WELLINGTON HARBOUR BORES – EXPLORATORY DRILLING FINDINGS

Rowan Oliver (Stantec), Hayden Pipe (Stantec)

ABSTRACT

Supply of water to Wellington City relies on bulk water mains that cross the Wellington Fault line in several locations. These pipelines are expected to break in a significant Wellington Fault rupture event resulting in Wellington being without water for an extended period of time, prior to repairs.

Unexpected failure of bulk supply assets during normal operation may also result in limited supply, water restrictions, or potentially even loss of supply to areas of Wellington City depending on the nature and location of the failure.

To improve the resilience of Wellington City's water supply, an alternative supply project has been proposed by Wellington Water. The Cross Harbour Pipeline (CHP) project aims to provide an alternative pipeline route that does not cross the Wellington Fault. A borefield located within Wellington Harbour was identified as a possible alternative solution at potentially significantly reduced cost. This would likely be the world's first offshore fresh water bore supply as whilst fresh water has been identified elsewhere below the seabed, no evidence was found suggesting an offshore borefield has been used for a significant drinking water supply.

This paper outlines the opportunity that the Harbour Bores option presented. This includes the investigations completed and results, the future planned use and applicability of the data obtained for the Wellington region's water supply, and wider geological implications for the data that has been obtained.

The Waterloo treatment plant currently sources water from the Waiwhetū Aquifer from bores along Knights Road in Lower Hutt. The same aquifer is understood to extend out underneath the Wellington Harbour, discharging at the 'Falcon Shoals' area near the harbour entrance. Drilling investigations were completed to determine if a suitable quality and sufficient flow of water could be obtained from the aquifer to provide an alternative water supply to Wellington City through a borefield located in the harbour.

The project involved drilling beneath the harbour floor, through the aquitard and into the Waiwhetū "Upper" and "Lower" aquifers, and the deeper Moera aquifer. Soil and water samples were taken during the drilling to assess the water, geological, and geotechnical properties of the harbour bed and aquifers, and low yield pump testing was carried out to estimate the potential flow a borefield would produce.

No hydrogeological or geological data has previously been obtained within the harbour south of Matiu/Somes Island leaving a significant gap in information and knowledge. The exploratory drilling has provided new data that is assisting the proposed Cross Harbour Pipeline project and has wider application throughout the Wellington region generally. Greater Wellington Regional Council is using the information to update existing hydrogeological models to better manage this critical regional water supply source, particularly with the management of the saline intrusion risk through known springs in the harbour and from other brackish aquifers. The National Institute of Water and Atmospheric Research (NIWA) and GNS Science (GNS) will be using the information to

undertake further analysis and update the understanding of the Wellington Region in their respective fields in future studies.

KEYWORDS

Wellington' water supply, Resilience, Exploratory Drilling,

PRESENTER PROFILE

Rowan Oliver is a Senior Project Manager at Stantec. His professional experience includes project management of large multidisciplinary projects in Transport and Water through planning, consenting, design and construction. He is the Stantec Team Leader for the Cross Harbour Pipeline Project.

Hayden Pipe is a Team Leader of the Wellington Water and Waste Group at Stantec. He is the Project Technical Lead of the Wellington Alternative Water Supply project which includes the Harbour Bores and Cross Harbour Pipeline Projects.

1 INTRODUCTION

In 2016, Stantec undertook the feasibility stage of the Cross Harbour Pipeline (CHP) project. This identified that the Upper Waiwhetū Aquifer, believed to be present under Wellington Harbour, provided the potential to construct a subsea borefield as an alternative solution to the CHP to help solve the water supply resilience issue for Wellington City.

The Harbour Bores project was initiated to investigate and obtain sufficient information to determine if a borefield in the Wellington Harbour could provide Wellington City with an alternative water supply. Desktop assessments at the time did not indicate any other subsea drinking water borefields that have been constructed elsewhere in the world.

Completion of the investigations required consideration of several complex issues related to the subsea location including the drilling methodology and maintaining aquifer security throughout the investigations. To complete the investigations a team of experienced professionals was formed that included drilling contractors, scientists, and engineers with specialist knowledge in their respective fields suited to the exploration. The team undertook extensive planning work to assess expected scenarios of what may be encountered. This planning allowed quick decision making depending on what was found at certain stages to allow progress to continue during the investigation process without costly delays.

In addition to helping to assess the feasibility of the harbour bores supply, the drilling exploration work also provides new information that will assist future projects for Greater Wellington Regional Council and Wellington Water Limited (Wellington Water) by providing a better understanding of the aquifer system that runs beneath Lower Hutt and the Wellington Harbour.

2 BACKGROUND

2.1 WELLINGTON'S BULK SUPPLY NETWORK

Much of Wellington City's potable water supply relies heavily upon water being transferred from the Waterloo Water Treatment Plant (WTP) in Lower Hutt and the Wainuiomata WTP, via the bulk water main that is located along State Highway 2. As shown in Figure 1, bulk water mains cross the Wellington Fault a number of times and are located in close proximity to the fault between Petone and Wellington City. The Wellington Fault is one of New Zealand's most active faults and puts the bulk main at significant risk of breakage during a seismic event, with resulting loss of supply for an extended period following a fault movement event.

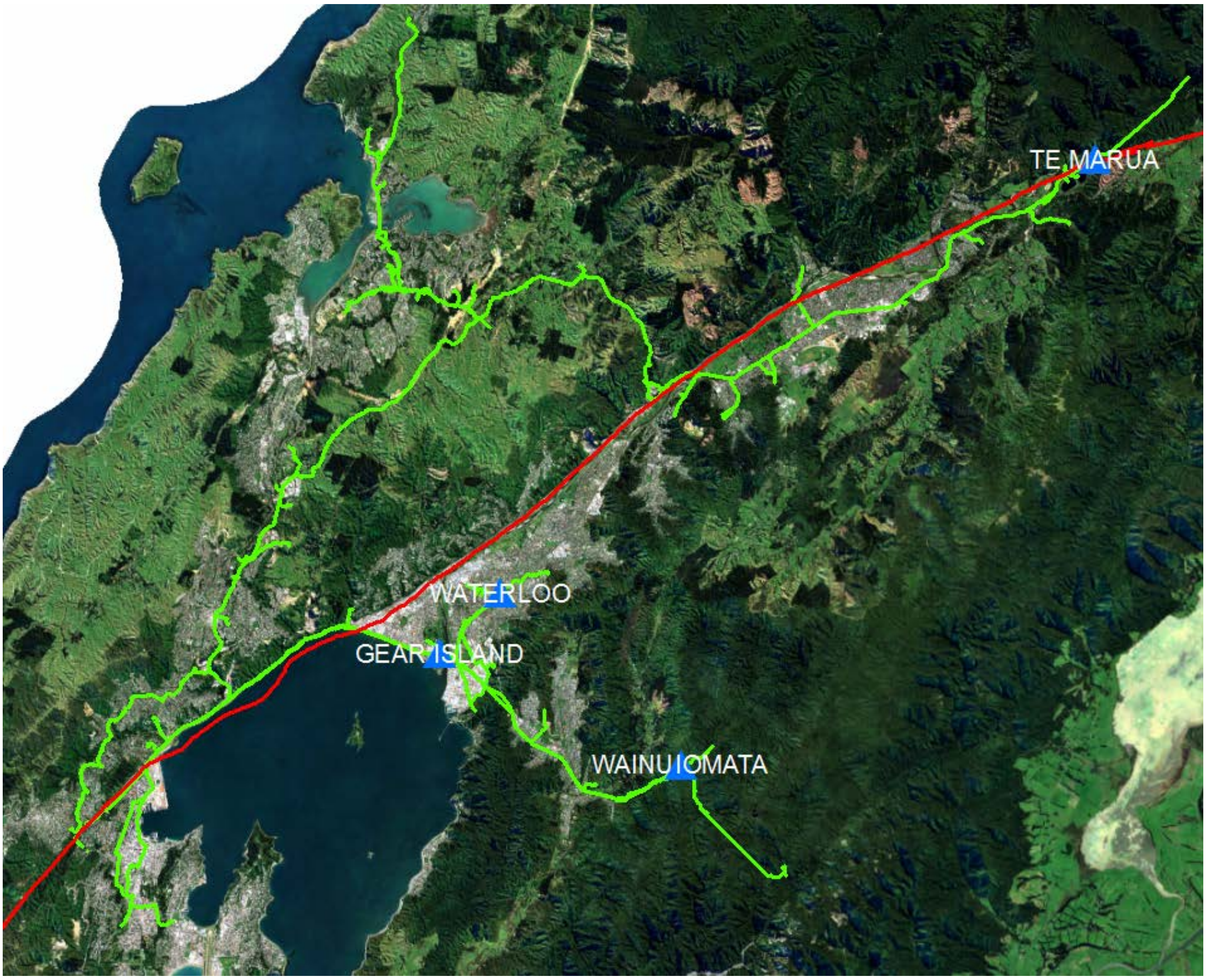

Figure 1 Wellington Fault Line (Red) and Bulk Water Network (Green)

