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Design, construction, installation and performance of a new headwater level gauge for Aviemore Dam

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Abstract
Existing water level instruments measuring the headwater level at Aviemore Dam on the Waitaki River were affected to different degrees by wind-generated waves, resulting in variable measurements of headwater level. This paper describes the selection of a new gauge site and the design, construction, installation and performance of the new gauge at Aviemore Dam to provide reliable and accurate measurements of headwater level for the purposes of fuel resource management, resource consent compliance and, above all, dam safety and security. The design of the new gauge was based on the theoretical behaviour of a linear tide well (Noye, 1974b) incorporating a large diameter stilling well and a long, horizontal intake pipe of small bore, and assuming unsteady laminar flow through the intake pipe. The new gauge was predicted to have an amplitude response inside the stilling well of less than 0.006% for short period waves with a maximum incident height of 2.5 m and a period of 3 seconds. The gauge was fabricated in May and June 2013, installed in August 2013 and commissioned in September and October 2013. The performance to date has been excellent, with stilling well oscillations of less than ± 2.5 mm when the incident waves were predicted to be in the order of 1.0 m high with a period of about 3.0 seconds during the severe wind storm of 10 September 2013.

Keywords
water level gauge, stilling well, intake pipe, wind-generated waves, seiche waves, hydrodynamic behaviour, amplitude response, phase lag, design, performance

Introduction
Reliable and accurate measurements in real time of headwater level at a large hydropower dam are critical for the purposes of fuel resource management, resource consent compliance and, above all, dam safety and security.

Water level gauges for measuring lake (and river) levels are typically comprised of a large diameter stilling well and a small diameter intake pipe, the combination of which is designed to filter out the effects of wind-generated and turbulence-induced surface waves. Assuming unsteady laminar flow through the intake pipe, the hydrodynamic response of a linear stilling well system is governed by two dimensionless parameters: a stilling (tide) well constant N and a frequency parameter β_2 (Noye, 1974b). The stilling well constant N is a function only of the well and intake pipe dimensions while the frequency parameter β_2 is a function of the wave period (covering both short period wind-generated waves and long period seiche waves) and the well and intake pipe dimensions.

The original gauge for lake level measurement on Aviemore Dam, designed and built by the Ministry of Works, was considered an appropriate design at the time (the dam became fully operational in the late 1960s) and operated satisfactorily for many years before the advent of automation and remote control methods. However, lake level measurements from the gauge exhibited considerable noise, due in part to the fact that the gauge was affected by wind-generated waves resulting from the frequent strong winds blowing down the lake and impinging on the dam headwall. A 2011 review of the condition and performance of Meridian Energy's portfolio of water level gauges identified that the gauge on Aviemore Dam, including the associated water level measurement instrumentation, did not meet the higher quality standards considered normal and achievable in the current age. The Aviemore Dam gauge and instrumentation were consequently recommended for replacement.

This paper describes the evaluation of potential alternative headwater level gauge sites for Aviemore Dam and the subsequent design, construction, installation and performance of a new headwater level gauge. The new headwater level gauge was of a conventional stilling well-type design. The design of the gauge was based on the design of linear tide wells (Noye, 1974b) using a large diameter well and small diameter intake pipe.

Site description

Location

Aviemore Dam forms part of a chain of hydropower dams on the Waitaki River used to generate electricity from the water resource provided by Lakes Tekapo, Pukaki and Ohau upstream. It lies between Benmore and Waitaki Dams on the mid-Waitaki part of the system and impounds Lake Aviemore.

Lake Aviemore is an approximately triangular-shaped lake, as shown in Figure 1, with a surface area of 28.8 km^2. The primary axis of the lake is aligned roughly in a west-north-west/east-south-east direction. Aviemore Dam is located at the south-east end of the lake so that it is directly exposed to the predominant north-westerly and westerly winds blowing down the lake.

Construction of Aviemore Dam was completed in 1968. The dam is comprised of two parts: a 335 m long concrete gravity component is founded on bedrock on the eastern side of the valley and a 457 m long earth-fill embankment dam component extends to the western side of the valley (see Fig. 2). The embankment dam component overlies alluvial foundation materials. A notable geological feature, the Waitangi Fault, crosses under the footprint of the embankment dam component immediately to the west of the junction with the concrete gravity dam component. The Waitangi Fault continues to follow a line parallel with the eastern side of the lake (see Fig. 1). The concrete gravity dam component of Aviemore Dam is a maximum of about 52 m high while the embankment dam component is a maximum of about 26 m high.

Headwater level range

The normal headwater level operating range for hydropower generation purposes for Lake Aviemore is between RL (Reduced Level) 267.7 and RL 268.3 m.[1] However, the headwater level could reach as high as RL 270.3 m under Probable Maximum Flood conditions (the dam crest level is RL 271.05 m). If the lake was to be drawn down for an emergency inspection of the

1 All levels quoted are referenced to the Mean Sea Level Lyttelton datum (1937).

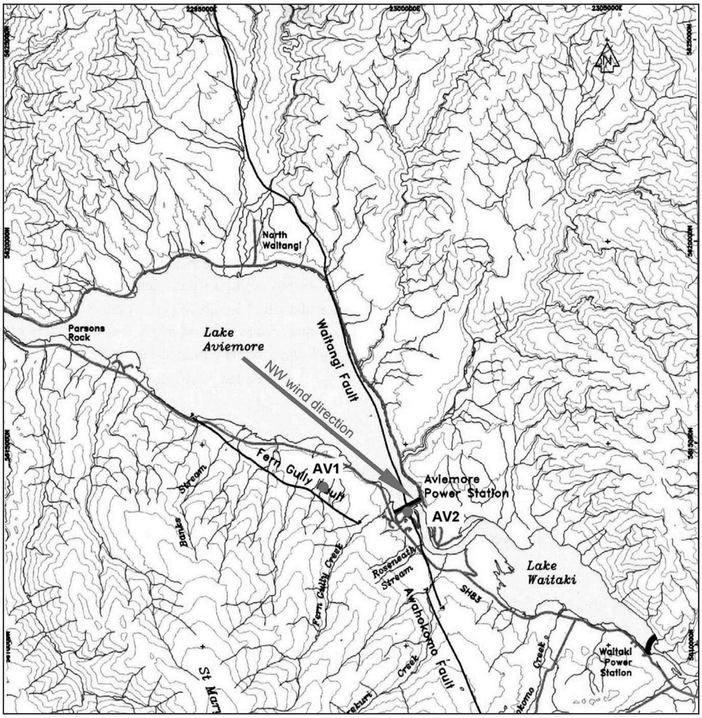

Figure 1 – Lake Aviemore showing alignment of lake relative to critical north-west wind direction and location and line of Waitangi Fault.

