MEMORANDUM

Bay of Plenty
REGIONAL COUNCIL

To: Andy Bruere
Manager

From: Peter West
Contract Engineer

Date: 17 November 2017

File Ref:

Copy To: Peter Blackwood

Subject: **Lake Okareka; Design of Pipeline Capacity; impacts on Lake Level management**

Andy,

Executive Summary

This memo reports on an assessment of the lake level management performance to be expected from a range of potential pipeline capacities.

BOPRC's water balance model for Lake Okareka from 2013[i,ii] has been re-run with 2017 rainfall data and finds close agreement with the observed lake levels, pipeline discharge estimates and pumping records.

A statistical assessment of Okareka (daily read) rainfall data since 1966 has been carried out to estimate the probability of long-duration high rainfall events in the future – probabilistic design rainfall. The likely effects of climate change have also been applied to these design rainfalls in the manner recommended by the Ministry for the Environment.

The design rainfall has been applied to the water balance model to determine the likely lake levels that would result from the design rainfall events; and against a range of potential pipeline capacities.

Tables of peak lake level, and lake recovery times, have been produced for 20, 50, 100 and 200 year ARI rainfall event probabilities; for pipeline capacities from 250 L/s to 600 L/s (in 50 L/s increments); and considering climate change to both 2040 and 2090 at MfE's guidance mid-range and high-range scenarios.

Background

Lake Okareka has no natural overland outflow. Natural under-ground seepages were augmented in 1965 by a gravity pipeline. In 2015 part of the 1965 pipeline was replaced and upgraded, increasing the system's discharge capacity. During the winter and spring of 2017 high rainfall has lead to very high lake levels. At the time of writing, temporary pumping is being used to supplement the gravity pipeline discharges.

To inform decisions about further pipeline upgrades, this assessment was carried out to find the relative benefits of a range of potential options. The detailed practicalities and costs of a selection of pipeline options are being investigated by others; it is intended that this (my) assessment –

which simply tests the likely range of pipeline capacities – will be used to provide performance-based context for those options.

For further detailed background on the Lake Okareka pipeline, water balance modelling, and lake level management recommendations refer to the memoranda listed in the end notes (i, ii, iii)

Part One

The assessment is in three parts.

BOPRC's water balance model for Lake Okareka was run with rainfall data from 1 January to 31 October 2017. The model was derived from historical observations and was most recently updated in 2013. It relates daily rainfall depth (mm) to total lake inflow (L/s) and includes a seasonal variation factor. 2017 has clearly been an exceptional year, and the purpose of re-running the model was to see how well it reproduces the observed lake levels, to check whether the relationships remain valid for the high-rainfall conditions experienced.

Table 1 below shows the times of pipeline management actions and the estimated rate of discharge resulting from those changes. The valve setting actions refer to a screw-actuated sliding-gate control valve that has been installed at a point mid-way along the pipeline. The settings are described by BOPRC staff in terms of full turns of the valve handle from the closed (fully seated) position.

These estimates of discharge are based on close inspection of the water level and gauging record on Waitangi Stream at the Spencer Road Culvert – a location downstream of the pipeline outlet. The stream is spring-fed and, in addition to the pipeline changes, its discharge responds to local rain as well as a seasonal variation in spring flow. Flows at the stream have been gauged 23 times since March 2015 (the period corresponding to the upgraded pipeline and valve). Automatic water level recordings at the culvert since 31 July 2017 are available. A rating curve is in use – although its reliability is limited due to the noise in the gauging data and suspected variability in hydraulic control. Pumping began on 8 August at an apparent rate of about 140 L/s. Full-shut-down actions of the pump and pipeline have occurred twice during this time – allowing indicative observations of stream base flows (which vary considerably). To capture the stop-start nature of the early pumping actions, starting on the 8th of August, the model discharge values have been taken directly from the rated flow records at Spencer Road Culvert with 60 L/s subtracted for spring flow.

Table 1: Pipeline valve settings by date with estimated discharge for the time following each change

Date	Action (valve setting)	Discharge (L/s from this date)
20/02/2017	Change to 2 turns	80
14/03/2017	Change to 4 turns	100
17/03/2017	Change to 8.5 turns	230
23/06/2017	Change to 10 turns	260
30/06/2017	Change to 12 turns	305
5/07/2017	Change to 13 turns	310
6/07/2017	Change to 16 turns	330
8/08/2017	Start of pumping	460 (average)

Figure 1 on the next page shows the results from the water balance model (blue line) alongside the lake level recordings (black line). The times of lake management actions are shown by the vertical red lines (labelled). Also showing is the rainfall record (daily rain depth in mm) from the raingauge in the village (named: Okareka at Blakely).

The results indicate that the model is reasonably reproducing what occurred over the ten month period. Levels are estimated with an average absolute discrepancy of 28.2mm over the period. The peak level is estimated within 13mm (~1% of the lake level range over the period). From a visual inspection of the graph the trends and other visual features are qualitatively similar.

Following inspection of the model results, it is considered that the water balance model can reasonably be used to predict lake level responses to periods of high rainfall such as in a design sense. Part of these fit-for-purpose considerations is the likely slight mis-representation of catchment-wide event rainfall from the single raingauge, and the measurement accuracies in the stream gauging and rating methods. It is acknowledged that the results of any such design work could be considered accurate to about 10% of the model range – say plus-or-minus 100mm when considering absolute levels. However relative levels are not subject to this margin so various pipeline options and probabilities can be compared (against each other) to a close degree of accuracy.