Wellington City is also vulnerable if breakages occur during normal operation due to the long "skinny" nature of the network which relies on the bulk supply pipelines. The supply is supplemented by local storage during the day when demand exceeds supply, with reservoirs being refilled overnight. Depending on the type and location, a major operational failure could result in no supply being available for up to three days until the repair is made. In this scenario the southern and eastern parts of the city would be reliant on the storage available prior to the failure and some limited flow provided from the Te Marua to Karori pipeline, likely resulting in reduced level of service, water restrictions, and potentially loss of supply to consumers.

2.2 ALTERNATIVE WATER SUPPLY PROJECT OBJECTIVES

The purpose of the alternative water supply project is to provide an additional resilient supply route to assist both Wellington City's initial emergency response and aid in its long-term recovery following a significant seismic event. It will also provide operational resilience following unexpected failure of existing supply during normal operation.

2.2.1 EMERGENCY OBJECTIVE

The emergency objective for the project is to assist in providing sufficient supply to meet Wellington Water's long term '80-30-80' strategy. This strategy is to progressively improve the resilience of the water network alongside community initiatives so that following a large seismic event, 80% of customers, within 30 days, will have 80% of their normal water needs. The alternative supply project forms a key part of the suite of improvements needed to increase the resilience of the city to such events.

2.2.2 OPERATIONAL OBJECTIVE

The operational objective of the project is to ensure that a critical network failure event during normal operation will not significantly reduce the level of service provided to customers. A worst-case scenario bulk main break during a high demand period might take up to three days to repair, potentially resulting in loss of supply to central, southern, and eastern areas of the city. The alternative supply project is required to provide the sufficient additional water demand exceeding the available storage from reservoirs and the limited flow available from the Te Marua to Karori pipeline.

2.3 PROJECT TIMELINE

Project stages and timeframes are summarised below.

Table 1 Alternative Supply Project Timeline

Date	Task
2015-2016	CHP feasibility assessment and Options assessment confirmed that a Harbour Bores option had potential and required further investigation
2017	Wellington Water Ltd 80-30-80 Strategy was published outlining the requirements of the alternative supply to Wellington City
2016-2018	Harbour Bores investigations – Drilling and assessment work completed
2018	Options assessment using Bores information confirmed the CHP as the preferred option to proceed

3 HARBOUR BORES INVESTIGATIONS

3.1 EXPECTATIONS

3.1.1 EXPLORATORY INVESTIGATIONS

Due to the limited understanding of the extent of the Waiwhetū Aquifer in the Wellington Harbour and also taking into account that a similar type of subsea borefield was not known to exist, it was important not to over invest in the drilling investigations in case an obvious fatal flaw was found early during drilling. Therefore, careful planning was required, and the work was staged with the ability to change the approach or suspend works altogether if results deemed this to be the best option.

The potential fatal flaw (PFF) questions that needed answering included:

PFF 1: Aquifer yield – Are there freshwater aquifers beneath the harbour floor with a reasonable yield to provide a viable source. In particular, can the Waiwhetū Aquifer (as identified onshore) be identified as a viable resource beneath the harbour?

PFF 2: Aquifer Water Quality – Is the groundwater quality in viable aquifers suitable for human consumption following affordable treatment?

PFF 3: Co-seismic wave effect on aquifer – Will this seismic activity render the aquifer unusable?

PFF 4: Aquitard shear potential and general aquifer performance after a seismic event – Will fault movement damage the aquifer?

PFF 5: Risk of saline intrusion into the aquifer – Will pumping instigate saline intrusion?

The exploratory investigations and assessments were used to confirm that a harbour borefield was not fatally flawed and compare its potential against other options. If results deemed that it was still the preferred option, then further stages of investigations would be required.

3.1.2 WHAT WE EXPECTED TO FIND

When the Harbour Bores project option was identified, it was widely understood that the Waiwhetū Aquifer, that supplies water to the Waterloo WTP, extends out into Wellington Harbour. The distance that the aquifer extended into the harbour and its viability for a borefield were unknown. However, evidence of the aquifer existed with natural springs in the harbour near Somes Island and Point Howard, and fresh water was thought to seep out at Falcon Shoals towards the harbour entrance. The conceptual understanding of the aquifer and harbour bores is illustrated in Figure 2 below. This figure was produced prior to drilling.

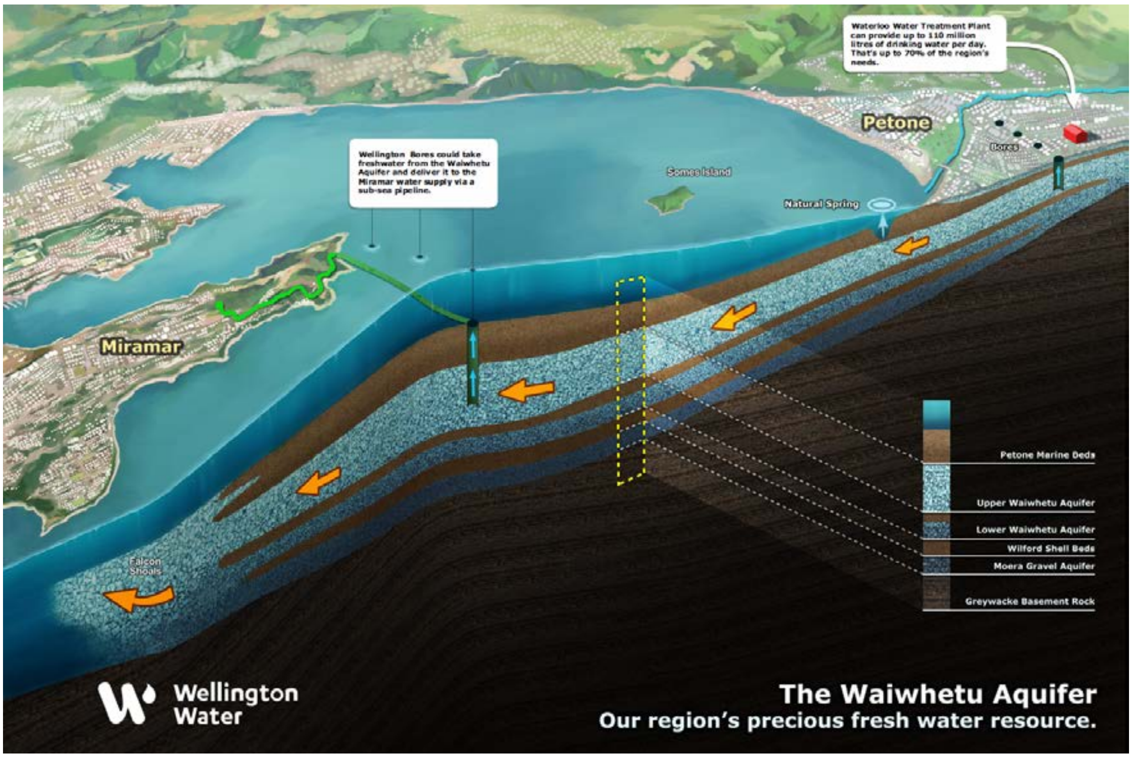

Figure 2 Wellington Harbour and Waiwhetū Aquifer Concept

Given Somes Island draws drinking water from the aquifer, it was expected that fresh water may be obtained at a borefield closer to the Miramar Peninsula. However further work was required to identify a location.

