within the Lake Elterwater catchment (Table 4-1).

Table 4-1: Annual rainfall at sites in the vicinity of the Lake Elterwater catchment.

Site	Agent Number	Start Date	Finish Date	Minimum [mm]	Mean [mm]	Maximum [mm]
Grassmere Salt Works	4420	1943	2021	331	577	913
Ward, Chancet	4425	1920	2021	442	761	1194
Flaxbourne at Corrie Downs	-	2006	2021	367	687	1032
Taimate Station	-	14-Jan-65 & 1-Jan-05	2-Dec-71 & 9-Dec-08			

There are also two shorter rainfall records available from Flaxbourne at Corrie Downs (maintained by Marlborough District Council) and Taimate Station. Rainfall at Flaxbourne at Corrie Downs has been recorded since 2006. Taimate Station rainfall data was first recorded from 1965-1971 and then again from 2005-2007. These data, however, include cumulative totals over several days rather than always discrete daily values. Since 2013, rainfall has been logged continuously and at a high temporal resolution; however, these data are not considered reliable.

4.2 Rainfall

In general, the east coast of Marlborough experiences low rainfall because it lies in the rain shadow of the mountains to the west; which force the prevailing westerly weather systems to rise. This results in a cooling of the air mass and precipitation of the water vapour. Water vapour tends to precipitate at these higher elevations (i.e. orographic enhancement) resulting in drier, warmer winds for the east coast.

In the Lake Elterwater catchment, this translates to relatively low rainfall; with some spatial variability. Mean annual rainfall has been estimated at approximately 780mm at Ward, Chancet and 600mm at the Grassmere Salt Works, (Figure 4-2). When this generalised information is compared to the empirical data (Table 4-1) a high degree of consistency is apparent. The mean annual rainfall since 1913 at Chancet is 761mm (compared to 780 interpolated from the isohyets). The mean annual rainfall at Grassmere is 577mm, compared to about 600mm from the isohyets.

These rain gauges, however, all record only daily data. This acts as a constraint on the level of precision and sophistication of any analysis. However, since runoff usually integrates rainfall over time, this is not regarded as a significant limitation to this study.

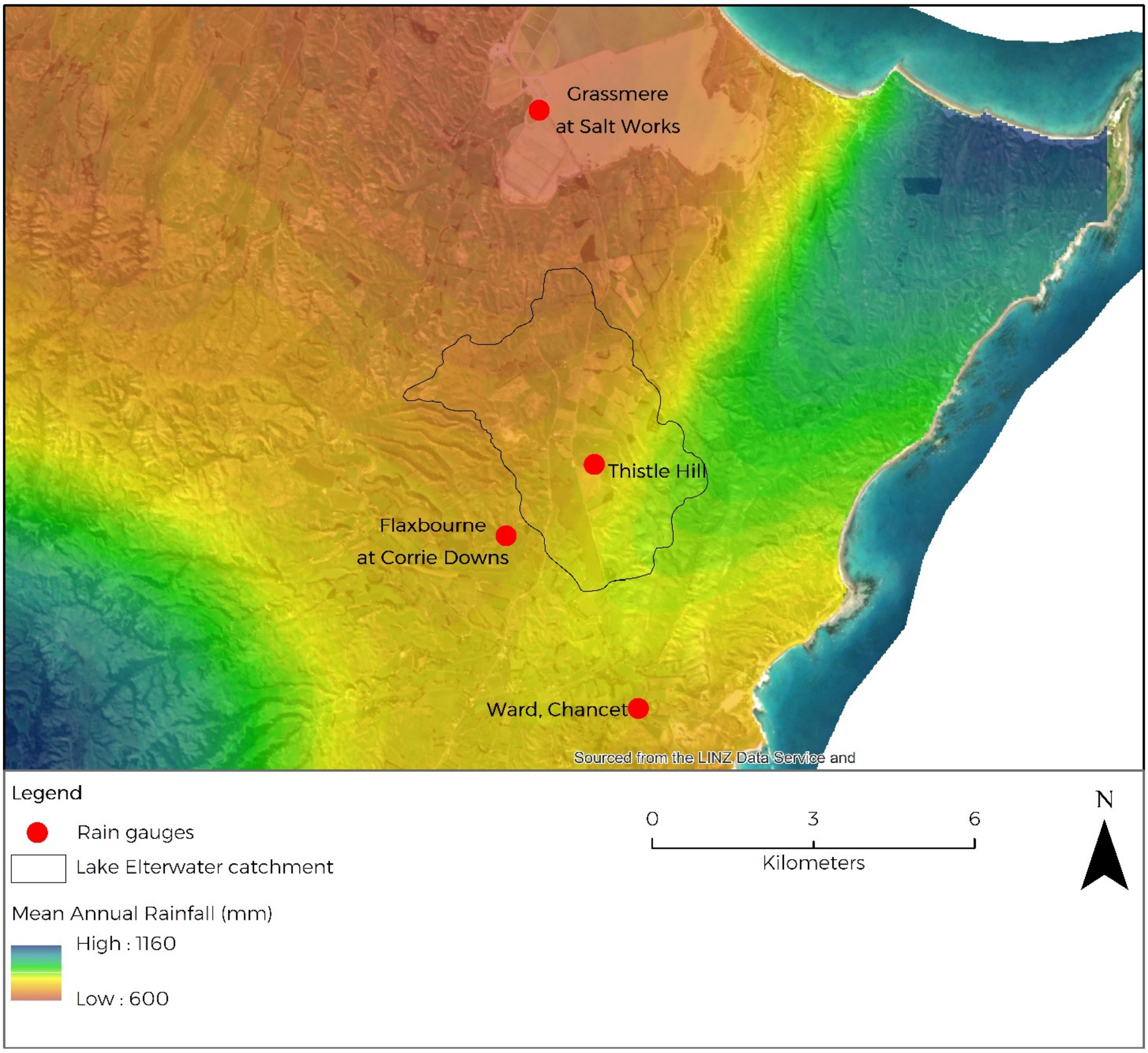

Figure 4-1: Mean annual rainfall around Lake Elterwater and location of rain gauges.

The two most important sites from the perspective of hydrological analysis are Ward, Chancet (because of its record length and proximity) and the Grassmere Salt Works (because of the completeness of the record). When the records from Ward, Chancet and Grassmere Salt Works are compared, it is apparent that Ward, Chancet receives significantly more rainfall each year; as expected from the regional pattern discussed earlier (Figure 4-2). Rainfall at Grassmere Salt Works is approximately 75% of that at Ward, Chancet.

Comparing the shorter rainfall records from Taimate Station and Flaxbourne at Corrie Downs, with those from Grassmere and Ward, shows that rainfall in the catchment is most likely to be similar to that recorded at the long-term gauge at Ward (Figure 4-3). Ward, Chancet therefore provides the most appropriate rainfall record for analysis.

The rainfall record from Ward, Chancet, the longest available, shows several characteristics of the likely rainfall pattern in the Elterwater catchment (Figure 4-4). The monthly data show a high degree of variability; from a minimum of zero to a maximum of over 450mm (March 1980). Although greater or less than average amounts of rainfall can occur in any month, there is still a strong seasonal pattern. Lower rainfalls tend to occur from December to April, and higher falls from May to November.

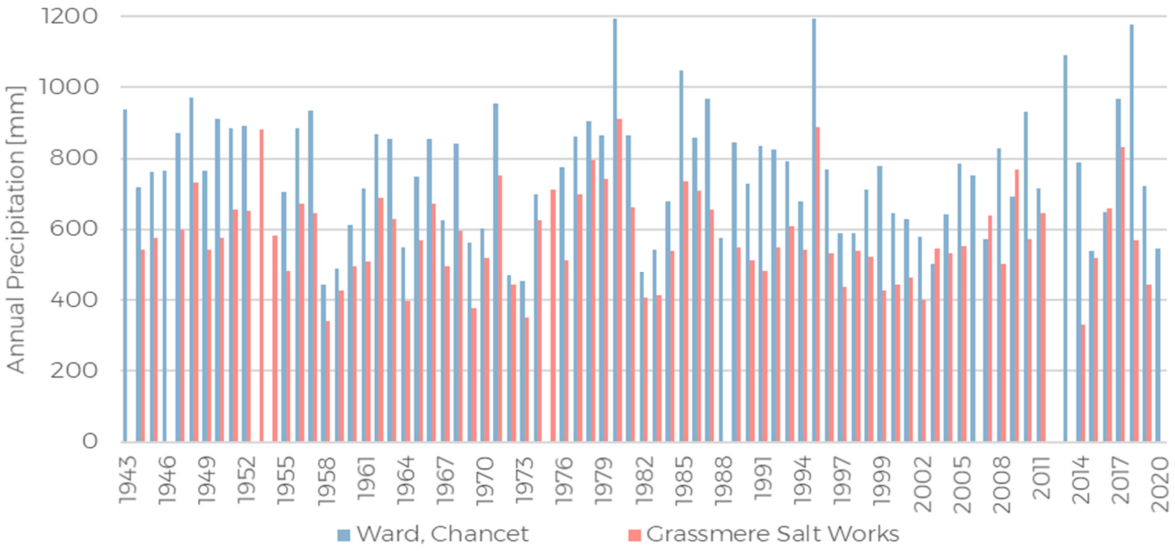

Figure 4-2: Annual rainfall at Ward, Chancet and Grassmere Salt Works (1943–2020).

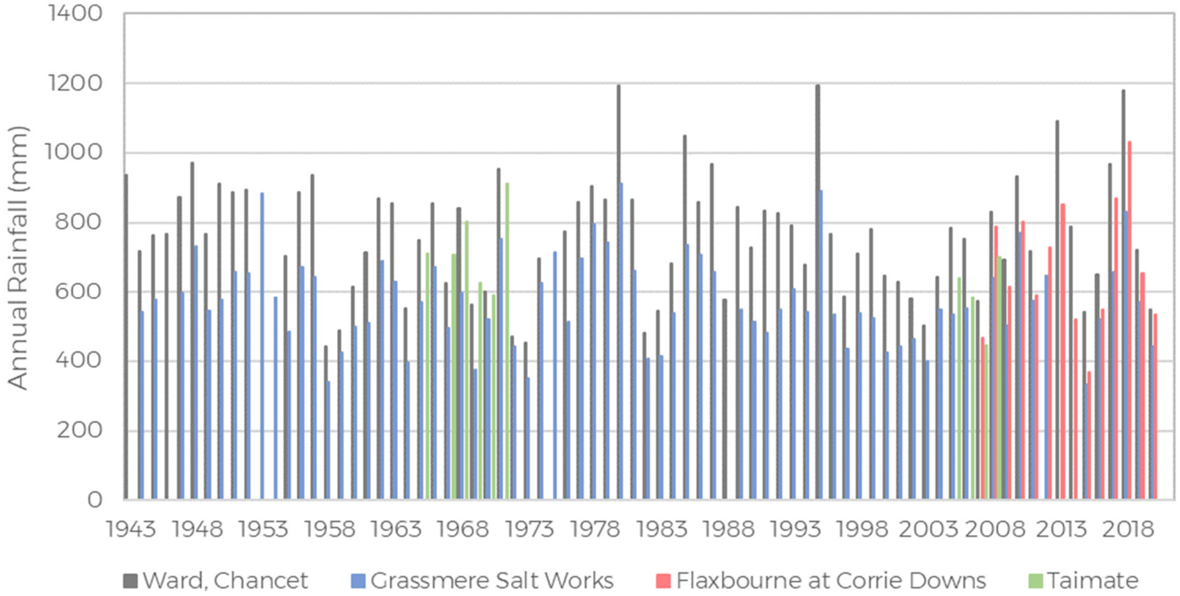

Figure 4-3: Comparison of rainfall recorded at Taimate Station, Flaxbourne at Corrie Downs, Ward, Chancet and Grassmere Salt Works.