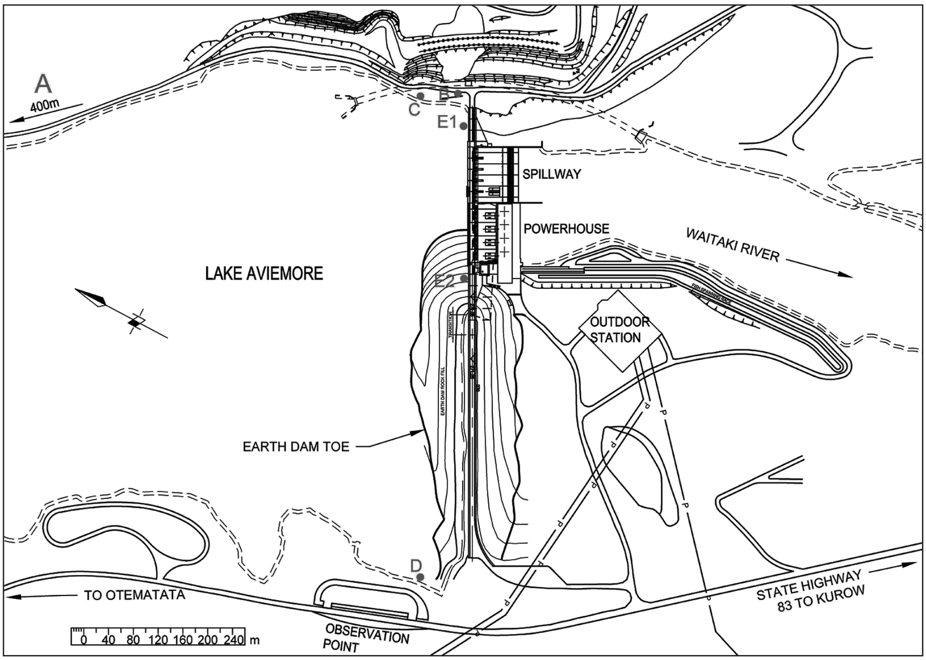

Figure 2 – Layout of Aviemore Dam and location of alternative sites for new headwater level gauge.

dam, the headwater level could fall below the extreme minimum operating level of RL 265.25 m to just above spillway crest level (RL 260.53 m) with the spillway gates lifted clear of the lake surface. Any headwater level gauge therefore needs to be able to measure headwater levels over at least a 12.0 m range between RL 260.0 and 272.0 m (see Fig. 3), which encompasses the spillway crest level and the predicted peak Probable Maximum Flood level. If the lake needed to be emptied even further below RL 260.0 m using the low-level sluice on the dam for emergency reasons, the lake level could be measured by an existing radar-type device.

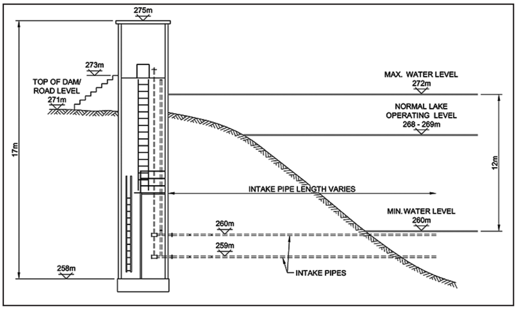

Figure 3 – Schematic diagram of stilling well structure based on design water level range for Lake Aviemore.

Wind and wave climate

Two three-hourly average wind speed[2] records are available for separate stations at Aviemore Dam (AV1 and AV2, Figure 1). The records are not particularly long, covering the periods January 1969 to December 1978 (AV1) and July 1978 to September 1988 (AV2). Unfortunately, the two stations were located at different elevations (RL 381 m and RL 241 m respectively[3]) and therefore wind boundary layer effects are likely to have been slightly different at each site.

Despite these limitations, the two records were initially spliced together to obtain an approximately 20-year long record, which was then analysed for ranges of wind speeds and directions. Although the stations are now closed the combined wind speed record is assumed to be indicative of the present day wind climate at Aviemore Dam. The range of wind directions and the distribution of wind speeds within each direction at Aviemore Dam are shown by the wind rose in Figure 4.

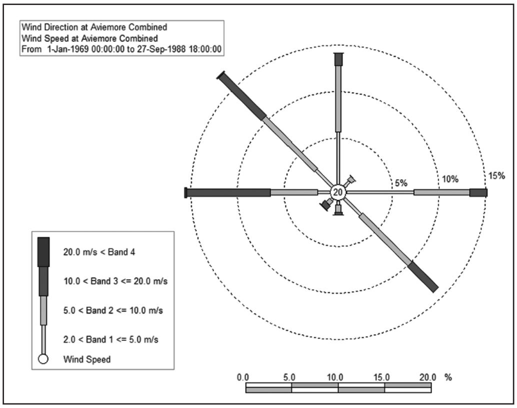

Figure 4 – Wind rose for Aviemore Dam based on data from 1969-1988.

Figure 4 indicates that wind directions are approximately equally distributed between the north, east, south-east, west and north-west directions, while winds blowing from the north-east, south and south-west directions are rare. It also indicates that the highest wind speeds (>20 m/s) are mostly experienced when the wind blows from either the west or north-west directions.

Winds blowing from the west are unlikely to generate large waves in the vicinity of Aviemore Dam as the fetch length for such winds is so small. However, winds blowing from the north-west are much more likely to generate large waves in the vicinity of the

2 A three-hourly average wind speed represents the average wind speed measured over a ten-minute period and recorded at three-hourly intervals.

3 The level of the Aviemore 2 station was below the level of the normal operating level for Lake Aviemore of RL 267.7-268.3 m.

dam as the direction is closely aligned with the predominant axis of the lake (see Fig. 1). The direct fetch length for north-westerly winds is approximately 8.4 km.

Subsequent inspection of the wind roses for the two separate wind records indicated that they were reasonably similar for the critical north-west direction. Despite the limited length of the two wind speed records, frequency analyses were carried out on the two separate wind speed annual maxima series for north-westerly winds only. Table 1 (below) summarises the results of these analyses.

Table 1 – Frequency estimates for north-westerly wind speeds at Aviemore Dam.

Annual Exceedance Probability (1 In T)	Wind Speed (m/s) – PE3		Ratio – Avie1/Avie2 (PE3)	Wind Speed (m/s) – GEV		Ratio – Avie1/Avie2 (GEV)
	Aviemore 1 – 381m MSL	Aviemore 2 – 241m MSL		Aviemore 1 – 381m MSL	Aviemore 2 – 241m MSL	
2.33	21.68	19.60	1.11	21.67	19.59	1.11
5	23.95	21.87	1.10	23.89	21.84	1.09
10	25.70	23.58	1.09	25.66	23.57	1.09
20	27.31	25.12	1.08	27.32	25.15	1.09
50	29.29	27.00	1.08	29.44	27.08	1.09
100	30.71	28.33	1.08	30.99	28.46	1.09

Two frequency distributions appeared to fit the annual NW wind speed maxima data equally well (Generalised Extreme Value (GEV) and Log Pearson 3 (PE3)); the frequency estimates resulting from each distribution are given in Table 1. The ratio between the corresponding frequency estimates for the two climate station sites is also given; this is a rough measure of boundary layer effects on the wind velocity distribution above the ground surface.

The wind speed frequency estimates indicate that there is approximately a 9% difference in average wind speeds between the two climate station sites due to the effects of site elevation. This is of the order expected from wind boundary layer considerations as defined in USACE (2008).

The wind speed frequency estimates for the lower elevation site were assumed to represent closely enough the characteristics of north-westerly wind speeds across the surface of Lake Aviemore. The effective fetch length across the lake for winds blowing from this direction towards the concrete gravity component of Aviemore Dam was estimated to be 5.60 km, based on the method of analysis outlined in USBR (1992)[4],while the critical wind speed duration for a fully arisen sea state was estimated to be less than 1 hour. This means that wind-generated waves from the north-west direction will be fetch limited.