3.2 METHODOLOGY

3.2.1 DRILLING

The drilling investigations were carried out from a jack-up barge to give the contractor a fixed platform to conduct the drilling off that could withstand most wind and swell conditions.

The jack-up barge used for the investigations is shown in Figure 3 below.

Figure 3 Jack-up barge in action

The drilling was undertaken with a sonic rig which involves advancing casing into the seabed using vibration. This type of drilling generally gives a relatively undisturbed high percentage of core recovery. Casings of multiple diameters were used to ensure cross contamination between aquifers was not possible due to the drilling. This involved using a smaller casing being advanced inside the larger casing each time a separate aquifer was encountered. The larger casing would remain in place penetrating completely through the upper aquifer and into the aquitard below to generate a seal so when the smaller casing is removed from below, the upper aquifer is sealed off and cross-contamination does not occur.

During the drilling, when water bearing gravel layers were encountered, drilling continued until the most favourable part of the aquifer was found for “well development”. This required large enough gravel particles and freshwater pressure being detected through water pushing up the casing. When conditions were suitable, pump testing would be carried out with water samples also being taken. The first part of the pump testing involved measuring the aquifer drawdown in the bore against the flow being pumped. Following this, flows in the bores that supply the Waterloo WTP were suddenly reduced to as low as possible to determine the effect it had on the aquifer. These results allowed an estimate of the transmissivity of the gravels to be calculated to determine the speed at which the gravels can pass water, or the aquifer can recharge during extraction. Once suitable data was obtained from pump testing, the pumping equipment would be removed and drilling would resume until further gravels were identified, or the drilling was terminated. Once terminated the borehole was plugged with grout as the casing was being withdrawn to ensure a secure seal was provided before the barge was shifted from site.

The subsea strata expected to be encountered during the drilling is illustrated in the cross section in Figure 2.

3.2.2 BORE SITING

Initially, two drilling target areas were identified for potential sub-sea aquifer development. The target areas were constrained by three principal considerations – saline intrusion risk, the conceptual geological understanding of the aquifer's characteristics, and seismic risk related to the location of known active and inactive faults.

Seismic reflection profiles provided information on geological features such as stratigraphy and faults beneath the harbour floor. The principal seismic risk identified during the bore siting process were the faults on each side of the Somes Island Horst structure. There are numerous faults running in an approximately north north-east to south south-west direction and there is good geophysical evidence that some of the faults displace the Waiwhetū gravels. The geophysical data indicates that the Upper Waiwhetū Aquifer thins significantly over the horst structure. A horst structure is a raised block of the earth's crust that has lifted or remained stationary, while the land on either side has subsided. It was recommended that the horst therefore be treated as an exclusion zone for any potential bore development due to the seismic risk and the probability that the aquifer is thinner over the structure. Other faults are present running across the harbour floor and a 200m exclusion zone was included along all these faults during the bore siting processes. Other considerations in siting were:

- Preferentially locating the bore where thicker, well developed Waiwhetū gravels were indicated on geophysical profiles;
- Avoidance of perceived saline intrusion risks;
- Avoidance of, and provision of an adequate buffer, to seismic risks associated with known active and inactive faults;
- Conceptual understanding of likely groundwater quality patterns; and
- Distance from the proposed treatment plant on the Miramar Peninsula (i.e. pipeline costs).

Prior to drilling the first borehole (labelled E3), the risk of saline intrusion occurring as a result of pumping-induced aquifer drawdowns was evaluated through taking into consideration the following:

- The location of the contact between greywacke basement and the Waiwhetū Aquifer;
- Confirmed or suspected submarine freshwater spring sites; and
- The Falcon Shoals area where aquifers may discharge or be unconfined.

The locations of the two completed exploratory bores (E3 and E8) are shown on Figure 4 below.

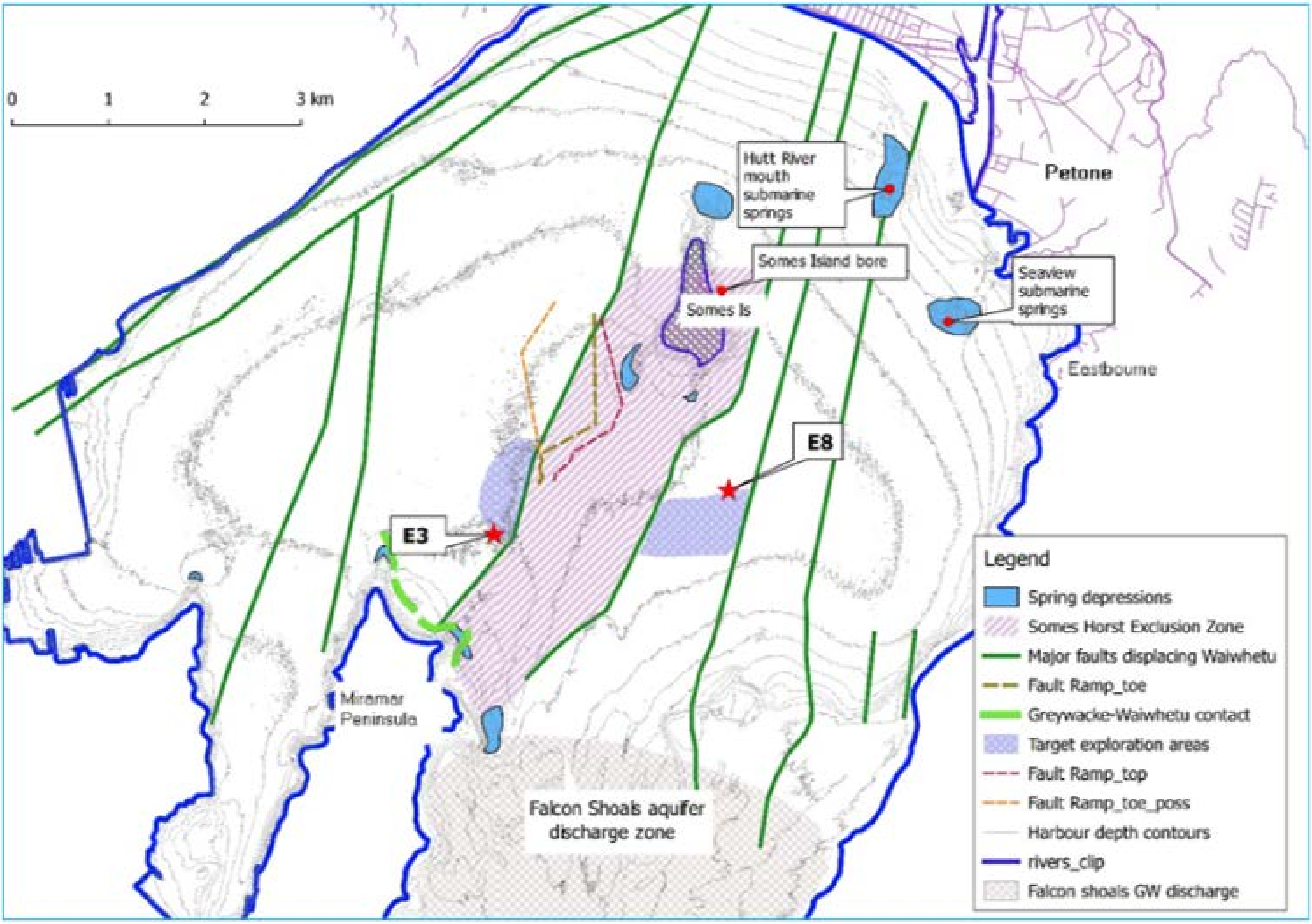

Figure 4 Bore locations and constraints (Earth in Mind 2018)

Following the drilling of the first borehole (E3), the second borehole location was revised. Initially it was expected to be located closer to E3 on the western side of the Somes Island Horst. Following the re-evaluation of the geophysical data using the results of E3 however, it was decided to change the location to the eastern side of the horst due to indications more favourable conditions were expected to be at the E8 location.