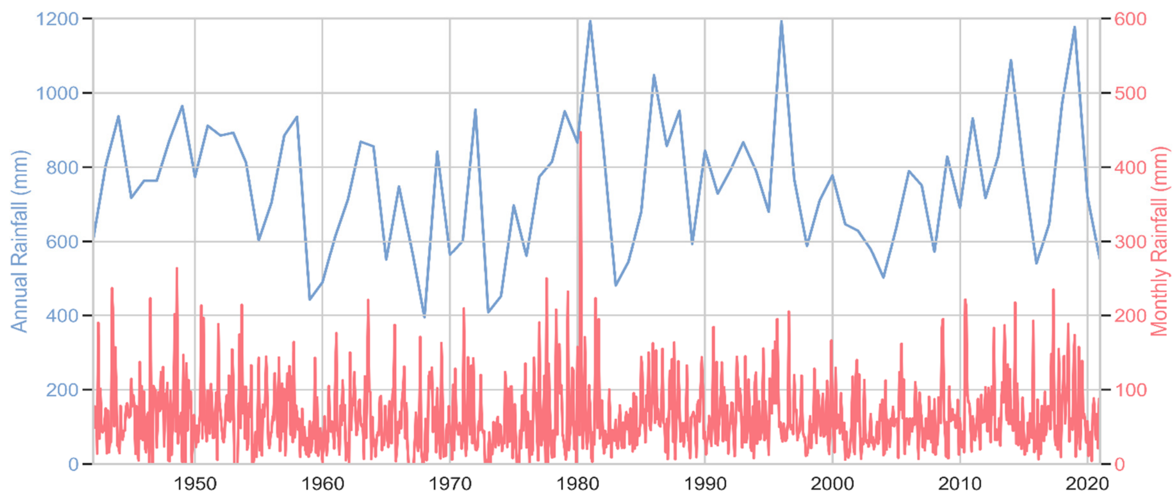

Figure 4-4: Rainfall recorded at Ward, Chancet. The red line shows the monthly totals while the blue line is the annual total.

The rainstorm on the 3-Mar-1980 produced a daily rainfall at Ward, Chancet of 222mm. Assuming that the annual rainfall maxima continue to approximate a Pearson 3 statistical distribution (Figure 4-5), this event had an Average Recurrence Interval (ARI) of 357-years (i.e. a ~0.3% Annual Exceedance Probability (AEP)). The extreme nature of this event is obvious when compared to the second largest event. This had a daily rainfall of only 167mm (i.e. a 48-year ARI or 2.1% AEP event).

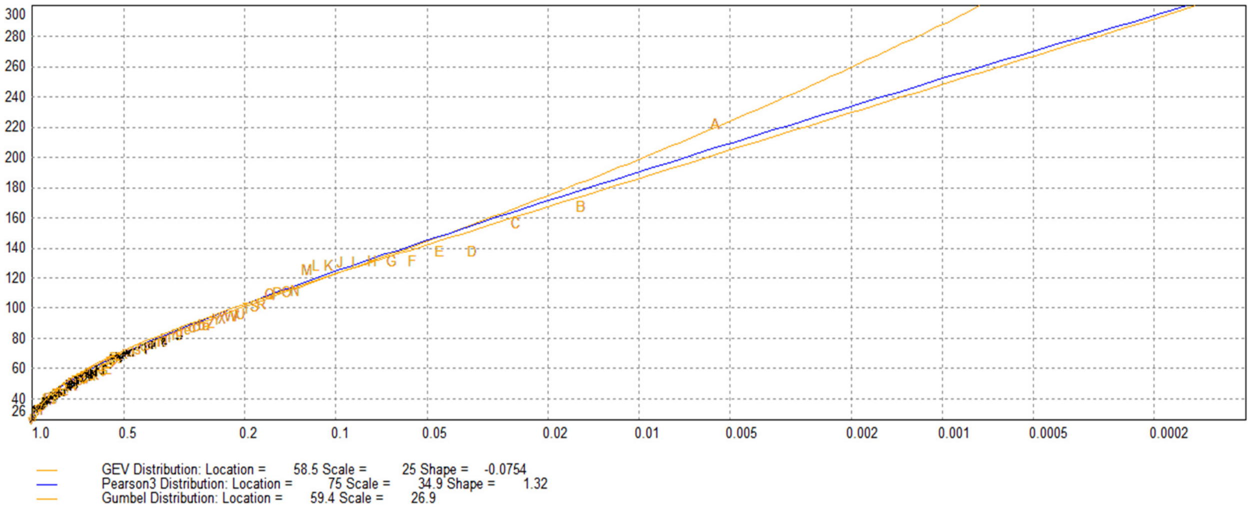

Figure 4-5: Frequency analysis of daily rainfall recorded at Ward, Chancet.

The largest daily rainfall recorded at Taimate was 115mm on 30-Jul-2008; on the same day that 128.5mm was recorded at Flaxbourne at Corrie Downs. During the same event, 131mm of rainfall was recorded at Ward, Chancet (i.e. a 20-year ARI or 5% AEP event).

These rainfall records show a high degree of variability in both monthly and annual totals. This has significant implications for potential runoff from those tributaries flowing into Lake Elterwater.

4.3 Evaporation

Whether any runoff is generated depends not only on the rainfall, but also on evaporation loses and changes in the moisture storage within the soil.

Evaporation losses are made up of three components: evaporation of water intercepted by various surfaces, transpiration through leaf surfaces, and evaporation from the soil moisture. It is usually impossible to separate these various components, and as a result they are usually lumped together and called evapotranspiration. The amount of water lost through evapotranspiration is controlled by both moisture and energy availability. Since it is actually the 'effective precipitation' (precipitation less evapotranspiration losses) that affects the amount of moisture potentially available to generate runoff, and maintain streamflow and plant health, it is important to see how this changes through time.

The availability of water throughout the year can be viewed as a simple water balance or budget. The water balance is a fundamental concept in hydrology and climatology, as it summarises the amount of water available to plants and animals, rather than just considering total precipitation.

Water enters the budget as precipitation, is lost through evapotranspiration and runoff, and can be stored in the soil. The potential evapotranspiration is essentially the maximum amount of water that will be 'lost' from the system if water is in unlimited supply. It is a function of incoming solar radiation, vapour pressure deficit, and wind speed. Values of potential evapotranspiration are usually calculated using equations, or it can be estimated from evaporation. While potential evapotranspiration is the maximum possible loss of water, this value is often not reached because of the limited availability of water.

Actual evapotranspiration therefore represents the amount of water that is actually lost. It is a function of both the potential evapotranspiration and water availability.

In a daily water budget, each day receives a certain amount of precipitation. The potential evapotranspiration (PE) for that day has the 'first call' on this moisture. If there is enough precipitation to meet potential evapotranspiration requirements, then the actual evapotranspiration (AE) will equal the potential evapotranspiration, i.e. AE will equal PE. Any moisture left over will either go into soil storage until it is full, or runoff. If the daily precipitation is less than PE, then moisture will be drawn from soil storage in an attempt to meet PE requirements. If sufficient moisture is present in the soil that AE can equal PE, and the environment will not be placed under stress. If, however, there is not enough moisture in the soil to meet PE requirements, then AE will be less than PE and a deficit will be experienced. It is during periods of deficit that plants experience stress and irrigation may be required to maintain plant growth and productivity.

There are three types of evaporation data available from Grassmere Salt Works: sunken pan; raised pan; and open water evaporation (Table 4-2). However, the different data sets are all of different lengths. The raised pan data set is the longest (1972-2021) and the sunken pan the shortest (1972-1984).

Table 4-2: Evaporation data from Grassmere Salt Works for the common period (1972-1984).

	Min	Mean	Max	LQ	Median	UQ
Raised pan	0	5.14	22.00	2.2	4.5	7.3
Sunken pan	0	4.89	22.90	2.5	4.6	7.1
Open pan	0	4.64	21.20	1.9	3.9	6.7

The annual evaporation data show a strong seasonal pattern; as to be expected. Values are highest during the summer, peaking in February or March. Lowest values are recorded during winter (Figure 4-6).

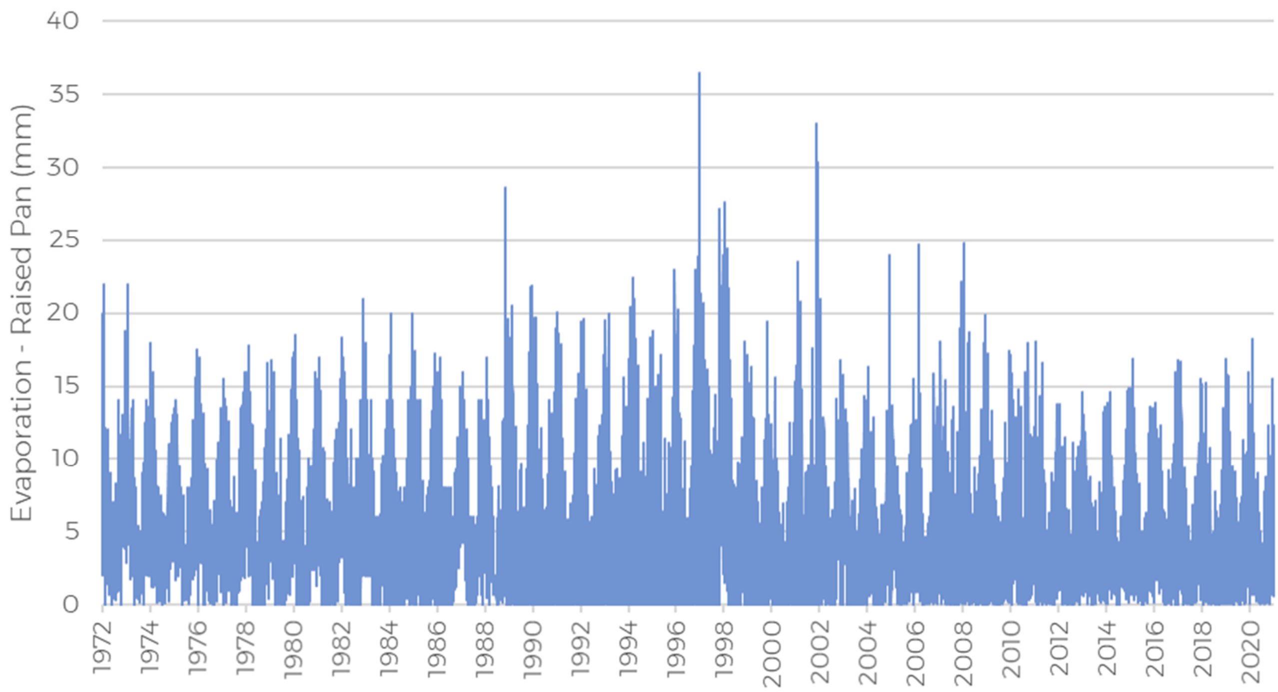

Figure 4-6: Raised pan evaporation at Lake Grassmere (1972-2021).