Application of the wave forecasting model described in USACE (2008) using the estimated fetch length and the wind speed frequency estimates from Table 1 based on the GEV distribution produced estimates of significant wave height and peak spectral period as given in Table 2.

4 The USBR (1992) method calculates the effective fetch length based on the average of nine fetch lengths over a range of different directions within ± 12 degrees of the central direction (spaced at intervals of 3 degrees about the central direction).

Table 2 – Estimates of significant wave height and peak spectral period for different wind speed frequencies.

Annual Exceedance Probability (1 in T)	Aviemore 2 3-hourly Average Wind Speed (m/s)	Aviemore 2 estimated 1-hourly Average Wind Speed (m/s)	Significant Wave Height (m)	Peak Spectral Wave Period (sec)
2.33	19.6	21.1	0.89	2.82
5	21.8	23.5	1.02	2.94
10	23.6	25.4	1.12	3.03
20	25.2	27.1	1.21	3.12
50	27.1	29.2	1.33	3.21
100	28.4	30.7	1.41	3.28

The forecast significant wave heights are the average heights of the highest one-third of all wind-generated waves produced by the specified hourly average wind speeds. For practical design purposes, the height of the highest wave in any irregular sea state is approximately equal to 1.8 times the significant wave height. For the 1% annual exceedance probability hourly average wind speed of 30.7 m/s, the significant wave height was estimated to be about 1.4 m with the maximum wave height likely to be about 2.5 m. The peak spectral wave period was estimated to be in the order of 3 seconds.

Existing headwater level gauge and instrumentation

Between 1997 and 2013 there were six different instruments measuring the headwater level at Aviemore Dam for hydropower fuel resource management, resource consent compliance and dam safety and security purposes.[5] The instruments were a mixture of radar type and MetriTape instruments mounted on the dam structure (although the radar devices were only installed as a test of that technology and were not used for headwater level control purposes (A. Turner-Heaton, Meridian Energy, *pers. comm.*). There was also a Jumo pressure transducer mounted alongside one of the MetriTape instruments on the face of the dam. Another of the MetriTape instruments was located in a 0.457 m (18 inch) diameter stilling well within the body of the concrete gravity component of the dam and connected to the lake by a 1.04 m (3 feet 5 inch) long intake pipe of 0.102 m (4 inch) diameter. This stilling well arrangement provided some filtering of wave-affected headwater levels although the measured headwater level record still exhibited considerable noise (the hydraulic response characteristics of this stilling well arrangement will be discussed in more detail subsequently). However, the remaining four instruments directly measured the fluctuating lake surface.

The frequent strong north-westerly winds blowing along the length of the lake generate considerable wave action which impinges

5 There may have been other instruments installed between dam commissioning and 1997. The New Zealand Electricity Department (NZED) and its successor organisation, the Electricity Corporation of New Zealand (ECNZ), had a preference for Druck transducers or Varec float activated sensors at their operational water level recorder sites (reviewer comment).

directly on the headwall at Aviemore Dam. This wave action resulted in the headwater level measurements from the 1997-2013 instruments exhibiting considerable noise.[6] A review of headwater level gauge performance in 2011 recommended replacement by a new gauge and instrumentation.

Requirements for a new headwater level gauge

A number of key design requirements were specified by Meridian Energy for the new headwater level gauge:

a) A robust stilling well structure was required to allow uninterrupted operation under normal lake level conditions, extreme flood conditions and dewatered lake conditions. In addition, the structure was required to sustain both pumped full and pumped dry conditions in combination with the design seismic and wind loadings.
b) The instrumentation and power/ communications cable architecture was required to be reliable and resilient to ensure uninterrupted service during normal operating conditions and following both a Safety Evaluation Earthquake[7] and a Maximum Design Earthquake.[7]
c) Installation of the stilling well structure including the intake pipes was to take place while the lake level was in its normal operating range.
d) The gauge was to be capable of measuring lake levels over the full range, between RL 260 m and 272 m.[8]
e) The gauge was to be capable of accurately measuring the true headwater level, unaffected by wind-generated wave action, hydraulic drawdown effects from spillway operation or turbine operation.
f) The gauge was required to be close to the Hydraulic Structures Control Building[9] for ease of connectivity to existing power/ communications.

All these design requirements were considered in conjunction with various assessment criteria in an evaluation of potential alternative sites for a new headwater level gauge.

Evaluation of alternative headwater level gauge sites

A range of potential sites around the lakeshore within the vicinity of the dam was identified. The location of these sites is shown in Figure 2.

The potential alternative gauge sites were assessed against a range of criteria: ease of construction and installation, whether they would be affected by adverse hydraulic conditions (afflux / backwater effects, sedimentation effects or water surface drawdown etc.), proximity to existing power and communications facilities, potential difficulties with obtaining planning and consents approvals, potential for damage or loss of functionality after the Safety Evaluation Earthquake, potential construction and operational risks, and potential overall cost. The positive and negative aspects of each alternative site were

6 Pre-1997 dam headwater level measurement systems in the earlier stilling well were also adversely affected by exposure to wave action at the dam face.
7 As defined in NZSOLD (2000).
8 This was not the full possible lake level range but it was much greater than the normal operating range for hydropower generation purposes. It allows for lake level measurement up to dam deck level for the monitoring of possible earthquake-induced seiche waves as well as down to sill level on the dam spillway in the event of the need for emergency drawdown of the lake.
9 The Hydraulic Structures Control Building contains an automated controller for maintaining normal remote control of flow past the dam, automated spill flow control and emergency backup spill response to ensure dam safety.

compared across these criteria using an eight-point rating scale ranging from 'significant issue(s)' (a rating that would preclude the option from further consideration) through to 'neutral' at the negative end and 'neutral' through to 'significant positive benefit(s)' at the positive end.

Site A was located 1.2 km north of Aviemore Dam along the eastern shore of Lake Aviemore where a causeway had been constructed across the steep-sided Deep Stream Gorge. This site was initially proposed because the embayment behind the causeway would be sheltered from wind-generated waves. Careful evaluation of Site A identified several significant issues. Monitoring of the Deep Stream outlet in 2011 determined that, under flood conditions, water levels in the Deep Stream embayment would be affected by head losses through the outlet. Over time, sediment deposition in the Deep Stream embayment could potentially block the intake pipes to a stilling well gauge. Power and communications difficulties with this more distant site (requiring trenching into bedrock and cabling over 1.2 km) were also negative factors.

Site B was located adjacent to the original diversion tunnel under the eastern abutment of the dam. A stilling well could be formed on the valley side by excavating down into rock and then drilling a horizontal intake pipe out into the lake. There were no significant hydraulic issues with this site other than the fact that it was exposed to wind-generated waves. However, there were considered to be significant construction difficulties with hard rock excavation likely to be slow and costly, and drilling of an intake pipe connection to the lake would be difficult and hazardous.

Site C was located close to Site B with the gauge formed by a steel structure rather than being excavated into the rock of the valley side. The lake is very deep at this location, which would require a very long structure founded on an excavated underwater bench with a platform providing access to land and structural support. As with Site B, there were no significant hydraulic issues with this site other than the fact that it was exposed to wind-generated waves. However, there were considered to be significant constructability issues with excavation of an underwater foundation bench likely to be difficult and expensive. There were also risks that there might not be a suitable location on the steep valley side on which to form a bench or that there might be a slope failure during bench construction or during a severe earthquake.