4 EXPLORATORY DRILLING FINDINGS

Figure 5 Harbour Bores Drilling Sites

4.1 GEOTECHNICAL RESULTS

Simplified borelog results are shown in Figure 6 below. Bore E3 identified two thin relatively permeable gravel aquifers; the Upper Waiwhetū approximately 4m thick, and the deeper Moera Aquifer approximately 3m thick. The Lower Waiwhetū Aquifer was identified as very thin silty gravel units at approximately 2m thick and 3m thick and did not produce suitable water bearing gravels to enable pump testing to occur.

At bore E8 the Upper and Lower Waiwhetū Aquifers were relatively well developed with both having thicknesses of approximately 11m. The top of the Moera Aquifer formation was encountered at E8 and was more compact and clay-bound compared to that seen in E3.

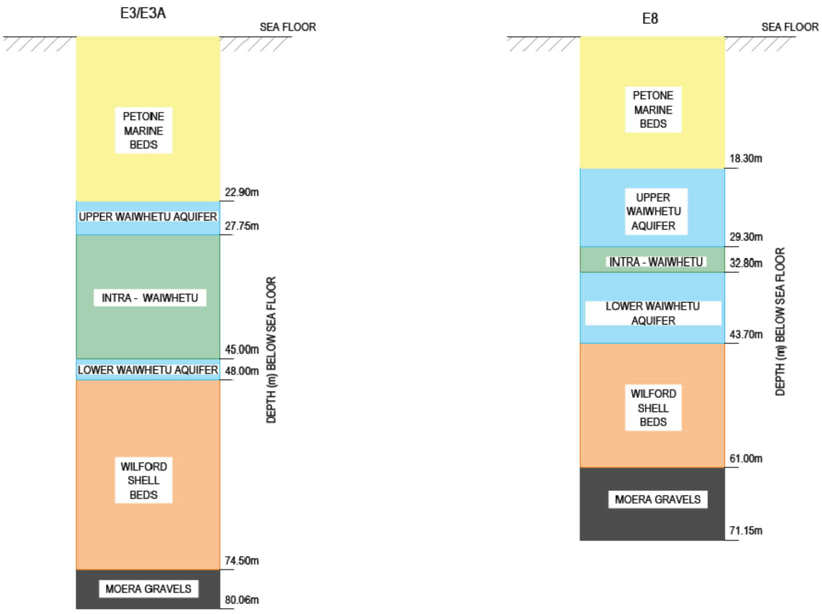

Figure 6 Harbour Bores – Simplified Bore Log

4.2 PUMP TESTING

The aquifer pump test results are shown in Table 2 below.

Table 2 Pump testing results for E3 and E8

Bore and Aquifer	**Pumping Test Rates (L/s)**	**Max. Drawdown (m) (in bore casing)**	**Transmissivity (m2/d)**
Upper Waiwhetū (E3)	5.5 – 17	3.9 – 6.9	26 – 1,056
Upper Waiwhetū (E8)	5.1 – 13.5	0.9 – 1.1	2,860 – 5,370
Lower Waiwhetū (E8)	5.9 – 11.5	1.3	812 – 930
Moera (E3)	12.3 – 13	1.2 – 4.9	195 – 3,530

Aquifer recovery and drawdown observations made on E3 and E8 during the Waterloo wellfield 'shut-down tests' were also analysed to obtain more regional aquifer parameter information for the Upper Waiwhetū Aquifer. Table 3 shows the analyses as well as transmissivity values interpreted for selected onshore bores for comparison.

Table 3 Waterloo wellfield shut-down test parameters

Bore	**Distance from Wellfield (m)**	**Transmissivity (m2/d)**
E3	9,417*	12,900
E8	7,670	30,200 – 35,500
Somes Island	5,992	25,000
McEwan Park	2,838	28,000 – 31,600
Randwick	1,362	19,500 – 20,000
Hutt Rec	725	10,900 – 11,000*

* Difficult to accurately remove tidal influence so accuracy may be questionable

The transmissivity results shown in Table 3 are significantly higher than the results from the pumping tests and are more consistent with onshore observations for the Upper Waiwhetū Aquifer. The hydraulic properties in Table 3 represent an average or bulk estimate of aquifer transmissivity and storage between the monitored bore and the wellfield and may not therefore be representative of local conditions in the vicinity of the exploration bores. In the absence of full-scale robust pumping tests on the exploration bores, it needs to be conservatively assumed that the transmissivity values lie within the ranges shown in Table 2.

Initial analytical modelling of the yield potential at location E3 for the two aquifers based upon the pumping test results suggested that approximately 2.6 – 2.8 Mega Litres per day (MLD) could be abstracted from the Moera Aquifer whilst the Upper Waiwhetū Aquifer may yield approximately 2 MLD.

The small thickness and low transmissivity of the Upper Waiwhetū Aquifer significantly hinders consideration of this aquifer as a viable source. It is also understood, following the revised geological and saline intrusion modelling, that this site lies in close proximity to the edge of the seawater interface mixing zone and anticipated poorer quality groundwater beneath the western part of the harbour. Following revision of the conceptual geological model, the E3 site is recognised as being peripheral to the main Waiwhetū Aquifer system which lies further to the east and therefore sustained abstraction is questionable. Water quality stability is also a major concern in this part of the aquifer. For these reasons, abstraction from the E3 site was not considered further.

The western target zone is not expected to extend further west of E3 because of the improved geological understanding of the Waiwhetū Aquifer extent, and the underlying lacustrine silts found at E3 which indicate the presence of a last glacial lake or swamp deposits rather than river gravels.

The E8 area is considered to be the most favourable general location for abstraction as it takes advantage of the good aquifer thickness (~10m), transmissivity, whilst avoiding known saline intrusion risks from the overlying ocean and seismic hazards. The Lower Waiwhetū Aquifer is not viable at either the E8 area (it is brackish and unpotable) or at the E3 site (the aquifer is too thin, exhibiting a low yield and poor water quality). Based on the interpretation of the offshore geology and saline intrusion risks, more favourable abstraction locations outside the E8 area have not been identified.

Modelling scenarios from the E8 bore indicate that, solely from an ocean-sourced saline intrusion risk perspective, that between about 10-20MLD could be abstracted, with the higher end of the range being attainable when the land-based Waterloo Bores are pumping at lower rates. The model results suggest that this abstraction range would prevent aquifer pressures at critical sites beneath submarine spring vents and levels on the eastern side of the harbour (Eastbourne coastline) dropping below critical thresholds thereby preventing invasion by seawater. This yield assessment however does not consider the risk of aquifer cross-contamination (from the brackish Lower Waiwhetū Aquifer). Management of this risk may require that the yield is further restricted.

It should be stressed that the simulated aquifer drawdowns, and therefore yield assessments, are based upon an unverified aquifer transmissivity for the Upper Waiwhetū Aquifer (regarded to be conservative). The E8 abstraction rates could be more confidently assessed on the basis of a full-scale and extended duration (i.e. months) pumping test and the yield revised upwards should a higher aquifer transmissivity than conservatively assumed is shown. It should also be appreciated that future pump testing, accompanied by monitoring of water quality and levels, and subsequent modelling of transmissivity and saline intrusion may also result in significantly lower yield being able to be extracted from a harbour borefield.