This seasonal pattern is more obvious when only one year of data is plotted. Evaporation is lowest from May through to August; with some days experiencing no evaporation. Values peak in summer, when almost 17mm could have potentially evaporated over one day (Figure 4-7).

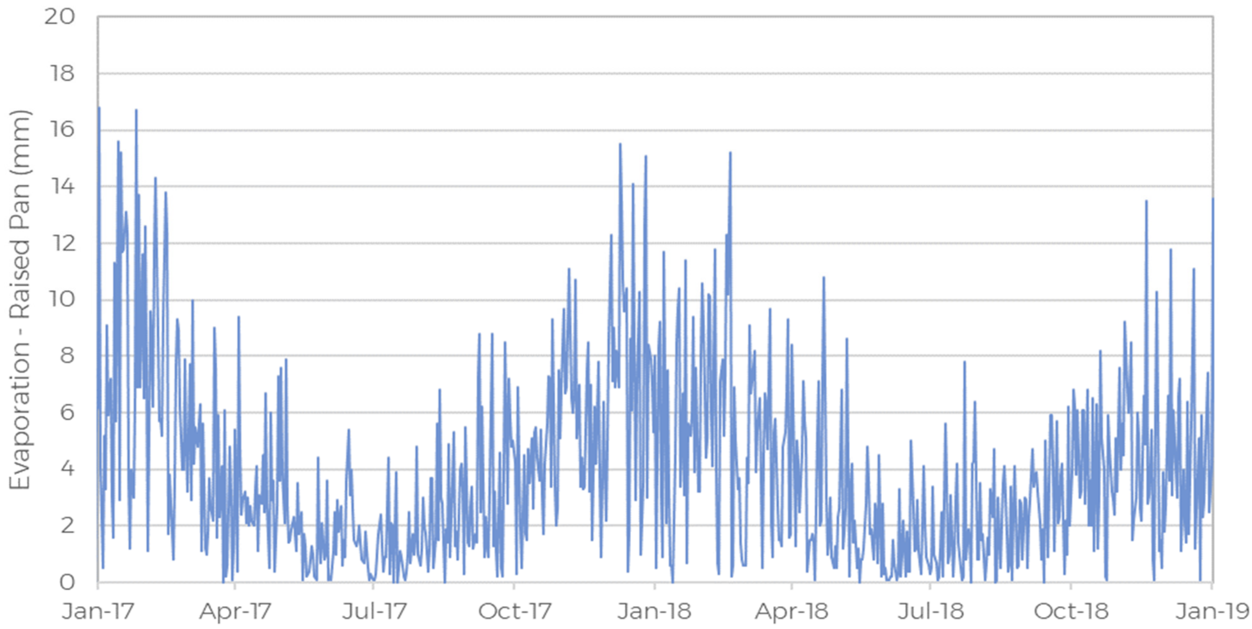

Figure 4-7: Raised pan evaporation data from Grassmere Salt works (2017-2018).

If daily precipitation, evaporation and soil moisture content are known, it is possible to calculate the actual evapotranspiration, i.e. the actual amount of water lost given both energy and moisture availability constraints. Consequently, the actual evapotranspiration at Ward and Grassmere Salt Works was determined (Figure 4-8).

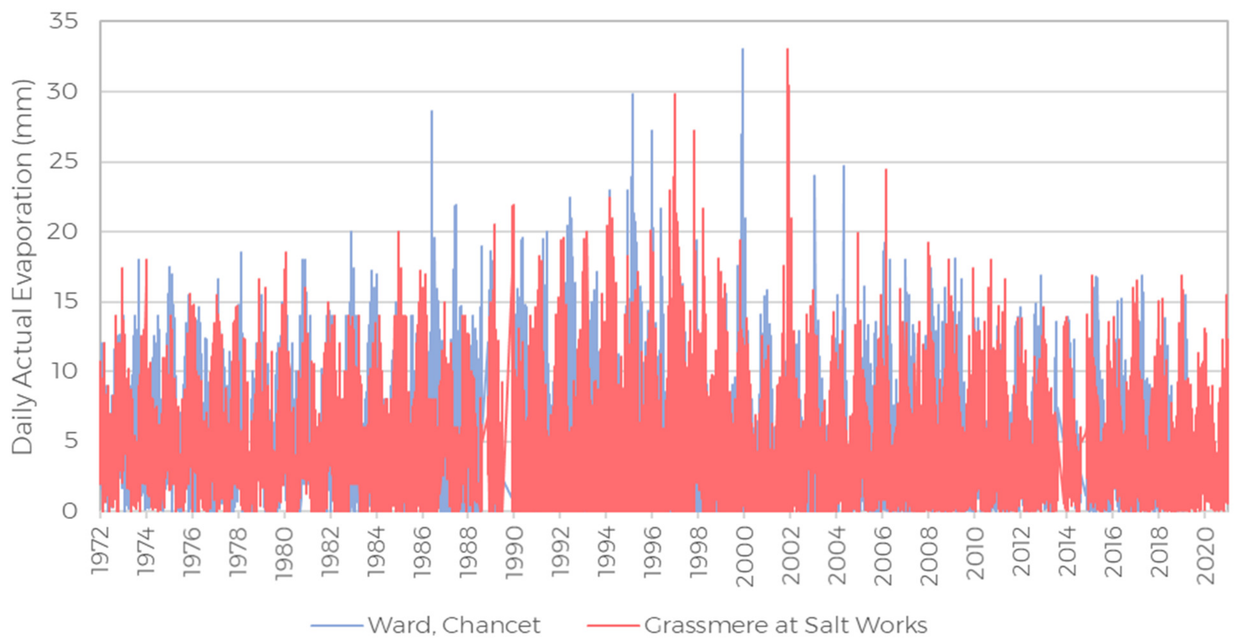

Figure 4-8: Actual evapotranspiration at Ward and Grassmere Salt Works.

When comparing Figure 4-6 with Figure 4-8, it is apparent that while the two graphs have similar trends, there are also distinct differences. First, the actual water loss is generally less than the potential loss, even given some slight location-related differences. This is because the availability of moisture at Ward is at times limited. It is not possible to evaporate water that does not exist within the soil. Second, the moisture losses tend to be highest in spring when water is available as a result of winter rains, even though the available energy is not at a maximum. Finally, losses are particularly low during summer, except on days when it rains, because there is little water in the system to evaporate.

When comparing the actual evapotranspiration at Ward and Grassmere Salt Works, a high degree of consistency is apparent (Figure 4-8). This is not surprising given the strong influence of energy on evapotranspiration, and the similarity of energy at both sites.

Ward tends to have slightly higher daily actual evapotranspiration rates because it has higher rainfall, and therefore greater available moisture. Although the energy to evaporate moisture is the same at both sites, the higher available moisture at Ward means that more water can be evaporated.

4.4 General runoff analysis

There are no flow data or runoff measurements available within the Lake Elterwater catchment. It is possible, however, using data available at Ward and Grassmere Salt Works, to calculate the likely timing and volume of any runoff. Runoff is expressed as depth (i.e. mm), so the units are the same as for rainfall and evapotranspiration.

Estimates of runoff are based on a water balance model using rainfall, evapotranspiration, and potential soil moisture storage as inputs. Runoff is calculated assuming that any precipitation that falls is absorbed until the ground is saturated, and then runs off. The available moisture holding capacity of the soil is assumed to be 150mm in the generalised models for Ward and Grassmere Salt Works.

It is likely that these models under-estimate runoff since the potential evapotranspiration data used does not fully account for restricted moisture losses from the soil and the leaves of plants. Also, no allowance is made for rainfall events where the precipitation intensity exceeds the infiltration rate of the soil.

Estimates of the daily runoff from both Ward and Grassmere Salt Works are shown in Figure 4-9. The runoff pattern is consistent for both sites, although Ward, Chancet tends to produce more runoff than Grassmere Salt Works. This is because of the higher rainfall experienced at Ward. The annual pattern of runoff, and the differences between the two sites, are highlighted when annual totals are compared (Figure 4-10).

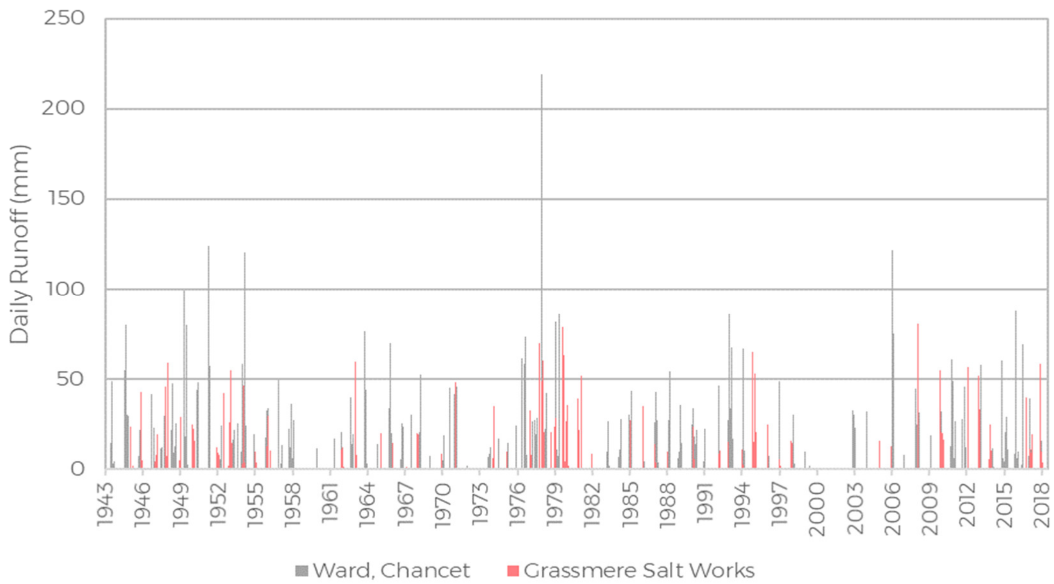

Figure 4-9: Estimates of daily runoff from Ward, Chancet and Grassmere Salt Works (mm).