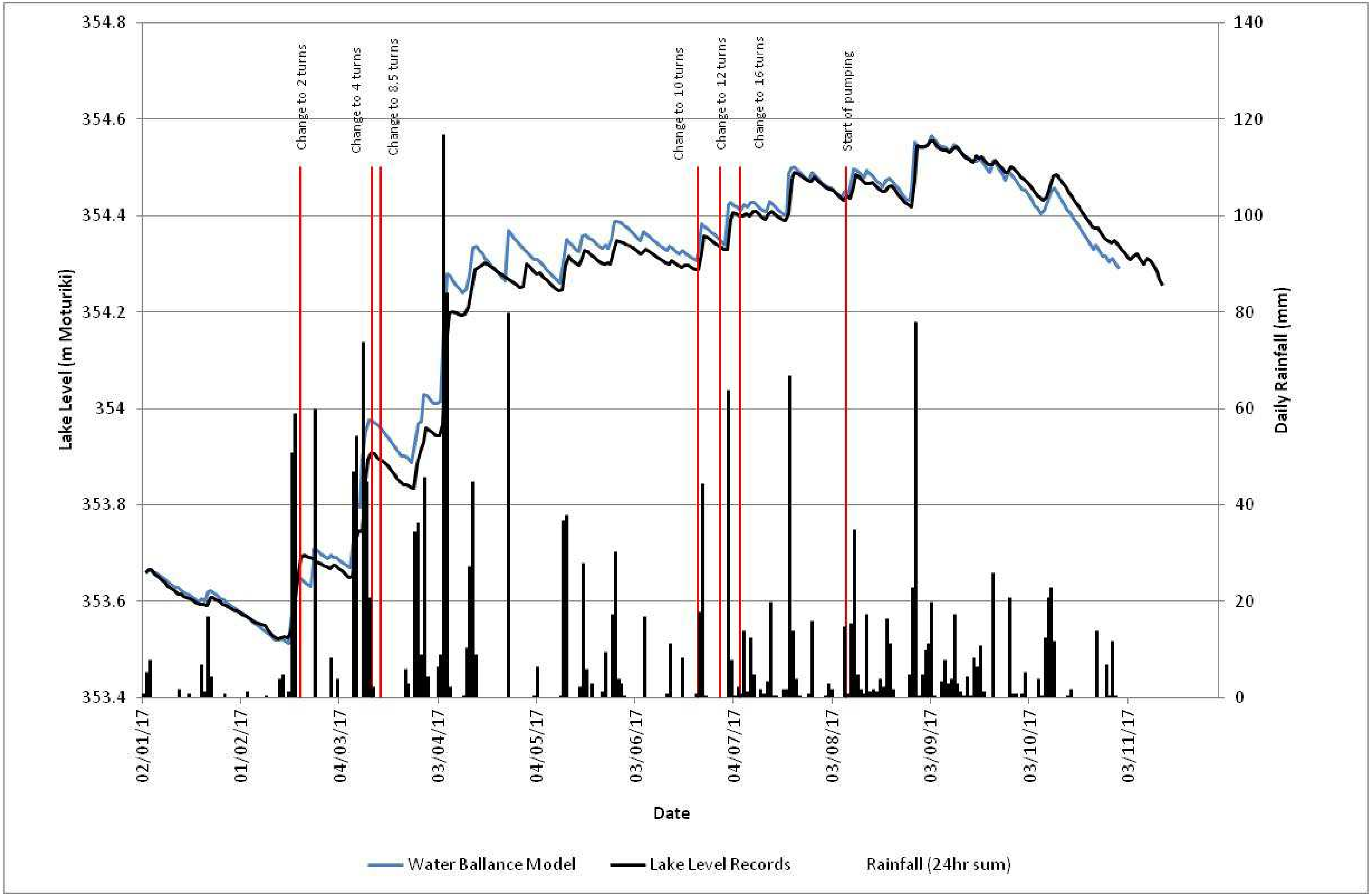

Figure 1: Water balance model results (blue) for January to October 2017 inclusive alongside recorded lake levels (black). Also showing daily rainfall (black bars) and times of lake management actions (vertical red lines).

Part Two

The second part was a statistical assessment of the long term rainfall record to determine appropriate rainfall depths for use in design. With some gaps, rainfall has been read daily at Lake Okareka since before 1966. Annual maxima for rain depth were extracted from the record for 17 different durations from 24 hours to 500 days. The calendar year for each maxima was based on the start date of the event (e.g. the largest accumulation of rain in any 500 day period that starts in that calendar year). These samples were fitted to an EV1 type distribution using the method of L-moments (Figure 2 below).