Site D was located at Observation Point adjacent to the western abutment of Aviemore Dam. Any gauge at this location would need to be sited sufficiently to the north along the lakeshore to avoid penetrating the upstream face of the embankment dam. From a hydraulic perspective, this site was the most sheltered from waves generated by northerly, north-westerly and westerly winds. However, construction in the alluvial gravels at the site would be difficult and the fairly flat ground would require an intake pipe for the gauge up to 150 m long. The site also would require very long runs for power and communications cables.

Sites E1 and E2 were located along the headwall of the concrete gravity component of the dam with E1 near the true left (eastern) abutment and E2 near the western end to the right of the penstock intakes to the powerhouse. Both sites envisaged a steel tubular stilling well structure mounted on the headwall of the dam. Site E1 was located approximately 27 m from the left side of the dam spillway and it was determined that the effects of drawdown over the spillway under extreme flood conditions, with the spillway gates fully open, could extend laterally beyond the site location. Site E2 was located approximately 37 m to the right of the penstock intakes, which are submerged below lake level and operate as closed conduits. The location of Site E2 was considered to be sufficiently far outside any zone of influence from the minor water surface disturbances at the penstock intakes that occur during power station turbine start-up and shutdown operations.

Based on this evaluation of potential alternative sites, Site E2 was recommended as the preferred site for a new headwater level gauge at Aviemore Dam.

Design of new headwater level gauge

General design guidance

The design of water level towers (or stilling wells) for stage measurement at river and stream gauging stations in New Zealand has historically relied on guidance from international practice: for example, the US Geological Survey's *Stage Measurement at Gaging Stations* (Sauer and Turnipseed, 2010) and the World Meteorological Organisation's *Manual on Stream Gauging* (WMO, 2010) and similar previous publications from these agencies. While manuals like this provide general guidance on the design of water level measurement gauges for riverine situations where the influence of turbulence-induced surface waves is required to be filtered out, they do not provide guidance on how to filter out the effects of larger amplitude and longer period wind-generated waves. NIWA's *Hydrologist's Field Manual* (NIWA, 1994; J. Fenwick, NIWA, *pers. comm.*) and the recent National Environmental Monitoring Standards guideline on water level recording[10] provide a rough rule of thumb of a 1:12 intake pipe / stilling well ratio for water level gauges at river gauging stations.

The issue of filtering out the influence of wind-generated waves has long been one of critical importance to the measurement of tide levels for navigation and prediction purposes. There is a large body of literature available related to conventional stilling well design for tide level measurement systems (IOC, 1985; IOC, 2002). Historically, most tide level measurement systems have used a large-diameter stilling well with a small entry orifice to dampen out water level fluctuations and a mechanical float inside to drive the tide level recording instrument (IOC, 1985), similar to that used on water level gauges for river and stream gauging stations.

Although such tide level measuring systems generally work well, they have a number of limitations. They require constant maintenance and, in a marine environment, may be subject to bio-fouling of the intake and resulting recording errors. Depending on the amplitude and period of the wind-generated waves that they are exposed to, they may also have a non-linear response to tide levels induced either by the short period waves themselves or by long period wave setup. The non-linear response may significantly distort the actual tide level record.

In more recent years, conventional stilling well-type tide level recorders have given way to a new generation of tide level monitoring stations (Shih and Bauer, 1991; Lennon and Mitchell, 1992; IOC, 2002). These use advanced acoustic and electronic components to supersede mechanical floats and recorders.

Linear behaviour of stilling well tide gauges

Noye (1974a, 1974b, 1974c) carried out a detailed theoretical and experimental analysis of conventional tide level recorders incorporating a stilling well and intake orifice. He demonstrated experimentally that such recorders need to be designed very carefully otherwise their response to either short period wind-generated waves (period $T \sim$ 1–10 seconds) or long period seiche or wave setup (surf beat) type waves can be non-linear (Noye, 1974a). He recommended a linear stilling well system, which can be

10 http://www.lawa.org.nz/media/16590/nems-water-level-recording-2013-06-1-.pdf

designed to accurately measure important long period waves superimposed on the tide level signal and yet eliminate the noise due to short period wave induced water level fluctuations (Noye, 1974b, 1974c).

Figure 5 shows a diagram of the linear stilling well that identifies the key dimensional parameters influencing its hydraulic behaviour. The well has two primary components: (a) a large well of inside diameter D_w; and (b) a small orifice comprised of a pipe of length L_p and inside diameter D_p. The bottom of the well needs to be sealed so that water only enters it through the intake pipe. Both primary components are required to be smooth and free of obstructions. This applies particularly to the intake pipe to ensure that laminar rather than turbulent flow occurs within it.

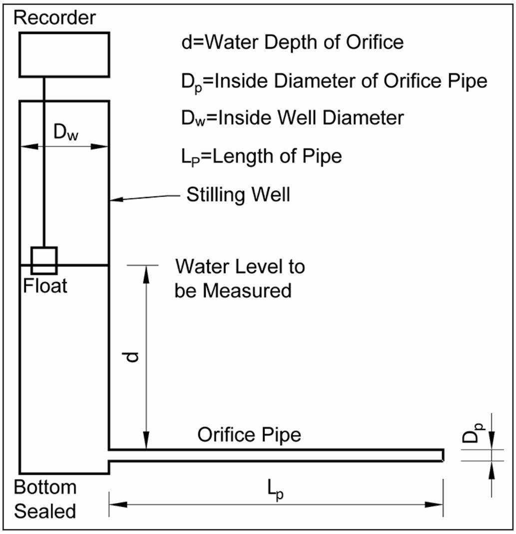

Figure 5 – Key parameters influencing hydraulic behaviour of linear stilling wells.

The parameters that can be varied in well design include the diameter of the well D_w, the diameter D_p and length of the intake pipe L_p, and the submergence depth of the intake pipe below water level d.

Based on theoretical analysis of unsteady laminar flow through the intake pipe, Noye (1974b, 1974c) established that the hydrodynamic response of a tide well is governed by two dimensionless parameters: a tide well constant parameter N and a frequency parameter β_2. The constant N is a function of the tide well and intake pipe dimensions (D_w, D_p and L_p), the kinematic viscosity of water (ν) and gravitational acceleration (g), as defined by Equation 1 below. The frequency parameter β_2 is also a function of the tide well and intake pipe dimensions (D_w, D_p and L_p), the kinematic viscosity of water (ν) and gravitational acceleration (g), as well as the period of the waves (T) (either short or long period) that the tide well is exposed to. It is defined by Equation 2 below.

$$N = 128\, \nu^2\, L_p\, D_w^2 / g\, D_p^2 \qquad (1)$$

$$\beta_2 = (32\, \nu\, L_p\, D_w^2 / g\, D_p^4)\, (2\pi / T) \qquad (2)$$

Figures 6(a) and (b) (after Noye (1974b) and Seelig (1977)) show the theoretical hydrodynamic response of a tide well in terms of the amplitude ratio α_2 (the ratio of the wave height inside the well to the wave height outside) and the phase lag ε_2 (the time lag between the wave response inside the well and the external forcing waves), as functions of both the dimensionless frequency β_2 for various constant values of the tide well constant N.