4.3 WATER QUALITY

The water quality results indicate that treatment would be necessary to meet NZ Drinking Water standards (DWSNZ). The results from the key water quality parameters are shown in Table 4 below.

Table 4 Key Water Quality Parameters

Parameter (mg/L)	NZ DWS		Upper Waiwhetū		Lower Waiwhetū	Moera
	Aesthetic	Human Health	E3a	E8	E8	E3a
Chloride	250	-	125	74.8	854	314
Ammonia N	1.5	-	3.41	1.08	7.75	5.14
TDS	1000	-	283	236	1750	596
Arsenic (total)	-	0.01	0.006	0.023	<0.001	<0.001
Iron (total)	0.2	-	2.65	0.515	2.45	1.59
Manganese (total)	0.04	0.4	0.537	0.123	0.389	0.299

Most of the exceedances are typical of older waters, but the higher salinity seen in the Lower Waiwhetū and Moera Aquifers is likely to be indicative of mixing with saline water. The water in bores E3 and E8 differs significantly from the water abstracted from the onshore aquifer.

The results of the age dating testing of the samples indicate that the groundwater in the aquifers at E3 and E8 have an average age of over 100 years. The results for the Upper Waiwhetū and Moera Aquifers in E3 suggest that the age of water within these aquifers is at least 205 and 175 years respectively. In comparison, age dating of samples collected from Somes Island indicates that groundwater there is generally younger with a mean residence time of 18 to 20 years. The results suggest that flow across the sub-harbour aquifer is relatively slow and provides support for the theory that groundwater is discharging via springs near Somes Island, allowing for more throughflow in this part of the aquifer.

A conceptual treatment assessment undertaken indicates that the cost of providing suitable treatment to bring the water at E8 within DWS requirements would increase a viable Harbour Bores project cost by at least 50%.

5 CONCLUSIONS

5.1 HARBOUR BOREFIELD

5.1.1 FATAL FLAW ASSESSMENT

The following has been concluded from the harbour bores investigations:

• PFF 1: Aquifer yield

Modelling of the Stage 1 data indicates that 10-20 MLD could potentially be extracted from the aquifer via an offshore borefield in the general area of E8, depending on the concurrent extraction rates from the Waterloo and Gear Island bores. High-yield, long-term testing is required to refine this conclusion, but there are significant uncertainties regarding performance of the aquifer when subject to high flow and long duration pumping.

• PFF 2: Aquifer Water Quality

Stage 1 exploration data indicates that the water obtained requires treatment to meet the DWSNZ which will remove manganese, iron, ammonia and arsenic. The cost of additional treatment to meet DWSNZ increases the project costs, however, there is a risk that the water quality may change when pumped at a high yield and for a long period of time.

• PFF 3: Seismic wave effect on aquifer and PFF 4: Aquitard shear potential and general aquifer performance after a seismic event.

Geohazards have been further considered from the initial version of this report with the additional core and CPT information from the exploratory bores being assessed. Whilst a study into the performance of the aquifer following a seismic event does not indicate any fatal flaws, it is possible that vertical deformation may reduce piezometric pressure within the aquifer (restrict the available flow from the aquifer) and increase potential for saltwater intrusion.

• PFF 5: Risk of saline intrusion into the aquifer

Prior to drilling, the potential saline intrusion risk was considered to be from the sea-water entering the aquifer. However, modelling predicts that in addition to this, there is an unexpected risk of saline intrusion from the Lower Waiwhetū Aquifer into the Upper Waiwhetū Aquifer. The inputs into the model are from sparse data and there is high uncertainty associated with the analysis. Further exploration drilling, high-yield, long-term testing and monitoring are required to refine this conclusion. Extended pump testing itself presents risks of saline intrusion and potential changes in the fresh and saline interface at Falcon Shoals. Figure 7 and 8 illustrate potential saline intrusion risks in the harbour that would require further significant investigations to confirm the likelihood and significance of these risks occurring.

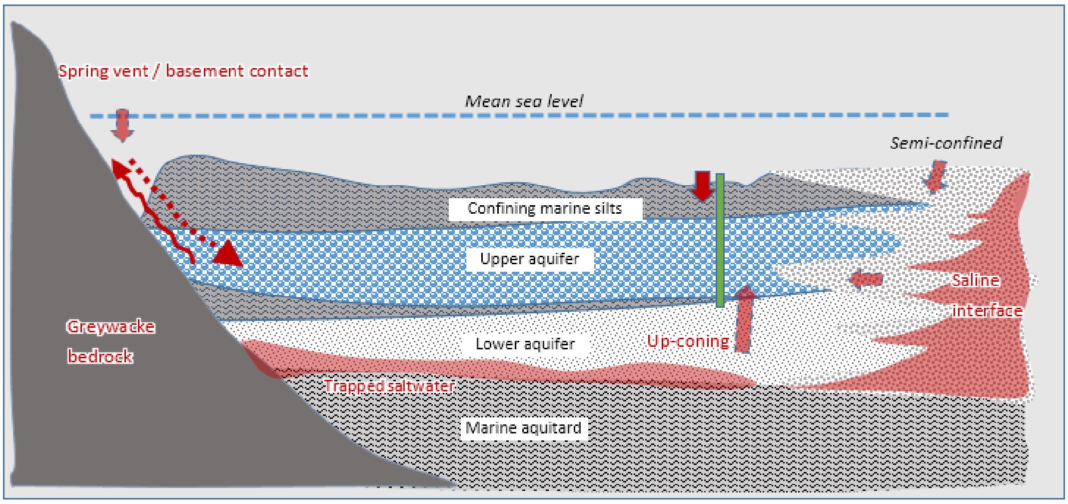

Figure 7 Saline Intrusion Risk concept (Earth in Mind 2018)