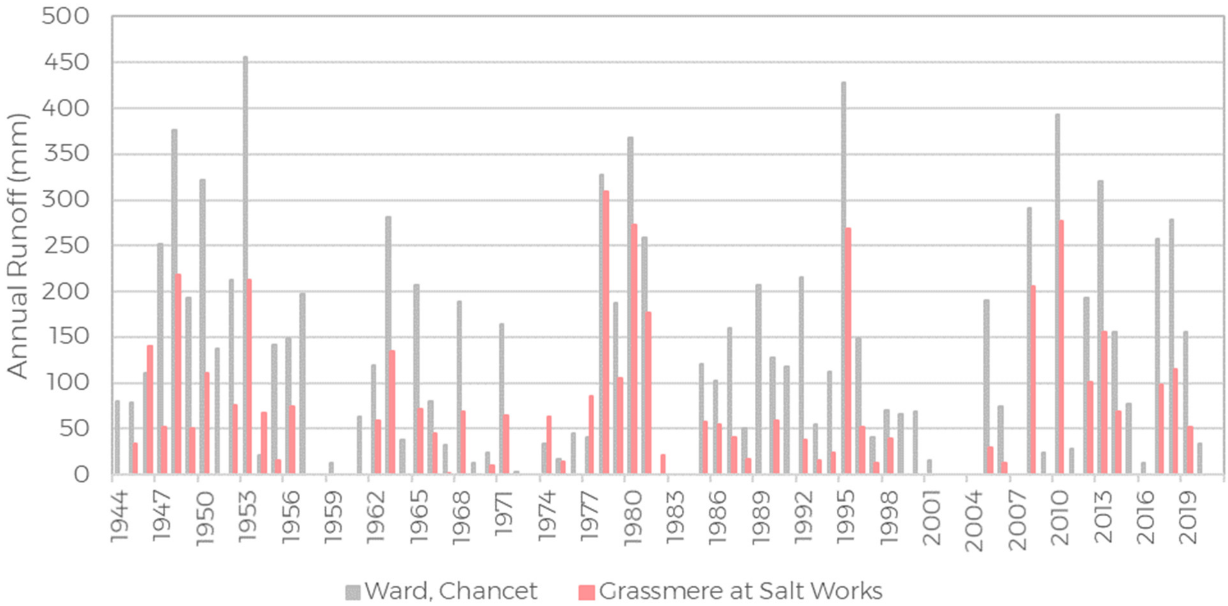

Figure 4-10: Annual runoff from Ward, Chancet and Grassmere Salt Works (mm).

There is almost twice as much runoff at Ward than at Grassmere Salt Works; because of the higher rainfall. Despite this, there are still some years when no runoff is produced. These years will be those when Lake Elterwater either gets very low, or goes dry, depending on antecedent conditions.

The annual pattern of runoff appears to exhibit some cyclic behaviour, but the long-term nature of the record allows the effect of this to be included in the summary statistics. The mean annual runoff depth at Ward is 130mm; the median is 102mm. These equate to runoff volumes in the Lake Elterwater catchment of approximately 2.1Mm^3 and 1.6Mm^3, respectively.

Since the runoff depths discussed above have been calculated using a simple water balance, it is important to have some validation of these data. This is difficult since there are no flow data available for any of the slopes in this area; or from any other locations in the wider vicinity.

However, one would expect that if the estimation of runoff is accurate, there should be a high correlation between runoff depth and stream flow. The nearest streamflow record to Ward is from the Flaxbourne River at Corrie Downs.

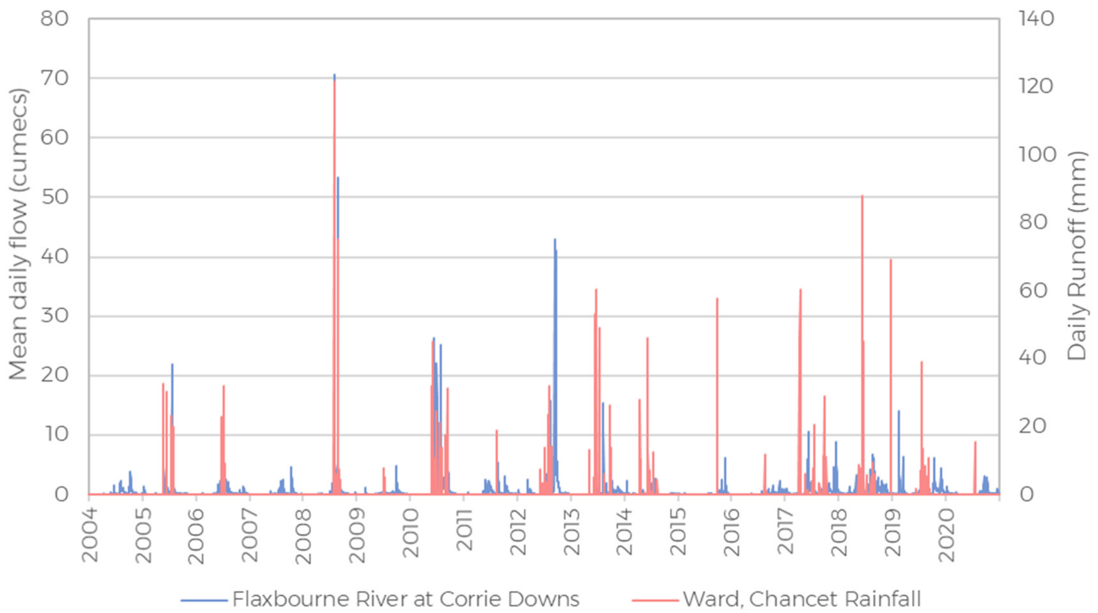

Figure 4-11: Derived runoff from Ward, Chancet compared to flow in the Flaxbourne River.

Figure 4-11 shows a high degree of correlation between predicted runoff and streamflow. The correlation is particularly strong during higher streamflow events. This is because these flows will have been generated when the soil storage is at capacity, i.e. there is slope runoff.

The estimates of runoff would therefore appear to have some validity in predicting the actual processes operating within the Lake Elterwater catchment.

Obviously, the major controls on runoff generation are the amount and timing of precipitation; the higher the annual rainfall, the higher the total annual runoff (Figure 4-12). Variation in annual rainfall can be used to explain over 62% of the variation in annual runoff. The rest of the variation is likely to be controlled by the temporal distribution and intensity of the specific rainfall events during the year.

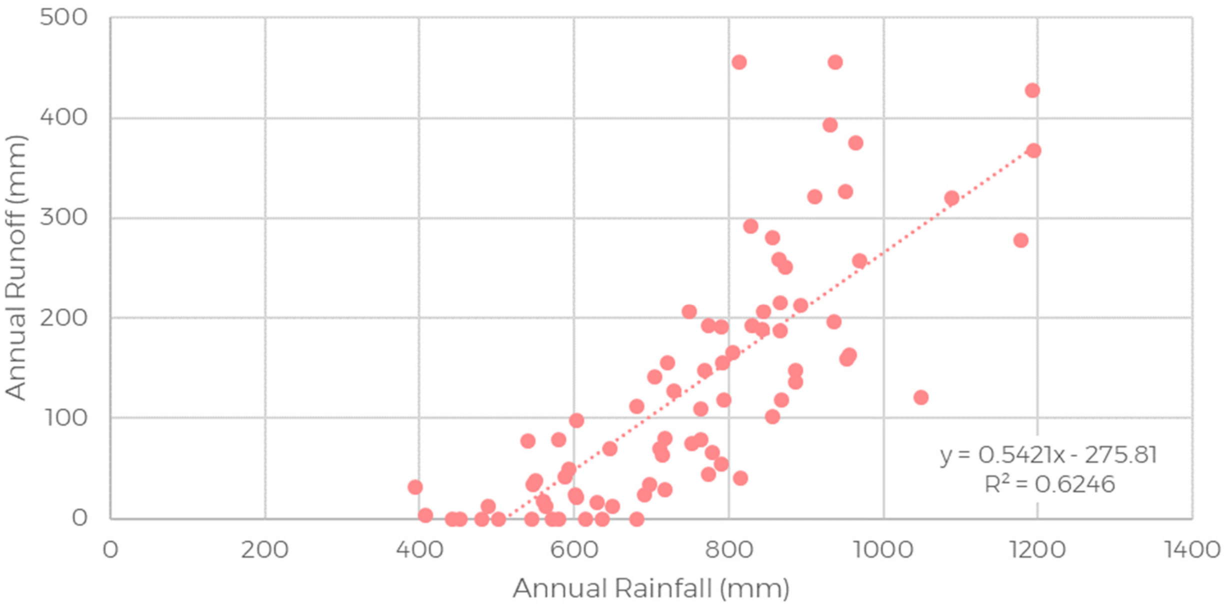

Figure 4-12: Relationship between total annual rainfall and total runoff at Ward.

4.5 Local runoff analysis

Given the above analysis, not all rainfall events will produce runoff. For runoff to be generated, either the rainfall intensity must be greater than the infiltration capacity, or the soil moisture storage must be full. As discussed previously, with respect to Ward and Grassmere Salt Works, it is possible to estimate runoff from rainfall, evapotranspiration and soil's moisture storage potential. Using the available data, a similar analysis was undertaken using rainfall data from Thistle Hill; approximately 800m east of Lake Elterwater.

There are no evapotranspiration data for Thistle Hill. Therefore, those data from Grassmere Salt Works were used. Although this site is about 7km from Lake Elterwater, evapotranspiration has been shown to be reasonably constant over large areas, especially when there is limited topographic variation.

A soil moisture storage of 150mm was assumed in the 'generalised runoff index' discussed earlier for both Grassmere Salt Works and Ward, Chancet. However, when attempting to model runoff at Thistle Hill, such a high soil moisture storage capacity generated no runoff; even on days when runoff was observed.

The soils in the Lake Elterwater catchment are estimated to have a Profile Available Water (PAW) of Class 3 or 4. These classes relate to a PAW ranging from 60-149mm. Since the PAW is the total available water in the soil profile to a depth of 0.9m, or to the potential rooting depth (whichever is the lesser), it is considered a surrogate for the available soil moisture capacity.