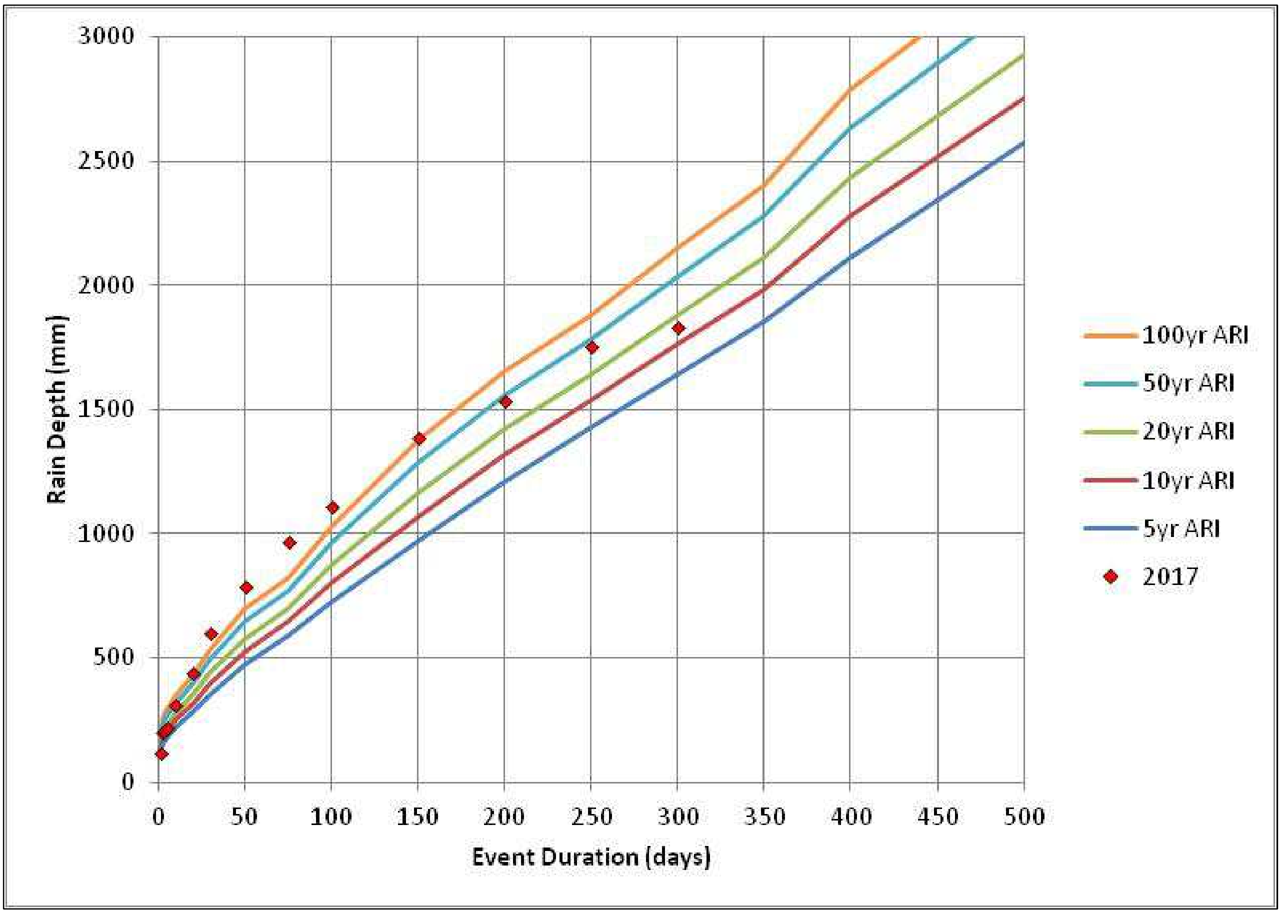

Figure 2: Extreme Value Type 1 statistical distribution fitted to historical rain depth data at Lake Okareka (1966 to 2017 inclusive; with several missing years). Showing a range of rain event durations from 24 hours to 500 days; at probabilities from 5 year to 100 year ARI. Also showing the observed maximum rainfall depths from 2017 for each duration (to the end of October).

Initially the analysis was carried out using the Generalised Extreme Value (GEV) distribution. The two distributions produce design rainfall results in close agreement, however the application of the GEV distribution over such a wide range of event durations was problematic. Typically the shorter storms fitted best to GEV Type 2 (upward curving when plotted on Gumbel paper), gradually changing to Type 3 as durations extended beyond about 200 days. This created difficulties when constructing combined hyetographs for design at extreme probabilities (for Part 3 below). It is considered, noting the close agreement between the two distributions for this raingauge, that the EV1 distribution is appropriate for this application. The full set of statistical calculations is appended to this report.

Table 2 on page 9 shows the resulting rainfall depths for Lake Okareka that were adopted for the design assessment.

By way of checking, the design rainfall values for Okareka were compared against a similar analysis carried out for Whakarewarewa (7.8km distant). Whakarewarewa gauge has been read since 1901 and has a higher standard of record (less gaps). Event durations of 24 hours, 10 days and 100 days were analysed. Close agreement was found: Whakarewarewa values were about 5% higher at the 24 hour duration; less than 1% lower at the 10 day duration; and about 2% lower at the 100 day duration (fairly consistently across probability values).

The maxima for 2017 were also used in the analysis even though the year is not completed and will not be technically complete until 500 days of data exists after the end of the year. This decision was based on its obvious significance as the largest depths on record for all durations between 30 days and 250 days.

Table 2: Design Rainfalls for Raingauge: Okareka at Blakely based on 43 to 50 years (depending on duration) of data from 1966 to 2017 (inclusive) fitted to EV1 distribution by the method of L-Moments.