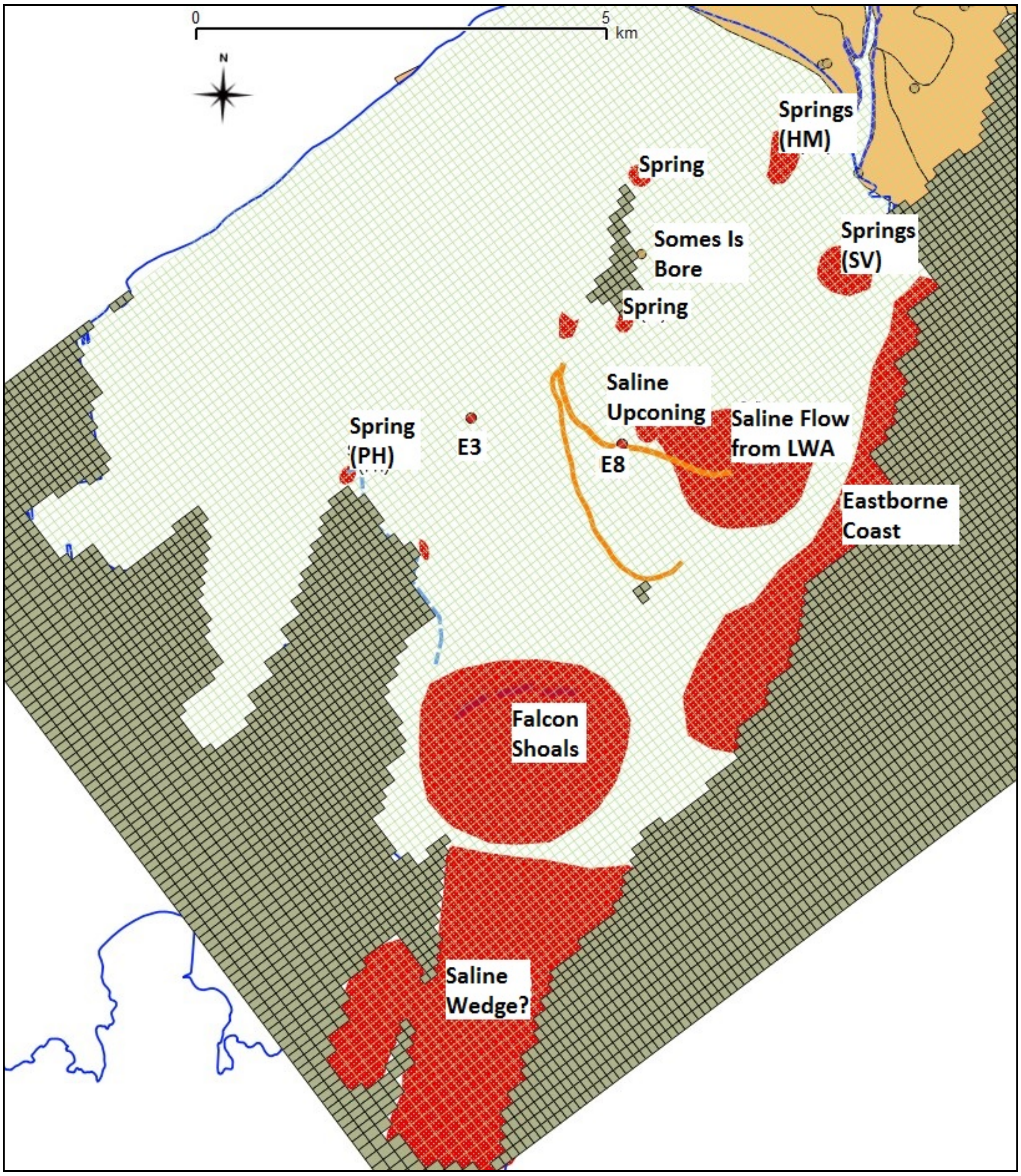

Figure 8 Saline Intrusion Risk Locations (Earth and Mind 2018)

5.1.2 HARBOUR BORES POTENTIAL

The Harbour Bores investigations confirmed that the Waiwhetū and Moera Aquifers extend out in to the harbour. The data obtained indicates that the quality and available yield of the water as it extends into the harbour is reduced when compared to the water obtained at the Waterloo Wellfield at Knights Road.

The first borehole at E3 identified limited aquifer thicknesses and yield potential. The geotechnical information was used to improve the calibration of the geophysical surveys previously undertaken. The improved geological understanding of the Waiwhetū Aquifer extent and underlying lacustrine silts identified at E3 indicated that it was unlikely that the aquifer extended further into the western target zone further to the west of E3.

Using the improved geological understanding from E3, the E8 location was identified as having the best potential for a successful borefield. E8 did provide improved yield, however the water quality still required treatment to meet the drinking water standards.

Overall, the investigations indicated that a harbour borefield water supply would require treatment to meet the DWSNZ, and was estimated to yield in the region of 10-20 MLD.

The treatment requirement increased the cost of the Harbour Bores option, and the estimated borefield yield of 10-20 MLD falls short of the alternative supply project target. The options assessment that was undertaken following the borefield investigations in 2018 concluded that the Cross Harbour Pipeline project was the preferred option to proceed for the alternative supply.

5.2 CROSS HARBOUR PIPELINE – USE OF BORES DATA

Progress has continued with the CHP project following the confirmation that this was the preferred alternative water supply solution ahead of the offshore borefield. The information collected during the bores investigations has proved useful for the CHP. The geotechnical information obtained through drilling and geophysics has provided insight into the seafloor parameters, including the thickness of the aquitard above the aquifer which will have an influence of how the pipeline is laid and how any fixings such as screw anchors are designed. The updated geology has also provided the ability to more accurately model the aquifer extents within the harbour which is important for locating future geotechnical investigations and informing pipe routing assessments. An important application of the data is shown in Figure 9 which illustrates a cross section of Wellington Harbour along the planned pipeline route indicating the extent of the Waiwhetū Aquifer gravels including where they terminate at either end of the pipeline.

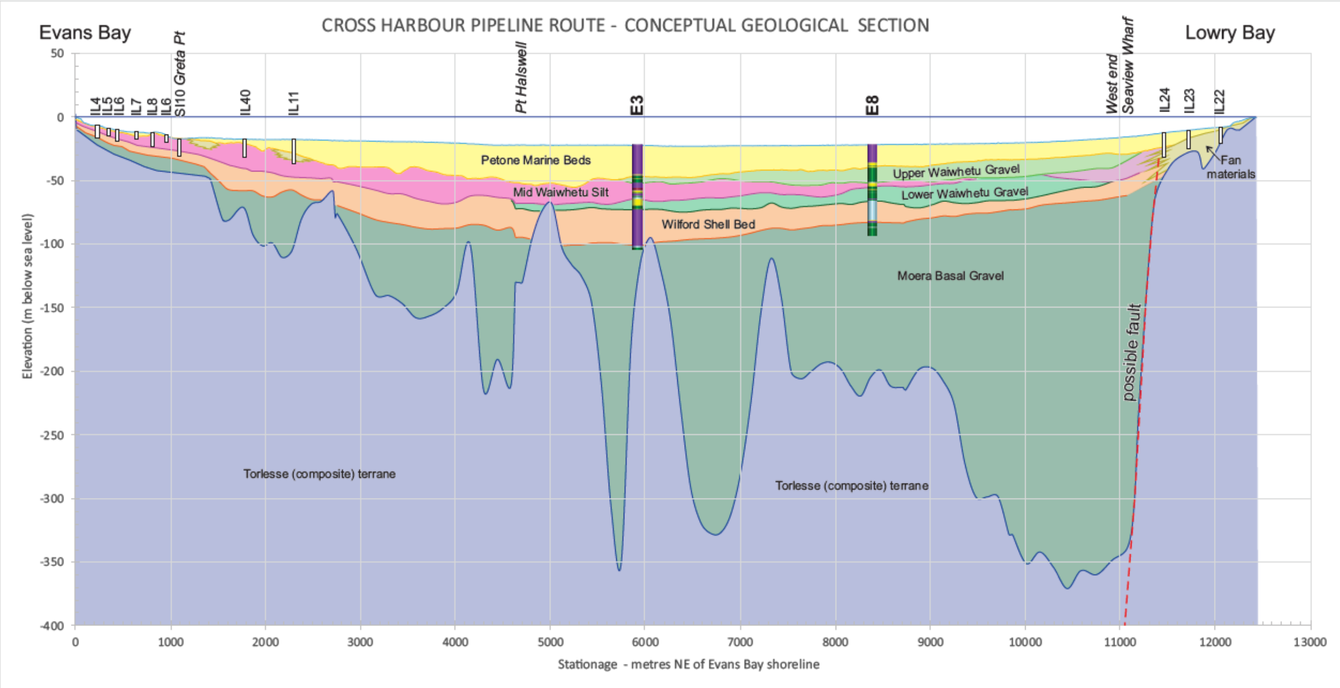

Figure 9 Wellington Harbour Stratigraphy (Begg 2019)

5.3 AQUIFER – LESSONS LEARNED

The information collected during the Harbour Bores investigations has identified an additional saline intrusion risk, which could result in saline water from the Lower Waiwhetū Aquifer being drawn into the Upper Waiwhetū Aquifer if the pumping rate from the Upper Waiwhetū Aquifer is too high. The risk is due to the thin aquitard between aquifers which is now understood to thin out completely with the 2 aquifers merging. The source of the saline water in the Lower Waiwhetū is unknown. It is possible that it could be old trapped water that has been laying there for a long period of time, or is a result of the Falcon Shoals fresh water and salt water interface moving and the heavier salt water protruding along the bottom of the Lower Waiwhetū Aquifer.

A key finding is the Waiwhetu aquifer is very limited to the west of the Somes Island Horst with the main extent of the aquifer being located to the east of the Somes Island Horst. The level of transmissivity of the aquifer between the Waterloo WTP and the bores is now better understood. This data has enabled the increased accuracy of the Hutt Aquifer Model (HAM3) used by GWRC and Wellington Water to manage the aquifer.