The chart for the amplitude response (α_2) indicates that the optimum tide well constant value is $N = 0.33$, as this ensures linear behaviour for short period wind-generated waves when $\beta_2 > 10$ ($\alpha_2 \rightarrow 0$) and also for long period waves when $0.1 < \beta_2 < 0.4$ ($\alpha_2 \rightarrow 1$). For large β_2 values (short period waves) with this optimum tide well constant value, the phase lag chart shows that the phase lag $\varepsilon_2 \rightarrow \pi$ while, for small values of β_2 (long period waves), $\varepsilon_2 \rightarrow 0$.

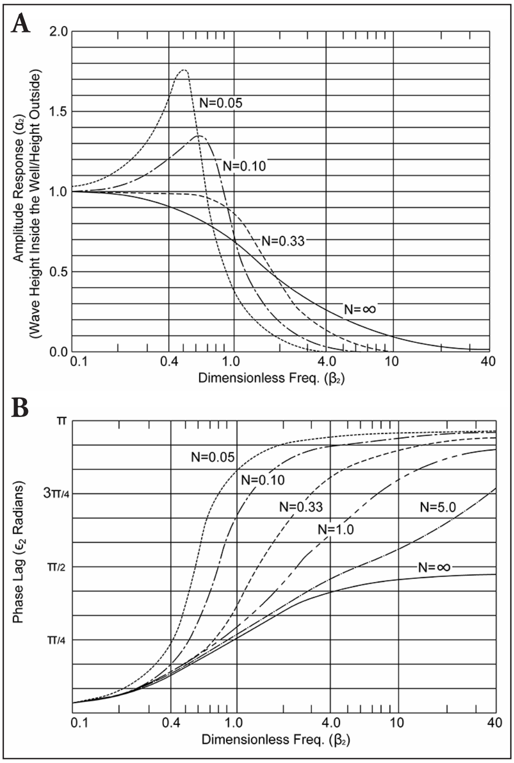

Figure 6 – Hydraulic response characteristics of linear stilling well (after Noye (1974b) and Seelig (1977)): (a) amplitude response and (b) phase response

Although the optimum tide well constant value is $N = 0.33$, Noye (1974b) notes that it is difficult to physically test wells designed based on this value of N, and so it is often best to design a well with tide well constant value of $N > 5$.

Hydrodynamic filtering due to depth for short period waves

Noye's (1974b) basic theoretical analysis of a linear stilling well tide gauge is valid for:

$$\omega^2 (h / g) << 1 \qquad (3)$$

where $\omega = 2\pi / T$ is the angular frequency of the wave oscillations and h is the water depth of the intake pipe below the water surface. In practice this means that, for an intake pipe with $h = 10$ m below the mean water surface, the wave period T must be greater than about 1 minute.

If $\omega^2 (h / g)$ is not small, as is the case with short period wind waves, then the hydrodynamic response of the intake pipe is affected by hydrodynamic filtering or pressure attenuation due to the submergence depth of the pipe. The wave pressure sensed at the tip of the intake pipe and transmitted through into the stilling well is attenuated by the pressure response factor from linear wave theory (USACE, 1984):

$$K_p = cosh\,[2\pi (h_b + z)/L]/cosh\,(2\pi h_b/L) \qquad (4)$$

where z is the invert level of the intake pipe (z is positive upwards from the water surface), h_b is the water depth at the gauge site and L is the wave length of the waves (L is related to both the wave period T and the water depth h_b).

The pressure response factor K_p causes the amplitude response α_2 of a stilling well gauge to reduce more rapidly than indicated in Figure 6(a) for large values of the frequency parameter β_2 (Noye, 1974b). However, it has no effect on the phase lag ε_2 of a gauge.

Inertial response of water in a stilling well

An inertial response factor for the water in a stilling well provides a further minor correction to the amplitude response α_2 and the phase lag ε_2 of a gauge at high wave frequencies, as occurs under wind wave conditions (Noye, 1974b).

Design method for a stilling well tide gauge

Noye (1974b) and Seelig (1977) outline a design approach for stilling well-type tide gauges with a linear response for both short and long period waves superimposed on the basic water level signal. This approach is summarised as follows:

a) identify the relevant period T for both short and long period waves that the proposed tide gauge is likely to be exposed to;

b) select a design value of the dimensionless tide well parameter N;
c) select a suitable intake pipe diameter D_p for the stilling well;
d) determine the minimum intake pipe length L_{pmin} based on the criterion $L_p > 100\ D_p$;
e) select a range of possible values for the intake pipe length L_p and determine values of the dimensionless frequency β_2 from Equation 2 and the stilling well diameter D_w from a rearranged form of Equation 1 for each value of L_p;
f) calculate the dimensionless amplitude response α_2 (corrected for pressure attenuation effects as required using Equation 4) and phase lag ε_2 for each value of L_p;
g) interpolate a suitable intake pipe length L_p from the calculations for the selected stilling well diameter D_w;
h) confirm that the dimensionless frequency $\beta_2 > 10$ for the largest expected short period waves so the dimensionless amplitude response $\alpha_2 \rightarrow 0$; and
i) confirm that the dimensionless frequency $0.1 < \beta_2 < 0.4$ for the range of expected long period seiche waves so that the dimensionless amplitude response $\alpha_2 \rightarrow 1$.

Application of this design procedure may require a few iterations to arrive at suitable intake pipe dimensions given the stilling well diameter D_w.

Design parameters for the new Aviemore Dam headwater level gauge

A conventional stilling well-type water level measurement system was selected for the new Aviemore Dam headwater level gauge. This was entirely appropriate as the purpose of the measurement system was to accurately monitor the level of Lake Aviemore in real time for both hydropower resource management and dam safety purposes. As the recommended recorder Site E2 is significantly exposed to wind-generated waves, it was essential that the water level measurement system was able to filter out the effects of such waves. It was considered that a stilling well type water level measurement system designed in accordance with Noye's (1974a, 1974b, 1974c) theory would be able to achieve this with appropriate correction for pressure attenuation due to intake pipe submergence.

A stilling well inside diameter value of $D_w = 1.88$ m was selected for design purposes. It was also assumed for design purposes that the intake pipe would be located at a level below RL 260 m, implying a depth of at least 8.3 m below the maximum normal lake operating level of RL 268.3 m. The water depth h_b approaching the selected gauge site (which affects the wave length L of the impinging short period wind waves) is variable due to the presence of the submerged upstream face of the embankment dam component (see Fig. 2) and lies in the range of 12-40 m.

Based on these parameter values, the above design method was applied in order to determine suitable intake pipe dimensions (diameter D_p and length L_p).

As discussed previously, the peak spectral wave period for the critical north-westerly generated wind waves was estimated to be in the order of $T = 3$ seconds. A 2007 investigation of wave seiching and run-up effects in Lake Aviemore from seismotectonic displacement caused by a rupture along the Waitangi Fault (Webby *et al.*, 2007) found that the seiche pattern had a period in the range of $T = 15$-25 minutes (900-1500 seconds). It was expected that wind-induced seiche waves in the lake would have a similar period. These short and long wave period values were therefore adopted for design purposes.

Design of new Aviemore Dam headwater level gauge

Previously it was noted that the optimum value of the dimensionless tide well constant had a value of $N = 0.33$ but that, from a practical point of view of being able to carry out a drainage test on the structure, it is often best to design a stilling well with a tide well constant value of $N > 5$. A suitable stilling well design was determined for constant values of $N = 0.33$ and $N = 5$, although it was recognised that the selected diameter for the proposed stilling well was such that it probably precluded physical testing of the design.