T	24hr	2day	3day	5day	10day	20day	30day	50day	75day
2.33yr ARI	85.3	112.8	126.7	143.3	182.7	239.8	301.8	408.2	518.5
5yr ARI	106.8	140.7	159.4	177.2	221.0	284.7	355.3	474.5	588.7
10yr ARI	124.4	163.5	186.0	204.8	252.3	321.3	398.9	528.6	645.8
20yr ARI	141.2	185.4	211.6	231.3	282.3	356.4	440.7	580.5	700.6
50yr ARI	163.0	213.7	244.7	265.5	321.1	401.9	494.8	647.6	771.6
100yr ARI	179.4	234.9	269.5	291.2	350.2	435.9	535.3	697.9	824.7
200yr ARI	195.6	256.1	294.2	316.8	379.2	469.8	575.7	748.0	877.7

T	100day	150day	200day	250day	300day	350day	400day	500day
2.33yr ARI	639.5	849.5	1076.9	1289.3	1493.3	1688.6	1913.4	2354.2
5yr ARI	728.7	970.0	1209.2	1425.2	1643.1	1852.0	2113.5	2576.3
10yr ARI	801.3	1068.2	1317.0	1535.8	1765.1	1985.2	2276.4	2757.2
20yr ARI	870.9	1162.3	1420.4	1641.9	1882.1	2112.9	2432.7	2930.8
50yr ARI	961.0	1284.2	1554.3	1779.2	2033.6	2278.2	2635.0	3155.4
100yr ARI	1028.6	1375.5	1654.5	1882.1	2147.1	2402.1	2786.6	3323.7
200yr ARI	1095.9	1466.4	1754.5	1984.7	2260.2	2525.6	2937.7	3491.4

Interdecadal Pacific Oscillation (IPO)

The effects of the IPO on the statistical analysis were not explicitly adjusted for. It was not considered that the effect is readily observable in the Okareka raingauge record (for example the 100 day duration annual maxima series in Figure 3 below) but is perhaps discernible at Whakarewarewa (Figure 4 below) where the negative phase appears to be associated with higher than average rainfall. It is noted that the record at Okareka (since 1966) includes 29 years in the negative phase and 21 years in the positive phase – therefore perhaps indicating a slightly conservative bias to these results.

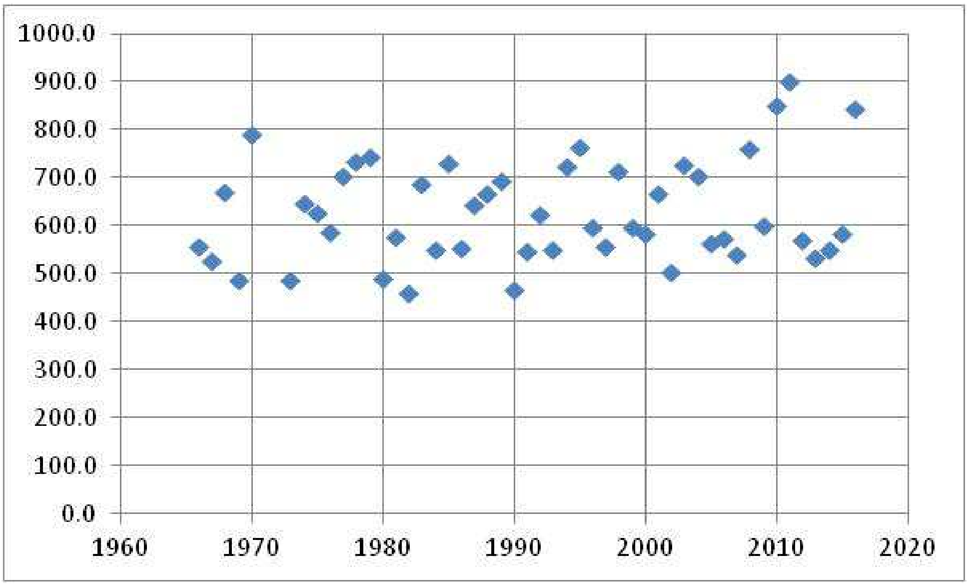

Figure 3: Annual maxima of 100 day duration rainfall for Okareka raingauge. Negative phases of the IPO are thought to cover 1946 to 1977 and then again from 1999 to present day.

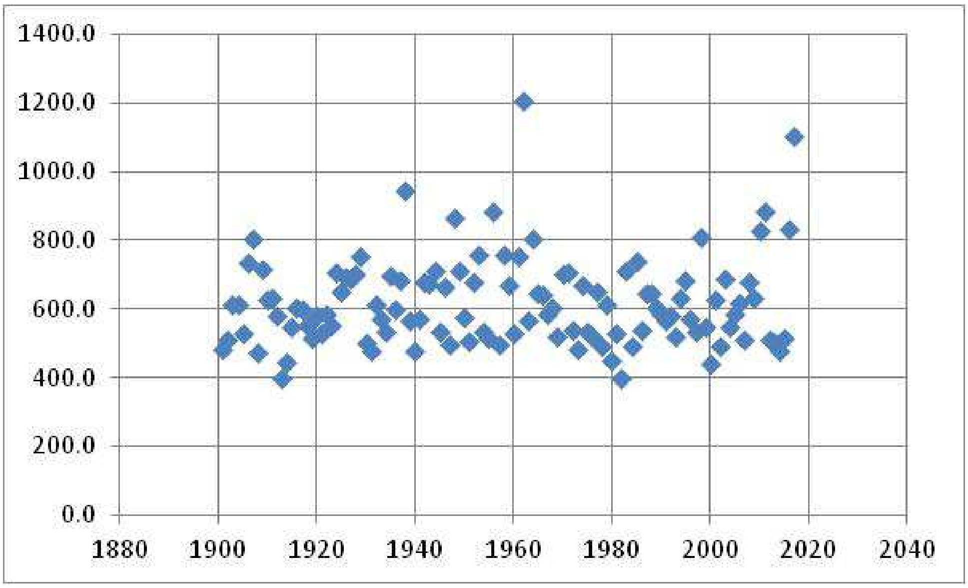

Figure 4: Annual maxima of 100 day duration rainfall at Whakarewarewa.