5.4 WELLINGTON REGION – NEW LEARNINGS AND DATA

5.4.1 DATA POTENTIAL

The data obtained from the Harbour Bores has provided important new information from an area and depth that had not been explored previously in the Wellington region. The depth allowed geological data to be obtained from periods as far back as 240,000 years ago. Key information obtained includes tectonic deformation derived from changes in elevations of marginal marine materials (paleoshorelines), the presence of plant/lake deposits that confirm correlations of alternating marine and non-marine materials.

Figure 10 illustrates the geophysical cross section correlated with the Bore logs which can then be used to ground truth the other geophysics in the harbour. It illustrates the new conclusions that have been made by GNS by using the bore logs and tests conducted in conjunction with the geophysics including soil types and age.

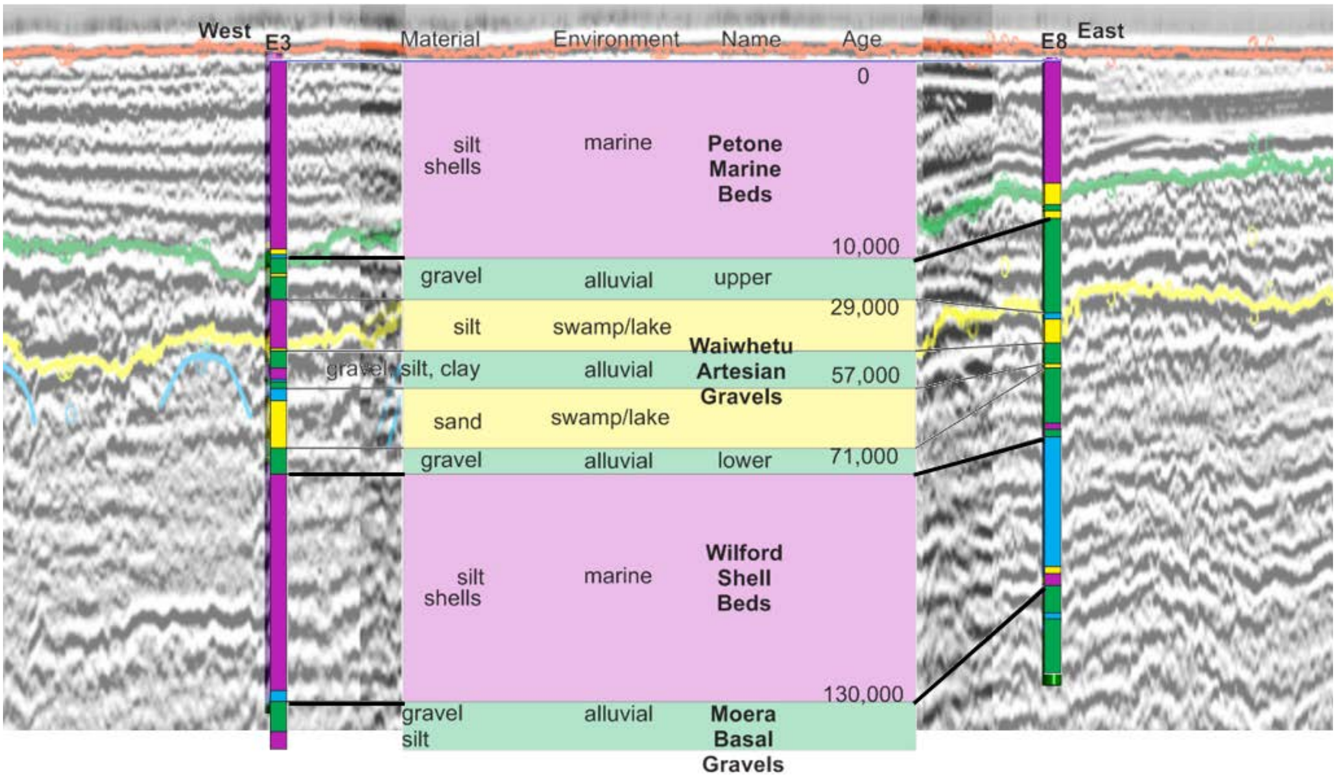

Figure 10 Geophysical Cross Section Correlation (Begg 2019)

5.4.2 NEW LEARNINGS

The information obtained has provided new insights into the geological history of Wellington Harbour. Figure 11 illustrates the likely paleogeography of Wellington Harbour during low sea level periods of the last glaciation (about 20,000 years ago). Bore E3 was drilled in an area that was a lake or swamp at the time, while bore E8 was located on the floodplain of the Hutt River of the time.

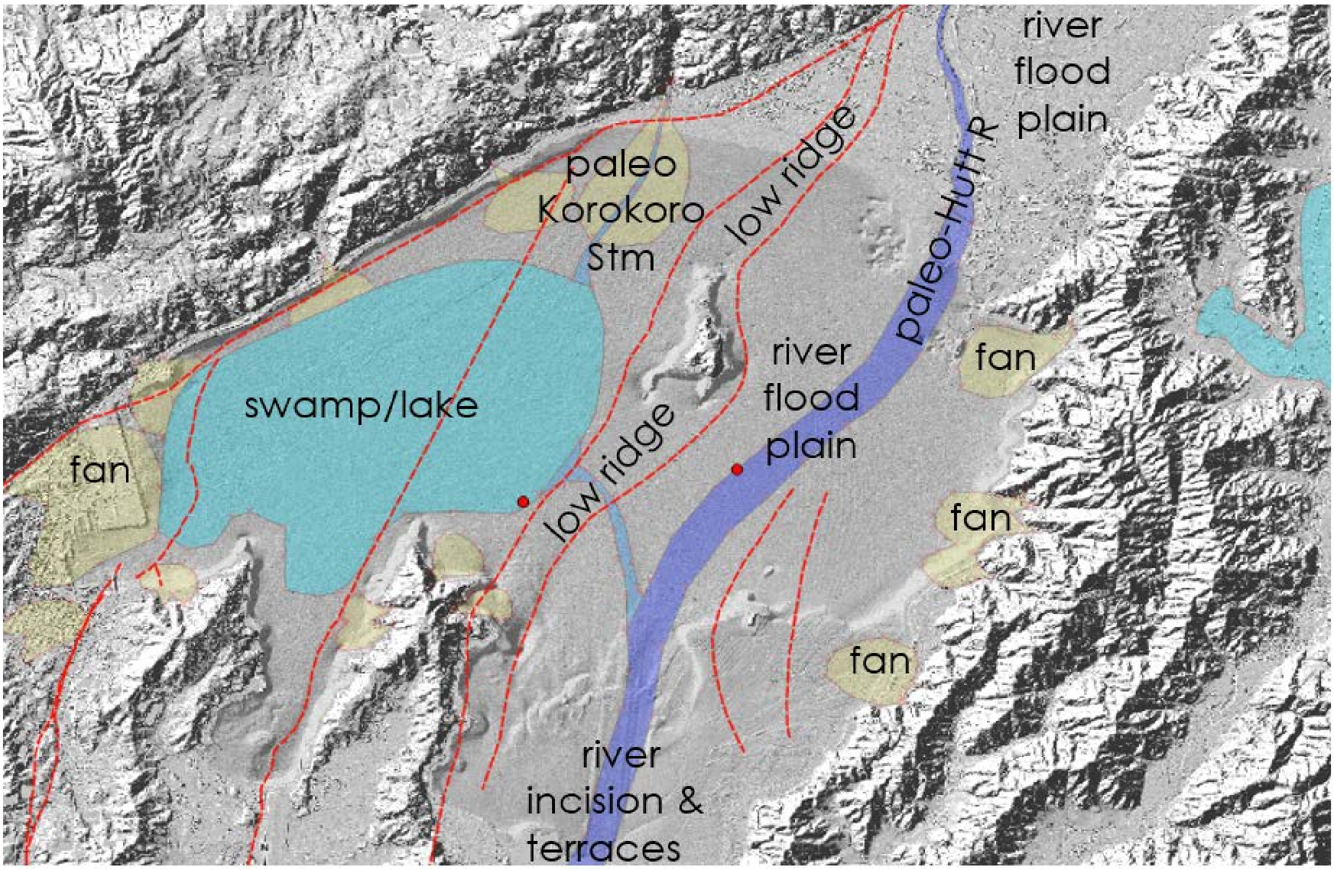

Figure 11 Wellington Harbour Low Sea Level Theory (Begg 2019)

The information collected has also provided much more refined insights into the long-term contributions to vertical deformation of the Wellington and Wairarapa faults.