Consequently, the standard runoff model used at Grassmere Salt Works was modified to include a soil capacity of 70mm, and the rainfall recorded at Thistle Hill, to provide an estimate of the runoff likely into Lake Elterwater (Figure 4-13).

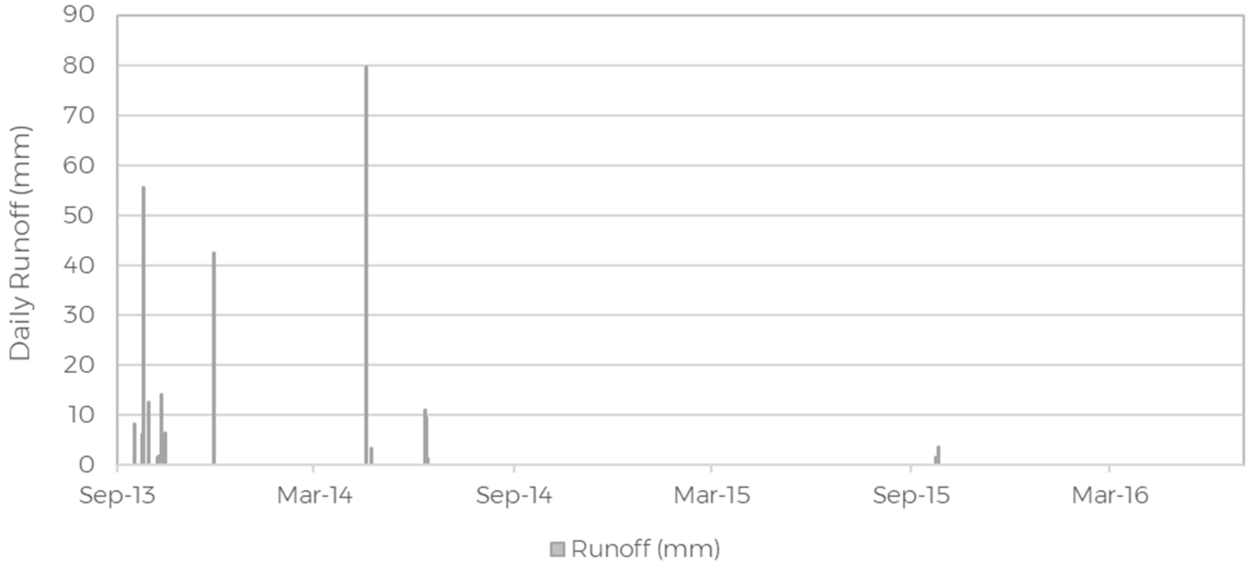

Figure 4-13: Daily runoff calculated for the Thistle Hill site (2013-2016).

A soil moisture capacity of 70mm generated runoff on the 13 August 2016, when runoff was observed within the catchment. A higher soil moisture storage capacity resulted in no runoff; even though runoff was observed. A lower soil moisture storage capacity produced too much runoff, i.e. runoff on numerous days when it did not actually occur.

4.6 Soil moisture

As discussed, the soil properties, and in particular the soil moisture content, are critical in determining whether any specific rainfall event generates runoff. The direct connection between rainfall, soil moisture storage, and runoff is key in the Lake Elterwater catchment because of the relatively impermeable bedrock and thin soils, and therefore limited groundwater flow.

The soils throughout the Elterwater catchment are various silt loams and hill soils; where at least 50% of the soil is comprised of silt, with varying components of sand and clay. This affects soil porosity, and therefore the infiltration of rainfall into the soil and the generation of runoff. Silt and clay soils typically have a porosity ranging from 0.35–0.50% by weight (Kopec, 1995). However, these soils, because of the small pore sizes, tend to have lower infiltration and consequently higher runoff given sufficient rainfall.

Soil moisture sensors were installed at Thistle Hill, approximately 800m east of Lake Elterwater, in 2013. The sensors are at two locations approximately 300m apart, and with the 'lower' sensor further down the slope (Figure 4-14). The sensors record the daily mean, minimum and maximum volumetric soil moisture content (Figure 4-15 & Figure 4-16). The record from the 'upper' sensor is approximately 5 months longer, commencing in September 2013; the 'lower' soil moisture sensor record starts in March 2014.

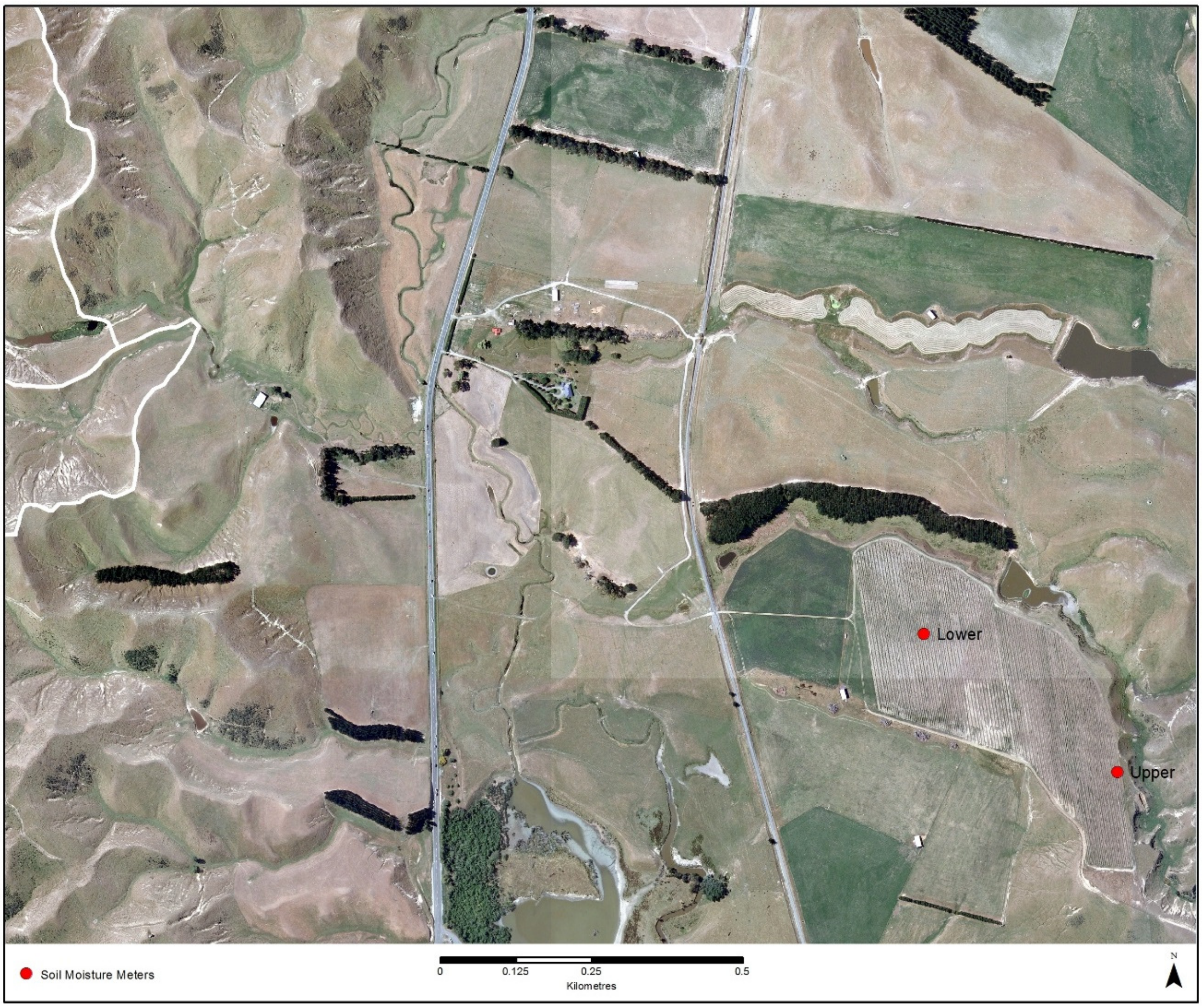

Figure 4-14: Location of the soil moisture sensors at Thistle Hill.

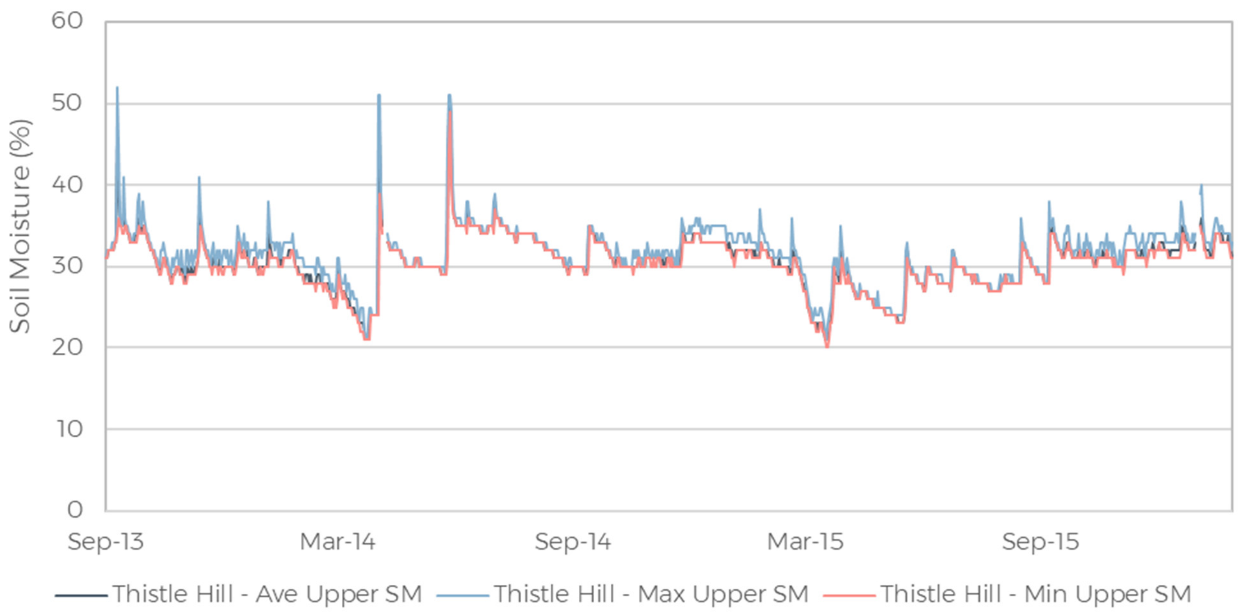

Figure 4-15: Daily minimum, average and maximum soil moisture contents recorded by the 'Upper' sensor at Thistle Hill (2013-2016).