Climate Change

The effects of climate change have not been applied to the statistical analysis of raingauge data. i.e. the samples have been treated as if coming from a static population. Guidance from NZ Ministry for the Environment (MfE) in 2008 and 2010 indicate that we should be experiencing the start of a trend towards increased likelihood of high rainfall. The impact on this study of not explicitly adjusting for this trend (which would be very difficult to observe in the data) is likely a slight conservative bias.

Climate change effects were included in the design scenarios (in Part 3). For the climate change scenarios the design rainfall depths determined above were increased by the factors recommended by the Ministry for the Environment[iv]. Table 3 below shows the percentage increases that were applied. Both mid range and high range values were tested. Mid range values are the average predictions from all of the climate studies analysed by MfE. High range values are the highest values of all of the studies.

It has not been common practice at BOPRC to apply climate change effects to present-day design scenarios. I understand that climate change impacts on New Zealand temperature, rainfall or river flow records have not yet been confirmed – due to the high degree of natural variability that could be masking such a trend. It is noted that MfE advice to NZ local government provides guideline values for 1990 and 2040, and that 2017 is approximately mid-way between these dates. An interpolated value of 0.4 degrees of atmospheric warming has been applied to this study for use in the 2017 design scenarios.

Table 3: Climate change scenarios and the design rainfall increases applied

Climate Change Scenario (year, high/med)	Projected Increase in mean atmospheric temperature (degC)	Percentage increase of rainfall depth
1990	0	0%
2017	0.4	3.2%
2040 (mid range)	0.9	7.2%
2040 (high range)	2.4	19.2%
2090 (mid range)	2.1	16.8%
2090 (high range)	5.5	44%

Part Three

BOPRC's Lake Okareka water balance model was run as a design tool. A matrix of scenarios were tested that included a range of 8 pipeline capacities; the range of 4 event probabilities; and the 6 climate change scenarios. Output is reported in graphical and tabular form. Selected tables and graphs have been included in the body of the report – the full set is appended.

The rainfall depths determined in Part 2 were assembled into fully-nested design hyetographs. Each hyetograph is a time-series of daily rainfall depths set on a date/time axis. The daily rainfall depths are determined to ensure that each hyetograph tests precisely the required rainfall depth at each of the (15) design event durations. Figure 5 below shows a single hyetograph as an example, drawn as accumulating rainfall. Table 4 shows the values. The full set of hyetographs is tabulated in an appendix.

The nesting method allows for skewing of the "focus point" of the rainfall. This factor was found to have very little impact on model results at Okareka. A focus factor of 0.5 was applied (50% of the rainfall falls before the focus date).

Due to the seasonal variability of the effect of rainfall at Lake Okareka, model results are sensitive to the timing of the application of the design rainfall. The seasonal factor has a 200 L/s difference in effective lake inflows. It is modelled to peak on the 237th day of the year (24th of August). Rainfall has its greatest impact on this date (in the model). For this assessment the nested design rainfall hyetograph was focussed on this date to find the highest lake levels that would result.

This selected timing of the design rainfall introduces a degree of conservatism to the results. i.e. it would be (roughly) equally probable that a rainfall event of 100 year ARI magnitude would fall in mid winter as in mid summer. The reduction in likelihood of the design scenario due to this selected timing has not been comprehensively evaluated. The degree of conservatism could be determined by way of a detailed bi-variate analysis, but this was considered beyond the scope of this study, but for context, the several scenarios tested found differences of around 150mm if the rain was focussed in mid summer instead of mid winter.

The starting lake level for the model has been taken from our 2013 review of the pipeline operating guidelines[ii] (i.e. full discharge at Level > 353.6mRL for March to August inclusive). Note that this is different from BOPRC's current pipeline operating guidelines that don't advise full discharge until lake level exceeds 353.75mRL.

An example of the design model output is shown in Figure 6 on page 15. The graph shows the lake levels resulting from the 100 year design rainfall adjusted for 0.4 degrees of atmospheric warming (2017 mid-range climate scenario). Results are shown for nine pipeline capacity values from 250 L/s to 600 L/s at 50 L/s increments. The full range of output graphs are appended to this memo.

Table 6 through Table 10 on pages 17 and 18 show the peak lake levels resulting from the full range of design scenarios tested.