The information indicates that the eastern side of the harbour is rising, and the western side is subsiding. Future vertical displacements are expected to reflect these trends. Tectonic tilting is illustrated in Figure 12 where the present elevations of the same paleoshoreline (about 125,000 years old); at Petone, close to the Wellington Fault this shoreline lies at over 100m below sea level (-106m yellow text at top of image), while on the south Wainuiomata coast, it is located at over 100m above sea level (120m yellow text at bottom right of image). The shoreline represented by these features was originally horizontal and has tilted as a result of these tectonic influences in the intervening period.

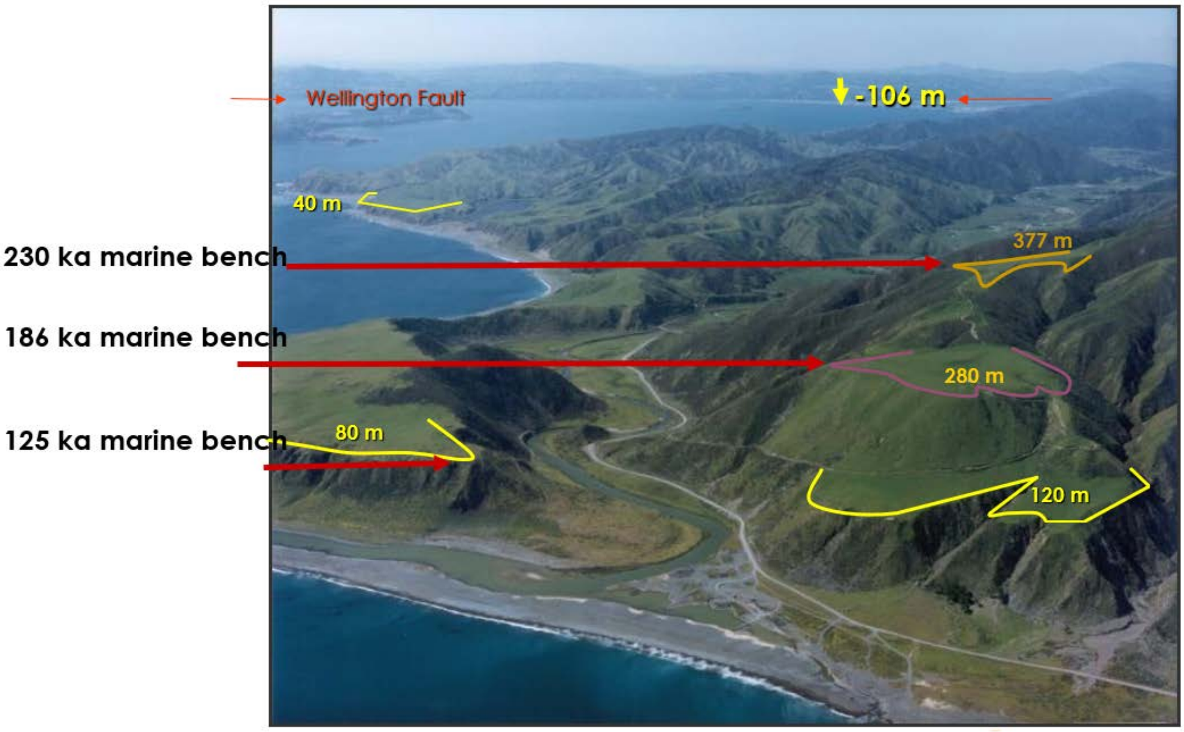

Figure 12 Illustration of seismic tilting (Begg 2019)

Figure 13 below comprises the global Oxygen Isotope curve for the last 240,000 years and illustrates changes in oxygen isotopes that result from climatic changes during this period. Cold climatic periods (ice ages) result in low sea levels while intervening warm climatic periods (interglacials) are associated with high sea levels. The elevations of paleoshorelines identified in the harbour bore logs can be combined with this data to derive average values of subsidence; Bores E3 and E8 have subsided at an average rate of 0.35m/1000 years over the past 130,000 years. Prior to drilling of these boreholes, no data was available in the harbour area to derive such rates of deformation.

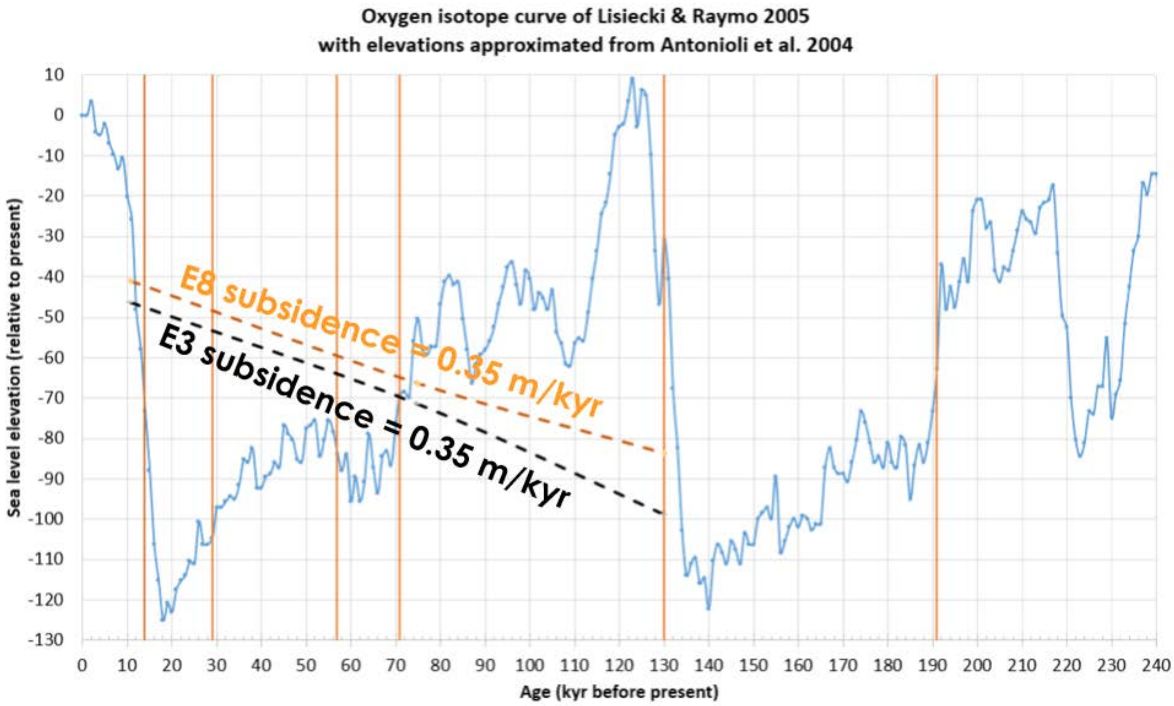

Figure 13 Oxygen Isotope Curve

5.4.3 FUTURE STUDIES

GNS currently hold the core from the offshore drilling and they plan to carry out other analysis as funding allows. This will include:

- Detailed study of the core including documenting pollens, shells, more radiocarbon dates
- Characterise changing climate and environments throughout the sequence
- Modelling the geological units across the entire harbour/Hutt Valley area
- Calculate subsidence rates across the entire basin

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