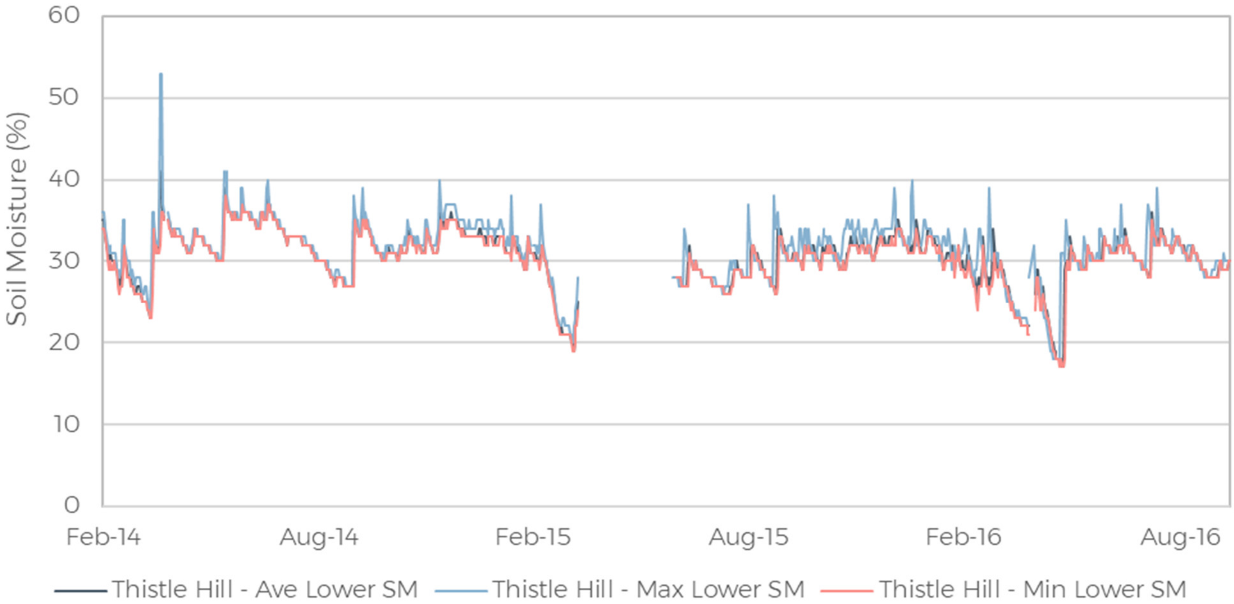

Figure 4-16: Daily minimum, average and maximum soil moisture contents recorded by the 'Lower' sensor at Thistle Hill (2014-2016).

The summary statistics of the soil moisture content recorded at the two locations are provided in Table 4-3.

Table 4-3: Summary statistics of the soil moisture content measured at two locations at Thistle Hill (2013/2014-2016).

Location	Minimum	Maximum	Mean	LQ	Median	UQ
Lower (Average)	17	41	30	29	31	33
Lower (Maximum)	18	53	31	30	32	34
Lower (Minimum)	17	38	30	29	31	32
Upper (Average)	20	50	30	29	31	32
Upper (Maximum)	20	52	31	30	32	33
Upper (Minimum)	20	49	30	29	30	32

The 'Upper' sensor provides a slightly longer record, with less missing data, compared to the 'Lower' sensor; although the overall patterns and trends at both sites are the same. The mean and median soil moisture content at Thistle Hill are approximately 31%. Soil moisture contents greater than this tend to rise rapidly (in response to rainfall) and then fall slowly (in response to evapotranspiration). Since the three values of soil moisture recorded each day are essentially the same (as expected), the 'maximum values' have been used for analysis and comparison.

4.7 Soil moisture and rainfall

As expected, the soil moisture content increases and decreases in response to rainfall (Figure 4-17). However, a large increase in soil moisture content requires either a high daily rainfall, or a large cumulative rainfall over several successive days. During periods without rain, the soil moisture slowly decreases as moisture is lost to meet evapotranspiration demand.

The soil moisture content varies between 17-53%; but for most of the time it is between 30-40%. Only occasionally does the soil moisture content go above 40% (Figure 4-17).

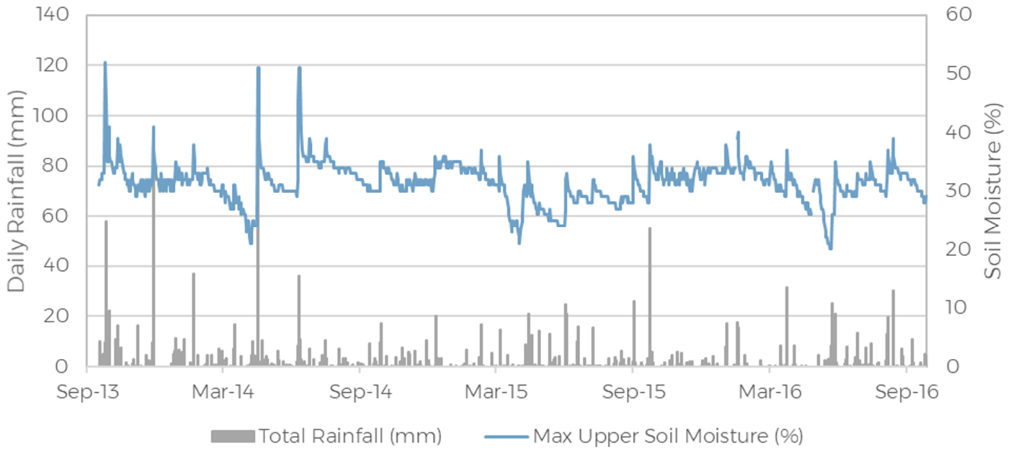

Figure 4-17: Comparison of soil moisture content and rainfall at Thistle Hill (2013-2016).

4.8 Soil moisture and runoff

When the synthetic runoff record is compared to the measured soil moisture content, it appears that runoff occurs when the soil moisture content exceeds about 40% *(*Figure 4-18*)*. This seems both reasonable and realistic.

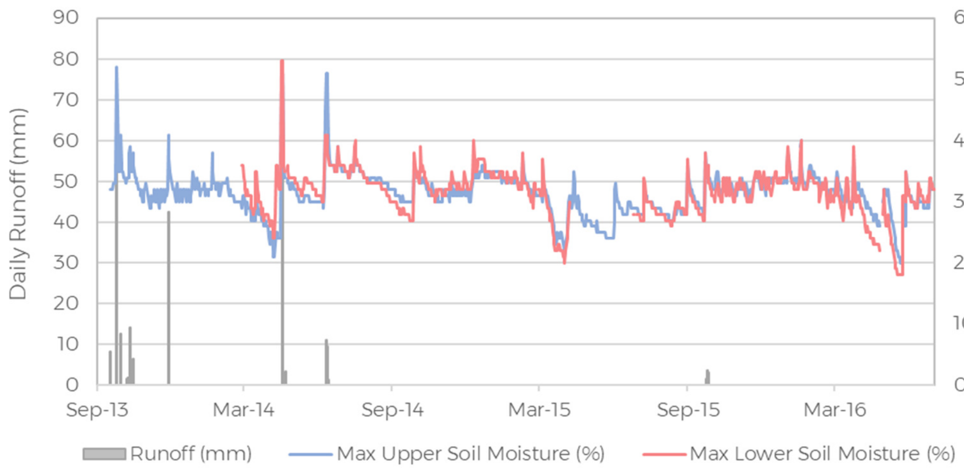

Figure 4-18: Daily runoff and soil moisture content at Thistle Hill.

As such, a soil moisture threshold of 40% could be used as a check on whether runoff would occur in the Lake Elterwater catchment (Figure 4-19).

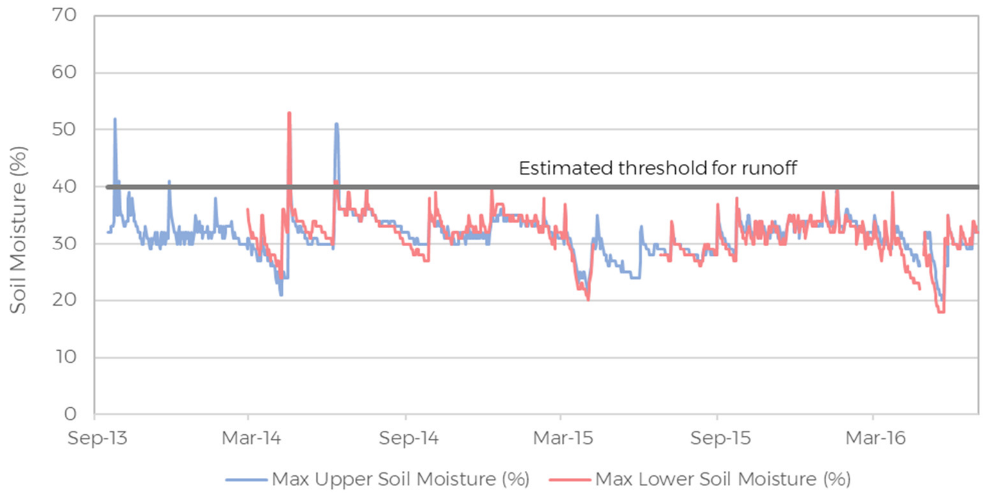

Figure 4-19: A soil moisture content of about 40% is required for runoff to be initiated in the Lake Elterwater catchment.

4.9 Summary

In general, the east coast of Marlborough is an area of low rainfall. There is a strong seasonal pattern; with lower rainfalls generally occurring from December to April, and higher falls from May to November. However, there is also a high degree of variability in monthly and annual rainfall which has significant implications for potential runoff into Lake Elterwater.

There is also a strong seasonal pattern to annual evaporation; evaporation is highest during the summer, peaking in February or March. Actual evapotranspiration rates are similar, although tend to peak in spring when more moisture is available as a result of winter rains, but the available energy has not yet increased to summer levels.

The modelled annual pattern of runoff (using Ward, Chancet and Grassmere at Salt Works observation records as surrogates) shows a high degree of correlation with streamflow in the Flaxbourne River at Corrie Downs. The correlation is particularly strong during higher streamflow events. This is because these flows have been generated when the soil storage is at capacity, i.e. there is slope runoff.

Variation in annual rainfall can be used to explain over 62% of the variation in annual runoff. The rest of the variation is likely to be controlled by the temporal distribution and intensity of the specific rainfall events. Soil moisture content increases and decreases in response to rainfall. However, a large increase in soil moisture content requires either a high daily rainfall, or a large cumulative rainfall over several successive days. During periods without rain, the soil moisture slowly decreases as moisture is lost to meet evapotranspiration demand.