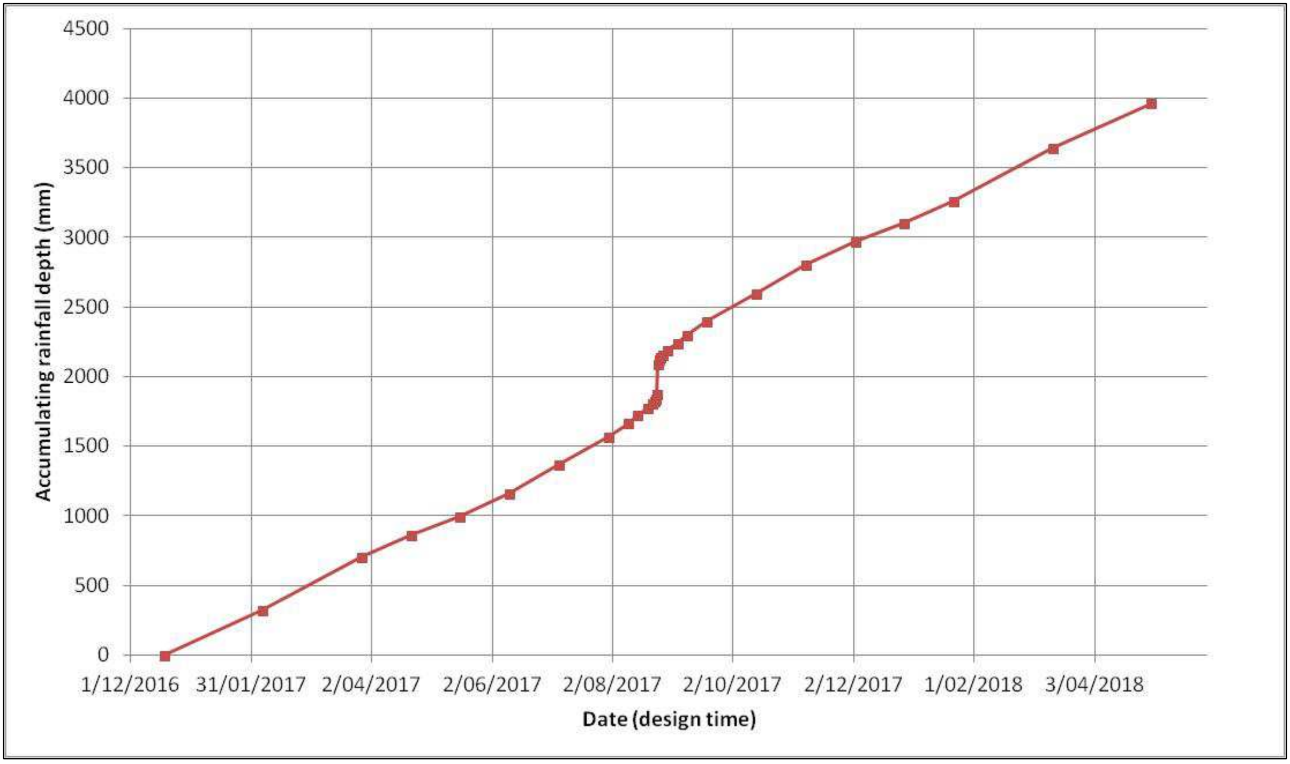

Figure 5: Design hyetograph (cumulating rainfall) for 100 year ARI 2040 high-range scenario

Table 4: Design hyetograph (cumulating rainfall) for 100 year ARI 2040 high-range scenario

Date Time	Depth (mm)	Date Time	Depth (mm)
17/12/2016 12:00	0.0	25/08/2017 0:00	2087.8
5/02/2017 12:00	320.1	25/08/2017 12:00	2120.9
27/03/2017 12:00	701.3	26/08/2017 0:00	2141.5
21/04/2017 12:00	859.2	27/08/2017 0:00	2154.5
16/05/2017 12:00	994.8	29/08/2017 12:00	2189.7
10/06/2017 12:00	1161.1	3/09/2017 12:00	2240.7
5/07/2017 12:00	1367.9	8/09/2017 12:00	2300.0
30/07/2017 12:00	1565.0	18/09/2017 12:00	2396.9
9/08/2017 12:00	1661.9	13/10/2017 12:00	2594.0
14/08/2017 12:00	1721.1	7/11/2017 12:00	2800.7
19/08/2017 12:00	1772.2	2/12/2017 12:00	2967.0
22/08/2017 0:00	1807.4	27/12/2017 12:00	3102.7
23/08/2017 0:00	1820.3	21/01/2018 12:00	3260.6
23/08/2017 12:00	1840.9	12/03/2018 12:00	3641.8
24/08/2017 0:00	1874.0	1/05/2018 12:00	3961.9