Figure 7 shows a graph of the stilling well diameter D_w plotted as a function of the intake pipe length L_p for the optimum tide well constant value of $N = 0.33$ and selected intake pipe diameter D_p values. Similarly, Figure 8 shows a graph of the stilling well diameter D_w plotted as a function of the intake pipe length L_p for a tide well constant value of $N = 5$ and selected intake pipe diameter D_p values.

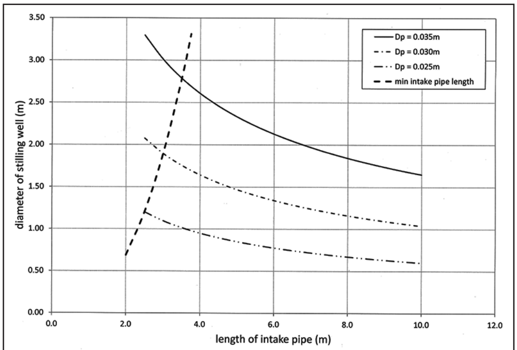

Figure 7 – Stilling well diameter D_w as a function of the intake pipe length L_p for optimum tide well constant value of $N = 0.33$.

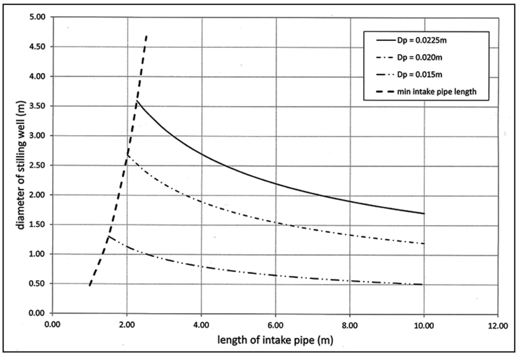

Figure 8 – Stilling well diameter D_w as a function of the intake pipe length L_p for tide well constant value of $N = 5$.

Figures 7 and 8 were used to interpolate appropriate intake pipe length L_p values for the design stilling well inside diameter D_w of 1.88 m. These are summarised in Table 3 for the two selected N values.

Table 3 – Interpolated intake pipe diameters D_p and lengths L_p for 1.88 m internal diameter stilling well and well constant values of $N = 0.33$ and $N = 5$.

Wave Type	Period (sec)	Well Constant N	Dim Freq B_2	Well Diameter D_w (m)	Intake Pipe Diameter D_p (m)	Intake Pipe Length L_p (m)	Dim Amp Response α_2
Short	3	0.33	119	1.88	0.030	3.07	4.35×10^{-6}
Long	900	0.33	0.396	1.88	0.030	3.07	1.002
Long	1500	0.33	0.238	1.88	0.030	3.07	1.001
Short	3	5	801	1.88	0.020	4.05	1.38×10^{-6}
Long	900	5	2.67	1.88	0.020	4.05	≈ 0.35
Long	1500	5	1.60	1.88	0.020	4.05	≈ 0.6

The predicted dimensionless amplitude response values in Table 3 indicate that the optimum tide well constant value of $N = 0.33$ with an intake pipe diameter of 0.030 m provides the best response for both short period wind-generated waves and long period seiche waves. The amplitude response inside the stilling well for short period waves, corrected for pressure attenuation effects, matches the amplitude of the external forcing waves to an accuracy of better than 0.0005%. For 1% annual exceedance probability short period north-westerly wind-generated waves with a maximum wave height of 2.5 m, the resulting wave amplitude inside the stilling well is predicted to be reduced to less than 0.02 mm. For long period seiche waves, the measured amplitude response is predicted to be within 0.2% of the external forcing waves.

The predicted dimensionless amplitude response values in Table 3 for the tide well constant value of $N = 5$ with an intake pipe diameter of 0.020 m indicate that the intake pipe design in this case is not able to allow the stilling well response to accurately reflect the amplitude of external forcing long period seiche waves. The measured amplitude response of such waves is only 35-60% of the amplitude of the forcing waves.

The intake pipe length requirements for a fixed intake pipe diameter of $D_p = 0.030$ m and stilling well diameters ranging from 0.75 m up to 1.5 m were also evaluated assuming an optimal tide well constant value of $N = 0.33$. Table 4 summarises the hydraulic response of a stilling well covering these design parameters for incident waves of maximum height 2.5 m and period 3.3 seconds. The hydraulic response of the initial 1.88 m diameter well is also included in this table. It was observed that smaller diameter stilling wells with a similar hydraulic response to a 1.88 m diameter one are feasible but would require a longer pipe intake length.

Table 4 – Hydraulic response of stilling wells of varying diameters for incident wave height of 2.5 m and period of 3.3 seconds.

Stilling Well Diameter (m)	Intake Pipe Diameter (m)	Intake Pipe Length (m)	Stilling Well Wave Height (mm)
0.75	0.030	19.00	0.026
1.00	0.030	10.70	0.026
1.25	0.030	6.90	0.026
1.50	0.030	4.76	0.026
1.88	0.030	3.07	0.026

If the intake pipe length for each of these stilling well diameters less than $D_w = 1.88$ m was restricted to the minimum value of $L_p = 3.0$ m for the fixed pipe diameter of $D_p = 0.030$ m, then the tide well constant gradually became less than the optimal value of $N = 0.33$.

Based on the results of these analyses, it was recommended that the proposed new stilling well-type headwater level gauge for Aviemore Dam should be 1.88 m in diameter and fitted with a nominal 0.030 m diameter and 3.07 m long horizontally-directed intake pipe at the stilling well base. The intake pipe length was fine-tuned after the actual intake pipe diameter was selected.

From a practical perspective, a stilling well of 1.88 m diameter was able to easily accommodate the internal ladders and platforms required to facilitate maintenance of a valve system for opening and closing the intake pipe and a flushing system to purge the intake pipe.

Hydraulic response of existing headwater level gauge

Prior to accepting the recommendation to construct a new stilling well-type headwater level gauge at Aviemore Dam based on these dimensions, a further review was sought on the hydraulic response of the existing stilling well gauge contained in the dam body, based on linear stilling well behaviour. As described previously, this gauge had a stilling well diameter of 0.457 m and an intake pipe diameter of 0.102 m and length of 1.04 m.

The 1.04 m length of the intake pipe did not satisfy the design criterion of $L_p > 100\, D_p$ for the minimum length for the intake pipe to ensure laminar flow behaviour. If this criterion was to be satisfied, then the intake pipe would need to be more than 10.2 m long for the same pipe diameter.

However, the diameter of the intake pipe was overly large such that it prevented the stilling well from damping the water level fluctuations of the lake surface induced by wind-generated waves. The intake pipe also had a wire mesh screen fitted to the pipe entrance on the dam face with the potential for blockage by submerged debris.

As described previously, the hydraulic response of a stilling well is governed by the dimensionless tide well constant N, which is a function of the tide well and intake pipe dimensions. The optimum tide well constant value is $N = 0.33$ but values as large as $N = 5$ can be satisfactory. In this case, the existing stilling well has a tide well constant N value of 4.43×10^{-6}, which is well below the recommended design range.