5 Stage/Storage Relationship

The following section quantifies effect of the Kaikōura Earthquake on the storage capacity and likely water balance of Lake Elterwater. Stage, surface area and water storage relationships for Lake Elterwater, assuming both pre- and post-earthquake topography, are quantified and compared.

5.1 Survey information

The bed of Lake Elterwater was surveyed by Gilbert Haymes and Associates Ltd in 2016-17. Significant differences in the topography and elevation of the lakebed were measured as a result of the Kaikōura Earthquake in November 2016. The lakebed after the earthquake is represented by the Site Plan provided. Changes in elevation were noted on the plan to show the variation from pre-earthquake ground levels.

5.2 Methodology

DEM generation

A Digital Elevation Model (DEM) was created from the contour lines provided by Gilbert Haymes and Associates Ltd using Inverse Distance Weighting interpolation in ArcGIS. The resultant terrain surface represents the elevation of the lakebed after the Kaikōura Earthquake (i.e. the post-quake DEM).

The changes in elevation (Figure 5-1) noted on the site plan were interpolated across the lake to create a surface of elevation change as a result of the earthquake. This elevation surface was added to the post-quake DEM to represent the lakebed before the earthquake (i.e. the pre-quake DEM).

The pre and post-earthquake DEMs are shown in Figure 5-2. The change in lakebed elevation is shown by the increase in area below 16.2masl after the quake. Greater change is evident towards the northern end of the lake. This is because of the larger drop in elevation (i.e. 0.17m and 0.24m) in the north compared to the south (i.e. only 0.03m).

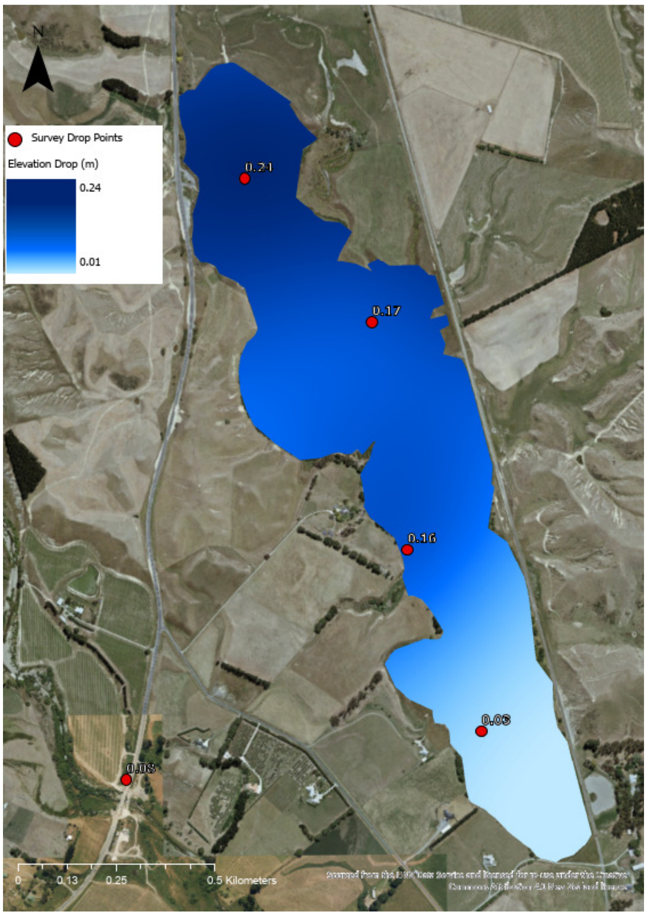

Figure 5-1: Elevation drop points noted in the Site Plan provided by surveyors.

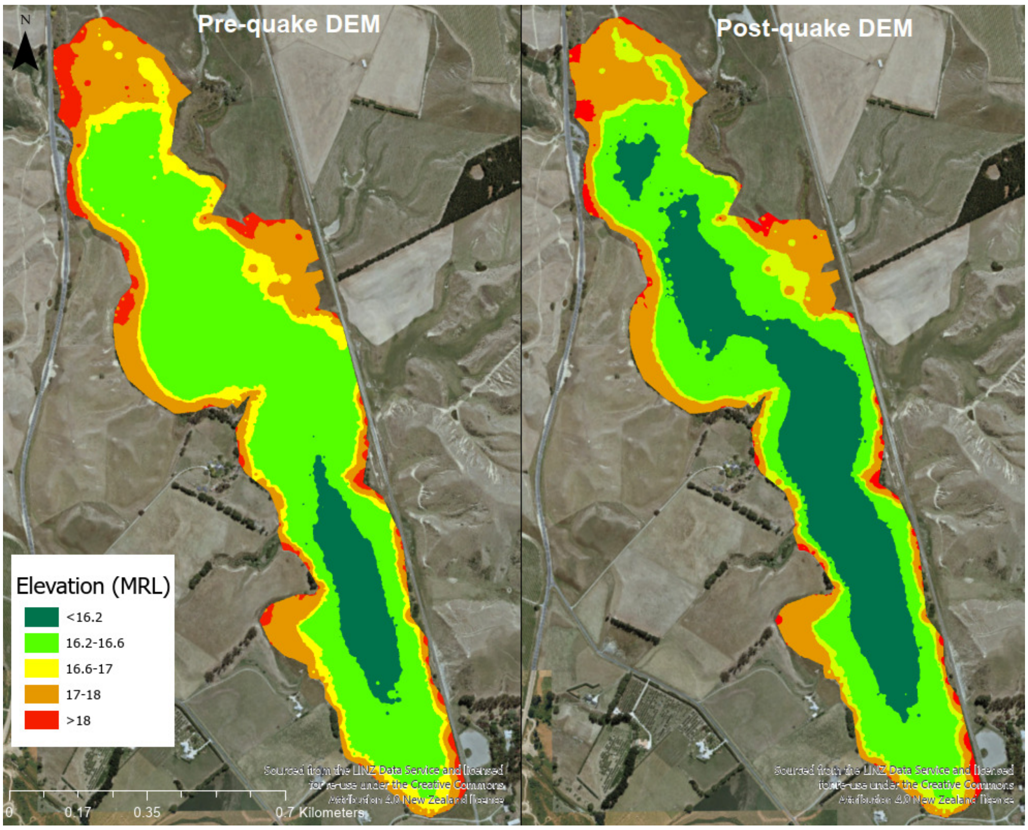

Figure 5-2: Pre-quake and post-quake DEMs of the lakebed.

The Zonal Statistics tool in ArcGIS was used to determine the minimum and maximum elevations in the pre- and post-quake DEMs (Table 5-1).

Table 5-1: Minimum and maximum elevations in the pre and post-quake DEMs.

	Minimum Level	Maximum Level
Pre-Quake Levels	16.07m	20.68m
Post-Quake Levels	15.99m	20.49m

The stage/surface area/water storage relationships for both pre- and post-earthquake DEMs were calculated based on an assumed maximum water level of 17.3masl. This is the height of the invert i.e. highest point, on the bed of the lake outlet that flows under the bridge on the road to London Hill. While the water level of Lake Elterwater can occasionally be higher than this, the invert level generally controls lake outflow.

Stage/surface area/storage relationships

Stage/surface area/storage relationships, at 0.1m increments, were calculated for the lake using an automated Python script. This script uses the pre-quake and post-quake DEMs, and the lake outline layer provided by the surveyors, to produce a text file of the water surface area and volume at each elevation i.e. stage.

5.3 Results

The stage/surface area/storage relationships for Lake Elterwater before and after the earthquake are shown in Table 5-2. The total volume of the lake, up to an elevation of 17.3masl, increased from 474,847m^3 to 553,024m^3 as a result of the earthquake (i.e. 78,177m^3 or ~16.5%). The maximum potential lake area at the invert level also increased from 562,567m^2 to 586,661m^2 (i.e. 24,094m^2 or ~4.3%). The surface area and volume of the lake at each stage are shown in Table 5-2 and Figure 5-3 & 5-4.

Table 5-2: Stage/surface area/storage relationships for Lake Elterwater before and after the Kaikōura Earthquake.

Pre-Earthquake Volume			Post-Earthquake Volume		
Elevation (m)	Area (m^2)	Storage Volume (m^3)	Elevation (m)	Area (m^2)	Storage Volume (m^3)
Water levels below channel invert					
-	-	-	15.99	-	-
16.07	-	-	16.0	48	0.2
16.1	2,625	13	16.1	82,542	2,814
16.2	61,245	2,910	16.2	224,601	17,840
16.3	174,917	14,177	16.3	358,391	47,722
16.4	293,456	37,671	16.4	418,069	86,824
16.5	400,618	73,061	16.5	457,417	130,790
16.6	447,352	115,730	16.6	482,043	177,883
16.7	473,686	161,898	16.7	498,947	226,929
16.8	492,183	210,237	16.8	515,164	277,636
16.9	508,129	260,258	16.9	530,339	329,930
17.0	523,172	311,823	17.0	543,907	383,645
17.1	537,272	364,855	17.1	556,776	438,682
17.2	549,888	419,219	17.2	571,698	495,095
17.3	562,567	474,847	17.3	586,661	553,024
Water levels above channel invert					
17.4	576,493	531,779	17.4	603,240	612,462
17.5	591,588	590,191	17.5	619,881	673,632
17.6	608,688	650,199	17.6	638,144	736,541
17.7	626,748	711,972	17.7	652,149	801,074
17.8	642,893	775,460	17.8	665,675	866,943
17.9	657,785	840,481	17.9	677,071	934,112
18.0	669,892	906,924	18.0	685,726	1,002,292
18.1	679,440	974,398	18.1	690,322	1,071,112

18.2	686,503	1,042,724	**18.2**	693,201	1,140,293
18.3	690,852	1,111,604	**18.3**	695,343	1,209,725
18.4	693,556	1,180,834	**18.4**	697,031	1,279,344
18.5	695,629	1,250,299	**18.5**	698,319	1,349,116
18.6	697,154	1,319,941	**18.6**	699,153	1,418,991
18.67	698,059	1,368,776	**18.67**	699,617	1,467,949