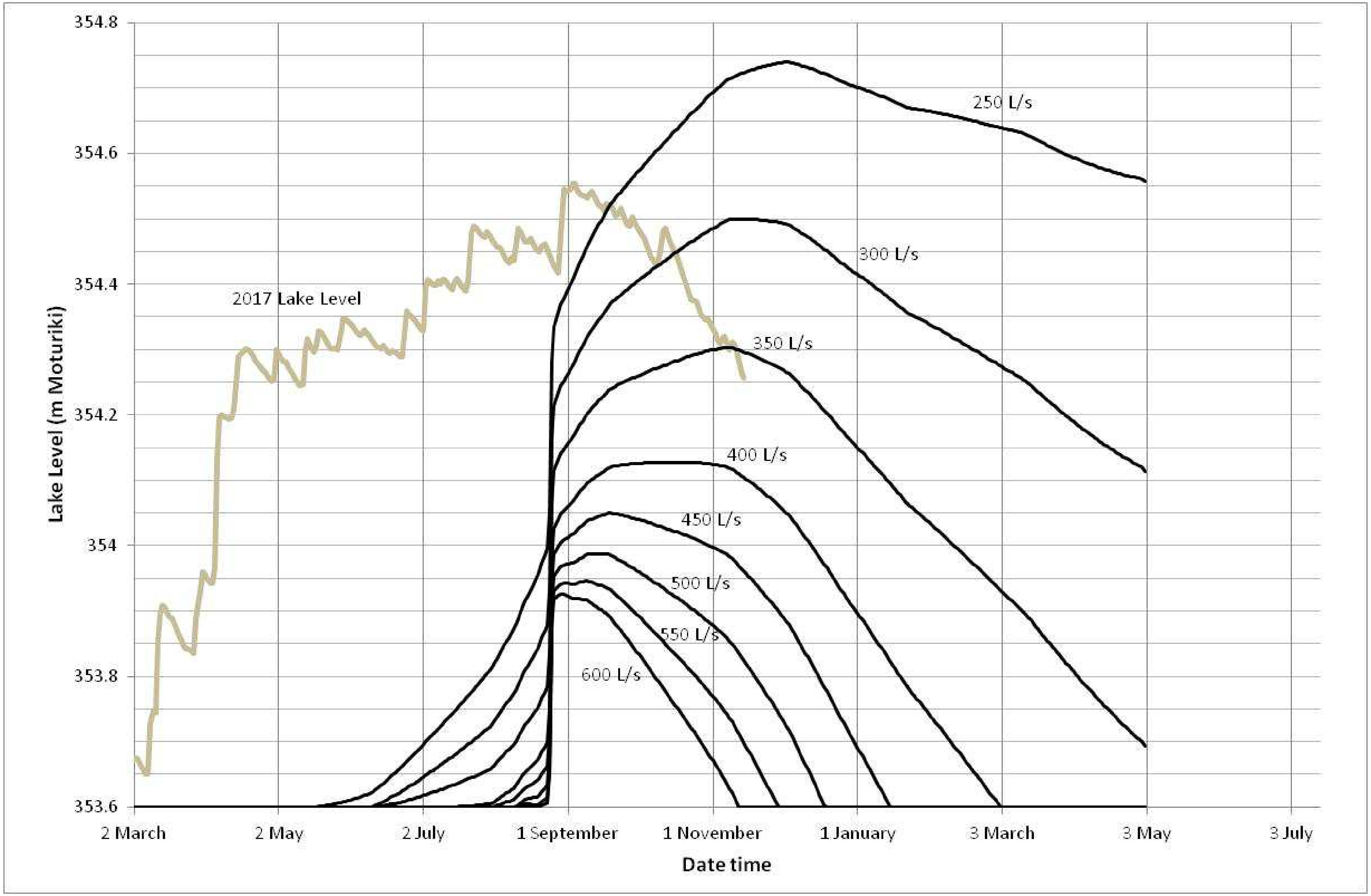

Figure 6: Example of model output: 100 year ARI design rainfall; 0.4 degrees of warming (2017 mid-range climate scenario); pipeline capacities from 250 L/s to 600 L/s. Also showing lake levels from 2017 for context

Table 5: Peak Design Lake Level – 1990 scenario (not adjusted for climate change)

Pipeline Capacity	Rain Event ARI			
(L/s)	20yr	50yr	100yr	200yr
250	354.48	354.53	354.67	354.81
300	354.27	354.31	354.44	354.57
350	354.09	354.12	354.25	354.37
400	353.99	354.02	354.09	354.19
450	353.93	353.95	354.02	354.09
500	353.89	353.91	353.96	354.03
550	353.87	353.88	353.93	353.98
600	353.86	353.87	353.91	353.95

Table 6: Peak Design Lake Level – 2017 mid range climate change scenario

Pipeline Capacity	Rain Event ARI			
(L/s)	20yr	50yr	100yr	200yr
250	354.55	354.59	354.74	354.88
300	354.32	354.37	354.50	354.64
350	354.13	354.17	354.30	354.43
400	354.02	354.04	354.13	354.24
450	353.95	353.98	354.05	354.12
500	353.91	353.93	353.99	354.06
550	353.88	353.90	353.95	354.01
600	353.87	353.88	353.93	353.97

Table 7: Peak Design Lake Level – 2040 mid range climate change scenario

Pipeline Capacity	Rain Event ARI			
(L/s)	20yr	50yr	100yr	200yr
250	354.63	354.68	354.83	354.98
300	354.39	354.43	354.58	354.72
350	354.19	354.24	354.38	354.51
400	354.05	354.08	354.19	354.32
450	353.99	354.01	354.09	354.16
500	353.93	353.95	354.02	354.10
550	353.90	353.91	353.97	354.04
600	353.89	353.90	353.94	354.00

Table 8: Peak Design Lake Level – 2040 high range climate change scenario

Pipeline Capacity	Rain Event ARI			
(L/s)	20yr	50yr	100yr	200yr
250	354.86	354.92	355.10	355.36
300	354.61	354.66	354.83	355.00
350	354.39	354.44	354.59	354.75
400	354.20	354.24	354.40	354.55
450	354.08	354.11	354.21	354.36
500	354.02	354.05	354.13	354.21
550	353.97	353.99	354.07	354.15
600	353.93	353.95	354.02	354.09