The existing stilling well could possibly have been made to work if the intake diameter was significantly reduced in diameter (to say $D_p = 0.03$ m) and the intake pipe length was increased to at least 100 D_p. It was not certain how practical this would be with the intake pipe set at a level of RL 258.25 m. The incident wave amplitude damping response of the existing stilling well modified in this manner would not be as good as that of a large diameter well, but it might be acceptable.

Table 5 summarises the predicted response for a range of incident wind-generated wave heights and periods. The incident wave amplitude damping response of the existing stilling well modified in this manner was an order of magnitude worse than for the design of the proposed new 1.88 m diameter stilling well gauge. While the damping response with the pressure attenuation correction for submergence of the intake pipe might have been acceptable for these short period wind waves, the modified stilling well would have produced an amplified response to long period seiche waves ($T = 900$-1500 seconds).

Table 5 – Hydraulic response of existing stilling well with modified intake pipe diameter of 0.030 m and length 3 m (tide well constant $N = 0.0192$).

Wave Period (secs)	Maximum Wave Height (m)	Stilling Well Wave Height (mm)
2.82	1.60	0.026
2.94	1.84	0.049
3.03	2.02	0.075
3.12	2.18	0.110
3.21	2.39	0.160
3.28	2.54	0.210

Another approach to using the existing stilling well gauge could have been to use data processing software to filter out the high frequency water level oscillations in the well. Although this would have been an effective means of accurately measuring the headwater level at the dam, the approach was considered and ruled out for dam safety reasons. Meridian Energy's policy is that dam safety critical sites should have three water level measuring devices. In the case of Aviemore Dam, it was also deemed necessary to have two independent measurement sites. The installation of a separate new stilling well gauge was required regardless due to the need for redundancy and to provide enough internal space to house all the necessary independent equipment.

Construction and installation of the new headwater level gauge

The new Aviemore Dam headwater level gauge was fabricated with two independent demountable intake pipes projecting like horizontal spokes from the base of the stilling well at an angle of 67 degrees from each other and at different levels. Each 2.720 m long stainless steel intake pipe of 32 mm bore was supported beneath a parallel steel universal column section off the 1.88 m diameter stilling well and mounted on an 80 mm diameter flanged pipe spacer passing through, and welded to, the wall of the well. On the inside of the stilling well, a stainless steel tee was bolted to the other end of each pipe spacer with a flushing pipe off the tee rising up to the control room floor at the top of the well. A stainless steel ball valve was connected to the other side of the tee section with a hand operated spindle for opening and closing the valve also rising up to the control room floor.

The design of the new headwater level gauge was innovative in the sense that the whole of the fairly substantial structure was fully assembled offsite, transported to site and then craned into position and fixed to the upstream face of the dam. Figure 9 shows the new headwater level gauge being lowered into position from the deck of the dam on 16 August 2013. The two intake pipes near the base of the stilling well are clearly visible along with the mounting frame for the gauge on the dam wall. When the well was mounted in position, the two intake pipes were fixed at levels of RL 260.15 m (just above the minimum lake level of RL 260.0 m) and RL 259.15 m.

Figure 9 – Installation of new headwater level gauge on Aviemore Dam.

The stilling well was fitted with two separate MTS magnetostrictive linear position sensor devices[11] for measuring water levels in the well. A third MTS magnetostrictive sensor device was fitted to the existing 0.457 m diameter stilling well gauge in the dam body. A radar device is also maintained on site for use should emergency lake dewatering below spillway sill level be required.

11 MTS is the trade name for a manufacturer of these devices. These linear position sensors measure absolute distance along a motion axis using the principle of magnetostriction. They are comprised of a position magnet sliding along a sensor rod and a sensor head housing an electronics module. The latter module measures the time delay between a transmitted sonic wave interrogation pulse and a return pulse generated by the interaction of the magnetic field from the position magnet and a second magnetic field generated by the initial transmitted pulse. The magnitude of the time delay indicates the location of the position magnet.
(refer http://www.controldesign.com/assets/wp_downloads/pdf/mts_sensors.pdf).
These particular sensor devices were chosen because of their robustness, ease of maintenance, reliability and accuracy. They also maintain linearity, do not require recalibration, and export data using the standard MODBUS instrumentation interface protocol used by Meridian Energy. They had already proved themselves recording wicket gate position on hydropower station turbines very reliably and accurately for a number of years.

Performance of the new headwater level gauge

The refinements to the headwater level gauge dimensions (intake pipe length L_p and diameter D_p), which occurred during the detailed structural design phase, caused the value of the tide well constant ($N = 0.200$) to be slightly lower than the optimum value ($N = 0.33$), although still quite acceptable. For wind-generated waves with a maximum period of $T = 3$ seconds, the frequency parameter for such waves has a value of $\beta_2 = 82.0$. Based on these values of N and β_2, the dimensionless amplitude response of the new stilling well was predicted to be $\alpha_2 = 5.6 \times 10^{-6}$ ($\approx 0.006\%$ of the amplitude of the external forcing waves outside the well) while the phase response was predicted to be $\varepsilon_2 = 0.978\ \pi$. This theoretical performance of the stilling well was considered to be very acceptable.

The new headwater level gauge was in place for the 10 September 2013 wind storm, which caused widespread damage throughout Canterbury and other parts of the South Island. Figure 10 shows wind-generated waves in Lake Aviemore during this event impacting on the dam at the headwater level gauge location.

Average wind speeds measured by Meridian Energy at a distant site in the Mackenzie Basin at the peak of the wind storm were in the range of 23.6-24.4 m/s (Fig. 11). Assuming that similar average wind speeds blew across the surface of Lake Aviemore at the same time, waves with a significant wave height of about 1.0 m and a peak period of about 3 seconds are likely to have occurred. The waves seen in Figure 10 are consistent with this hindcasting prediction.

Figure 10 – Wave action impacting new Aviemore Dam headwater level gauge during wind storm of 10 September 2013.

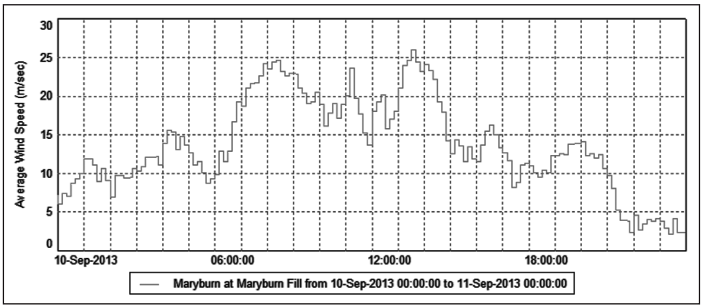

Figure 11 – Wind speed record from Maryburn at Maryburn Fill Station in Mackenzie Basin for wind storm of 10 September 2013 (continuous 10-minute average values).

Figures 12(a) and (b) show the lake level over the course of the wind storm on 10 September 2013 as measured by high frequency sampling of the two MTS magnetostrictive devices inside the stilling well of the headwater level gauge. The stilling well response is very steady, with the measurements by the two separate devices virtually identical. The maximum water level fluctuations measured inside the stilling well were about ± 2.5 mm, which is an order of magnitude larger than the amplitude response predicted by Noye's (1974a, 1974b, 1974c) tide well theory. These minor fluctuations probably reflect the measurement error of the MTS magnetostrictive devices, the sloshing of the water surface inside the stilling well due to wave impact induced vibration of the well casing, or a combination of both.