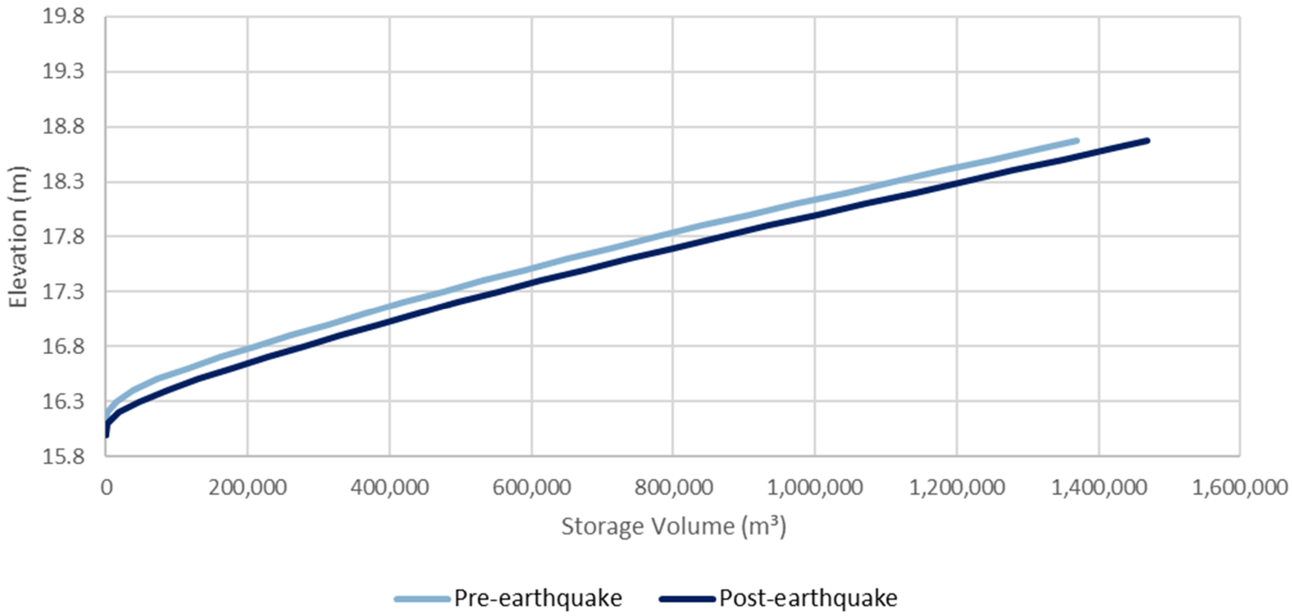

Figure 5-3: Stage/storage volume relationship for Lake Elterwater before and after the Kaikōura Earthquake.

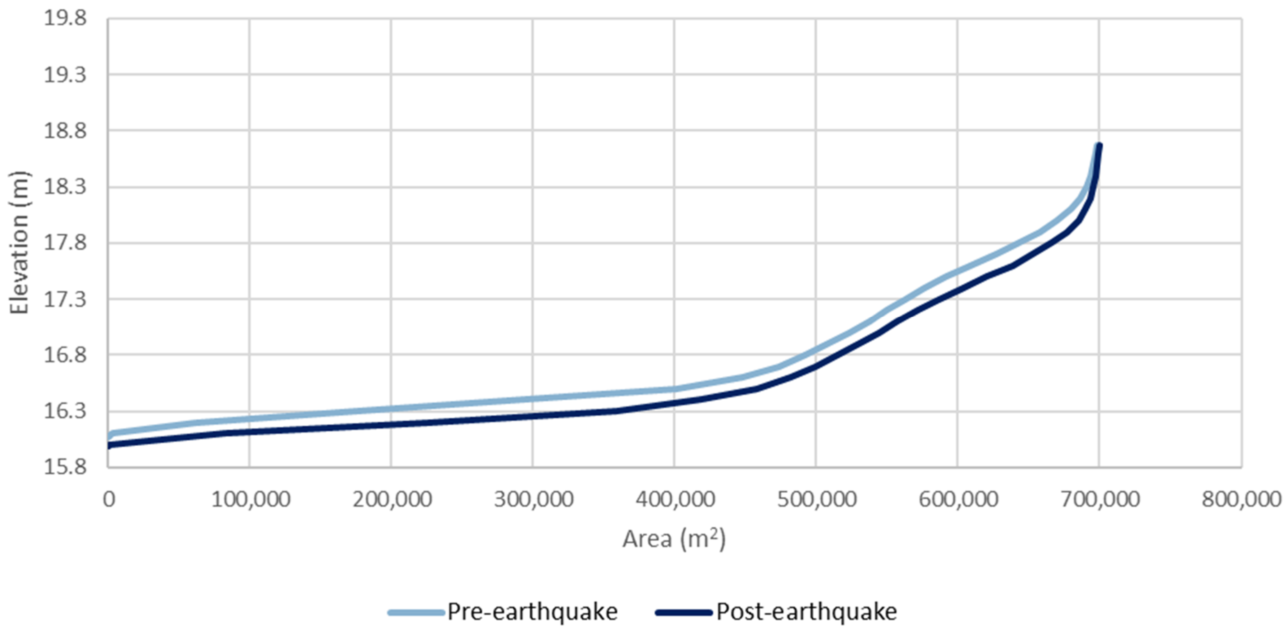

Figure 5-4: Stage/surface area relationship for Lake Elterwater before and after the Kaikōura Earthquake.

5.4 Impact on Lake Elterwater

The storage capacity of Lake Elterwater has increased as a result of the Kaikōura Earthquake. An additional 78,177m^3 of water (i.e. ~16.5%) can now be stored within the lake below the invert of the channel at 17.3masl. The maximum potential lake surface area at the invert level has also increased, by 24,094m^2 (i.e. ~4.3%).

The lowest elevation of the lakebed after the earthquake is 16masl; a decrease of ~10cm because of the earthquake. While the magnitude of this decrease is not large, it occurred over an area of 79,917m^2, or approximately 11% of the lakebed.

The flow into Lake Elterwater is unlikely to have changed because of the earthquake; however, the increase in both the potential depth and volume of water able to be stored will likely impact the aquatic habitat i.e. the area of wetland will increase slightly. Since the lake can hold more water, the water level will decrease more slowly during summer. Overall, there is likely to be a slightly greater area of wetland habitat, and wetland conditions are likely to persist for longer periods. It is also possible that any flow downstream of Lake Elterwater into the Flaxbourne River will be moderated and attenuated.

5.5 Summary

Comparison of the pre- and post-earthquake DEMs shows that the relative elevation of the lakebed has decreased towards the northern end of the lake. The stage/surface area/storage relationships for both the pre- and post-earthquake topographies assume a maximum water level of 17.3masl; which is the invert level of the outlet channel. Stage/surface area/storage relationships to the maximum of 18.7masl are also shown to cover a range of high lake level scenarios. At higher water levels, water overflows the road to London Hill.

The potential volume of Lake Elterwater has increased by 78,177m^3 (i.e. ~16.5%), and its area by 24,094m^2 (i.e. ~4.3%).

The flow into Lake Elterwater is unlikely to have changed because of the earthquake; however, the increase in both the potential depth and volume of water able to be stored will likely impact the aquatic habitat i.e. the area of wetland will increase slightly. Since the lake can hold more water, the water level will decrease more slowly during summer. Overall, there is likely to be a slightly greater area of wetland habitat, and wetland conditions are likely to persist for longer periods. It is also possible that any flow downstream of Lake Elterwater into the Flaxbourne River will be moderated and attenuated.

6 Environmental Monitoring

As discussed above, there is limited environmental data available currently relating to Lake Elterwater and its wider catchment. Therefore, because of the significance of Lake Elterwater, MDC, with support from the Flaxbourne Settlers' Association and the Ministry of Primary Industries, have installed, additional environmental monitoring. This includes:

- The installation of a continuous lake level recorder. This has been installed at close as possible to the deepest area of the lake to provide a water level record over almost the full range of levels likely to be experienced; and

- An automated climate station to collect high-resolution data relating to a wide range of parameters; including rainfall, temperature, humidity and wind. This data will fill the significant gap in available climate information that exists between Lake Grassmere and Ward.

It is also anticipated that when Lake Elterwater is discharging to the Flaxbourne River, flow measurements will be undertaken at the outlet from the lake. Over time, these will allow the development of a flow rating. When these data are combined with the lake level record, it will be possible to develop a water balance for Lake Elterwater that quantifies, for the first time, inflows, outflows and changes in storage.

Because of the significance of Lake Elterwater and its wetland habitat, Marlborough District Council is to include information relating to the lake in its State of the Environment reporting.

The above actions and strategy will ensure that high quality environmental data and information are collected for Lake Elterwater, and that its condition is monitored on an ongoing basis.

7 Conclusions

The above analysis shows that:

- Lake Elterwater is the largest surface water body in the Flaxbourne-Mirza-Waima (Ure) area and has high ecological significance. It is a highly dynamic system that functions as both a lake and wetland environment depending on conditions.
- The soils and geology of the Lake Elterwater catchment affect runoff processes. In combination with the climate, they explain why runoff is intermittent and why the streams are ephemeral and generally flow only from May until September.
- Rainfall and evaporation show a strong seasonal patterns. Rainfall is highest during winter months, while evaporation is highest during the warmer and drier spring and summer months.
- Predicted runoff into Lake Elterwater shows a strong correlation with streamflow in the Flaxbourne River at Corrie Downs. The correlation is particularly strong during larger streamflow events.
- Variation in annual rainfall explains over 62% of the variation in annual runoff. The rest of the variation is likely to be controlled by the temporal distribution and intensity of the specific rainfall events. Soil moisture content also increases and decreases in response to rainfall.
- The Kaikōura Earthquake raised the southern end of Lake Elterwater relative to the northern end.
- This ‘tilting’ has increased the potential volume of the lake by 78,177m^3 (~16.5%), and its maximum surface area by 24,094m^2 (~4.3%).
- The flow into Lake Elterwater is unlikely to have changed because of the earthquake; however, the increase in both the potential depth and volume of water able to be stored will likely impact the aquatic habitat i.e. the area of wetland will increase slightly. Since the lake can hold more water, the water level will decrease more slowly during summer. Overall, there is likely to be a slightly greater area of wetland habitat, and wetland conditions are likely to persist for longer periods. It is also possible that any flow downstream of Lake Elterwater into the Flaxbourne River will be moderated and attenuated.

- A water level recorder has been installed by MDC, with support from the Flaxbourne Settlers' Association and the Ministry of Primary Industries, towards the deepest area of the lake. This will provide a continuous record of the lake level over almost its entire range.
- An automated climate station has also been installed by MDC, with support from the Flaxbourne Settlers' Association and the Ministry of Primary Industries. This will provide high-resolution data relating to a wide range of parameters, including rainfall, temperature, humidity and wind, of direct relevance to Lake Elterwater. This data will fill the significant gap in available climate information that exists between Lake Grassmere and Ward.
- When Lake Elterwater is discharging to the Flaxbourne River, flow measurements will be undertaken at the outlet from the lake. These will allow the development of a flow rating. When these data are combined with the lake level record, it will be possible to develop a water balance for Lake Elterwater that quantifies inflows, outflows and changes in storage.
- Because of the significance of Lake Elterwater and its wetland habitat, Marlborough District Council is to include information relating to the lake in its State of the Environment reporting.
- The above actions and strategy will ensure that high quality environmental data and information are collected for Lake Elterwater, and that its condition is monitored on an ongoing basis.

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