Table 9: Peak Design Lake Level – 2090 mid range climate change scenario

Pipeline Capacity	Rain Event ARI			
(L/s)	20yr	50yr	100yr	200yr
250	354.82	354.87	355.04	355.26
300	354.56	354.61	354.78	354.94
350	354.35	354.40	354.55	354.70
400	354.17	354.21	354.35	354.50
450	354.06	354.09	354.18	354.31
500	354.00	354.03	354.11	354.19
550	353.95	353.97	354.04	354.13
600	353.92	353.94	354.00	354.07

Table 10: Peak Design Lake Level – 2090 high range climate change scenario

Pipeline Capacity	Rain Event ARI			
(L/s)	20yr	50yr	100yr	200yr
250	355.72	355.84	356.18	356.51
300	355.10	355.19	355.53	355.87
350	354.84	354.91	355.11	355.31
400	354.60	354.66	354.85	355.05
450	354.40	354.46	354.65	354.83
500	354.23	354.28	354.45	354.64
550	354.15	354.19	354.29	354.44
600	354.09	354.12	354.22	354.33

Table 11 through Table 16 below and on page 20 show lake level recovery times in days. This is the time modelled in the design scenarios for the lake level to return to 353.9m (the consented upper guideline level). For those scenarios that did not recover within the modelled time sequence, the tables show “>Limit” for those scenarios that did not exceed the upper guideline level the tables show “<WL Max”.

Table 11: Recovery time – 1990 scenario (not adjusted for climate change)

Pipeline Capacity	Rain Event ARI			
(L/s)	20yr	50yr	100yr	200yr
250	>Limit	>Limit	>Limit	>Limit
300	283 days	300 days	>Limit	>Limit
350	179 days	194 days	246 days	291 days
400	112 days	121 days	143 days	195 days
450	56 days	73 days	108 days	130 days
500	<WL Max	36 days	63 days	98 days
550	<WL Max	<WL Max	41 days	60 days
600	<WL Max	<WL Max	18 days	35 days

Table 12: Recovery time – 2017 mid range climate change scenario

Pipeline Capacity	Rain Event ARI			
(L/s)	20yr	50yr	100yr	200yr
250	>Limit	>Limit	>Limit	>Limit
300	311 days	>Limit	>Limit	>Limit
350	199 days	216 days	271 days	319 days
400	124 days	131 days	165 days	219 days
450	77 days	90 days	120 days	139 days
500	38 days	47 days	76 days	110 days
550	<WL Max	<WL Max	49 days	71 days
600	<WL Max	<WL Max	26 days	42 days

Table 13: Recovery time – 2040 mid range climate change scenario

Pipeline Capacity	Rain Event ARI			
(L/s)	20yr	50yr	100yr	200yr
250	>Limit	>Limit	>Limit	>Limit
300	>Limit	>Limit	>Limit	>Limit
350	229 days	248 days	299 days	>Limit
400	137 days	149 days	200 days	254 days
450	97 days	107 days	131 days	150 days
500	50 days	59 days	99 days	123 days
550	<WL Max	37 days	60 days	87 days
600	<WL Max	10 days	33 days	60 days

Table 14: Recovery time – 2040 high range climate change scenario

Pipeline Capacity	Rain Event ARI			
(L/s)	20yr	50yr	100yr	200yr
250	>Limit	>Limit	>Limit	>Limit
300	>Limit	>Limit	>Limit	>Limit
350	>Limit	>Limit	>Limit	>Limit
400	211 days	232 days	290 days	>Limit
450	135 days	144 days	186 days	251 days
500	102 days	111 days	134 days	154 days
550	60 days	69 days	105 days	128 days
600	33 days	47 days	70 days	95 days

Table 15: Recovery time – 2090 mid range climate change scenario

Pipeline Capacity	Rain Event ARI			
(L/s)	20yr	50yr	100yr	200yr
250	>Limit	>Limit	>Limit	>Limit
300	>Limit	>Limit	>Limit	>Limit
350	302 days	>Limit	>Limit	>Limit
400	195 days	213 days	275 days	>Limit
450	129 days	136 days	167 days	231 days
500	91 days	104 days	129 days	146 days
550	53 days	62 days	93 days	121 days
600	28 days	35 days	64 days	90 days

Table 16: Recovery time – 2090 high range climate change scenario

Pipeline Capacity	Rain Event ARI			
(L/s)	20yr	50yr	100yr	200yr
250	>Limit	>Limit	>Limit	>Limit
300	>Limit	>Limit	>Limit	>Limit
350	>Limit	>Limit	>Limit	>Limit
400	>Limit	>Limit	>Limit	>Limit
450	288 days	311 days	>Limit	>Limit
500	184 days	207 days	280 days	>Limit
550	137 days	144 days	170 days	251 days
600	108 days	118 days	140 days	162 days

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[i] West P, January 2012, *Lake Ōkāreka Outlet Pipeline; Water Balance Modelling for Pipeline Design*, BOPRC Memorandum to Colin Meadowcroft BOPRC Engineering Manager

[ii] West P, March 2013, *Lake Okareka Outlet Pipeline; Review of Operating Guidelines*, BOPRC Memorandum to Clive Tozer Acting Engineering Manager

[iii] West P, December 2008, *Lake Ōkāreka Outlet Structures; High Lake Levels; Pipeline Capacity*, BOPRC Memorandum to Mangala Wickramanayake BOPRC Engineering Manager.

[iv] New Zealand Ministry for the Environment, *Preparing for Climate Change, a Guideline for Local Government*, MfE pub, no. 891