In contrast, Figure 12(c) shows the lake level measured by the existing small diameter headwater level gauge in the dam body during the wind storm on 10 September 2013. Maximum water level fluctuations inside the stilling well on this gauge were as much as 50-60 mm, which is an order of magnitude larger than those inside the stilling well on the new headwater level gauge.

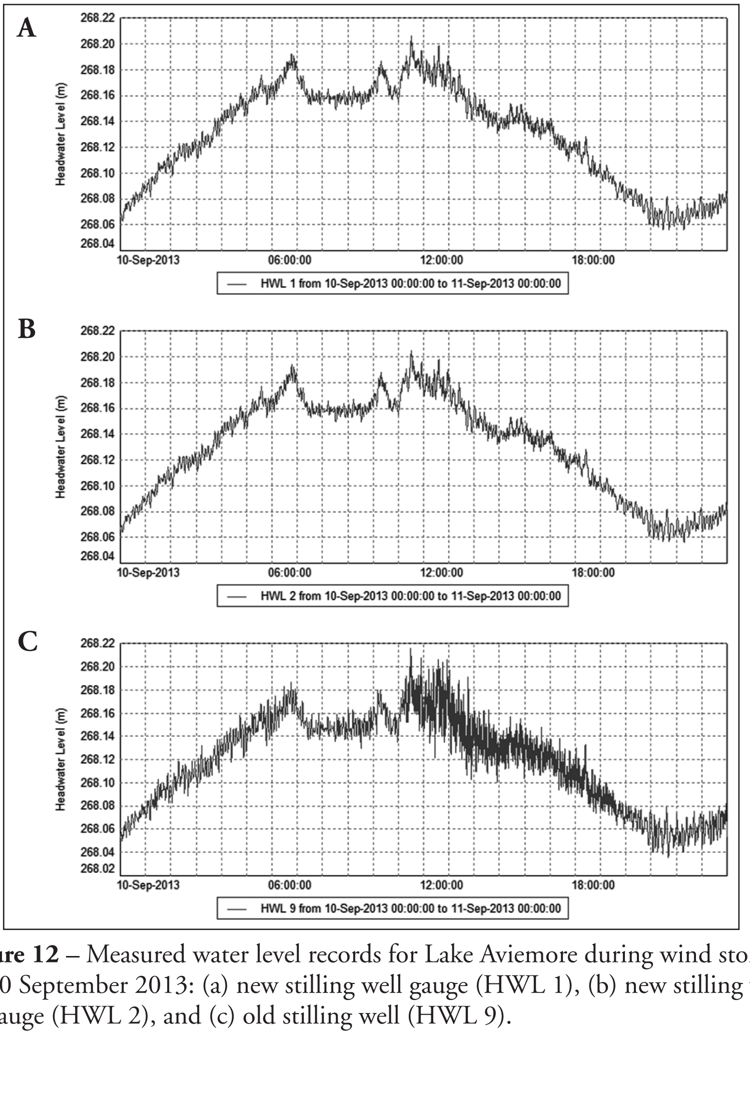

Figure 12 – Measured water level records for Lake Aviemore during wind storm of 10 September 2013: (a) new stilling well gauge (HWL 1), (b) new stilling well gauge (HWL 2), and (c) old stilling well (HWL 9).

Conclusions

The preferred location for a new gauge to accurately and reliably measure headwater levels at Aviemore Dam was on the dam headwall. This location was sufficiently far from the penstock intakes to be unaffected by minor water surface disturbances caused by power station turbine start-up and shutdown. However, the location was exposed to the surface waves generated by strong north-west winds blowing down the length of Lake Aviemore.

For the effective fetch length down the lake of 5.6 km, wind-generated waves from the north-west direction will be fetch limited with the critical wind speed duration for a fully arisen sea estimated to be less than 1 hour (USACE, 2008). Based on historic wind records from Aviemore Dam, the 1% annual exceedance probability hourly average north-westerly wind speed is estimated to be 30.7 m/s. For this wind speed, the significant wave height is estimated to be about 1.4 m with a maximum wave height likely to be about 2.5 m (USACE, 2008). The peak spectral wave period is estimated to be in the order of 3 seconds.

The design of a new headwater level gauge at Aviemore Dam was based on a conventional stilling well-type tide level gauge with a large diameter well and a long horizontal intake pipe of small bore. The behaviour of linear tide wells is described by Noye's (1974a, 1974b, 1974c) theoretical analysis, which assumes unsteady laminar flow through the long intake pipe under external wave forcing conditions. Noye (1974b) established that the hydrodynamic response of a tide well is governed by two dimensionless parameters: a tide well constant parameter N, which is a function solely of the stilling well and intake pipe dimensions, and a frequency parameter β_2, which is a function of these same dimensions as well as the period of the external forcing waves. The optimum value of the tide well constant is $N = 0.33$, which ensures linear behaviour for short period (wind-generated) waves when $\beta_2 > 10$ and also for long period seiche waves when $0.1 < \beta_2 < 0.4$.

The new headwater level gauge was fabricated with twin independently-operated intake pipes projecting like spokes from the base of the stilling well. The fabricated gauge had a tide well constant value of $N = 0.200$, which was slightly less than the optimum value but still quite acceptable. Based on the fabricated gauge dimensions, the frequency parameter has a value of $\beta_2 = 82.0$ for wind-generated waves with a maximum period of $T = 3$ seconds. For these values of N and β_2, the dimensionless amplitude response of the gauge well was predicted to be approximately 0.006% of the amplitude of external forcing waves. This corresponds to a maximum water level oscillation in the gauge well of about 0.014 mm for a maximum external wave height of 2.5 m.

The new gauge was successfully installed in August 2013 and then commissioned in September 2013. During the peak of the severe 10 September 2013 wind storm, in which average wind speeds were possibly in the order of 24 m/s and significant wave heights on Lake Aviemore in the order of 1.0 m with a peak period of about 3 seconds, the peak water level fluctuations measured in the stilling well were about ± 2.5 mm. This amplitude response is an order of magnitude larger than that predicted by Noye's (1974a, 1974b, 1974c) tide well theory. The measured minor water level fluctuations in the gauge well therefore probably reflect the measurement error of the water level measuring devices, the effects of vibration of the well casing from wave impact, or a combination of both.

The new gauge has provided accurate and reliable measurements of headwater level at Aviemore Dam since it was first installed. The two MTS water level sensor devices have performed faultlessly since installation. Meridian Energy's Generation Controllers have since completely forgotten the old days when the level of Lake Aviemore was only known to be within a range of values. Field staff can now get reliable electric plumb bob readings without having to wait for a rare day when the lake is calm.

The new gauge has clearly satisfied the original performance requirements specified by Meridian Energy prior to its design.

Acknowledgements

The replacement of the existing Aviemore Dam headwater level gauge was a joint project between Meridian Energy (Meridian) and Opus International Consultants (Opus). Meridian staff expended considerable time and effort investigating possible options for improving headwater level measurements at Aviemore Dam prior to Opus's involvement in the project. Meridian staff carried out all the electrical and control design required for the new gauge and also assisted with the provision of various manufacturing and equipment specifications. The contributions of key Meridian staff members, Andrew Turner-Heaton (Control and Instrumentation Engineer), Tim Mills (Civil Engineer) and Don Elphinstone (Project Manager), are acknowledged in particular.

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