LINCOLN AGRITECH LTD

Wairau Aquifer Stratigraphy Review

Report 1053-1-R1

Scott Wilson

Lincoln Agritech Ltd

21 March 2016

MEASURE. MODEL. MANAGE.

Registered company office:

Lincoln Agritech Limited

Engineering Drive, Lincoln University

Lincoln 7640

Christchurch

New Zealand

PO Box 69133

Ph: +64 3 325 3700

Document Acceptance:

Action	Name	Date
Report prepared and revised by Scott Wilson		21 March 2016
Reviewed by Jens Rekker		9 March 2016
Approved for release by Blair Miller		9 March 2016

EXECUTIVE SUMMARY

This report reviews the stratigraphy of the Rapaura Formation, the sediments that host the Wairau Aquifer. The review followed a three stage process involving an initial data scan, 3D visualisation, and a final refinement by plotting the intercepts of distinctive units in GIS.

The surface of the Speargrass Formation marks the effective base of the Wairau Aquifer. This surface is now been better defined since Len Brown's early studies (1980, 1980a) with the inclusion of new bore log data. Structure contours on the surface of the Speargrass Formation indicate that the Rapaura Formation has a maximum thickness of 30 to 35m, but is 20m over most of the aquifer.

The stratigraphy review has confirmed that the Wairau Aquifer consists of shallow and deep layers of higher permeability. These have been termed the 'upper' and 'lower' members of the Rapaura Formation respectively. The lower member overlies the Speargrass Formation and forms the confined Wairau Aquifer beneath the Dillon's Point Formation aquitard. The lower member is thought to have been deposited during the early Holocene (around 9.5 to 7 thousand years ago (ka).

Overlying the lower member is a low-permeability clay-rich gravel 3-9 m thick, which is sometimes poorly water bearing. This lower permeability material is thought to have been deposited as over-bank flow deposits when sea levels began to stabilise about 6.5ka.

The upper member of the Rapaura Formation is most readily identified between Rapaura Road and The Wairau River. In this area the upper member forms a high-permeability shallow aquifer up to 12m thick, which has been termed the 'Rapaura facies'. Outside of this area the aquifer tends to be highly stratified and comprised of ~2m thick inter-fingered lenses of high and low permeability material. Shallow high-permeability gravels associated with the old Opawa River channel are locally present, having been incised into the stratified deposits.

The transition from low permeability over-bank flow deposits (6.5ka) to clast-supported or sandy matrix supported gravels in the upper member records a dramatic increase in the sediment load of the Wairau River. While deposition of the upper member is thought to have commenced about 6ka, it is likely that the rate of deposition increased rapidly during last 700 years in response to vegetation loss caused by fires on the southern hills.

The different lithological assemblages identified in this review show distinctly different hydraulic properties. Specific capacity values are highest in reworked areas of the upper member (eg Rapaura facies) and tend to decrease with depth. Transmissivity values typically exceed 1,000 m^2/day in both the upper and lower Wairau Aquifer, and are highest in the upper member of the Rapaura Formation.

The stratigraphy review identifies three areas where preferential recharge of the Wairau Aquifer may occur:

- A 3km stretch of river below Rock Ferry. The lower member of the Rapaura Formation is in contact with the active river channel gravels, allowing the potential for deep Wairau Aquifer recharge to occur

- Above Conders Bend via gravels associated with the old Opawa River channel. The channel is now blocked by Conders Groyne (1914-1926)
- A 3-4 km stretch of river below Boyces Road. In this area the river traverses a thickening section of the Rapaura facies of the upper member of the Rapaura Formation.

The Rapaura facies is thought to be the most transmissive part of the Wairau Aquifer, and forms a rapid groundwater flow pathway between the Wairau River and Spring Creek.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 STUDY OBJECTIVES

Previous work carried out in the Wairau Aquifer suggests it may be a two-layered system. This hypothesis was first proposed by Len Brown (1980), who identified:

a. A deeper layer of lower permeability gravels deposited prior to and during sea level rise (~13,000 to 6,500 years), prior to and during deposition of the Dillons Point Formation.

b. A shallower upper layer of reworked gravels that were deposited during a period of river entrenchment after the stabilisation of sea levels 6,500 years ago.

If this two-layered system concept is correct, it implies that the majority of aquifer recharge and dynamic groundwater flow (and nutrient transport) will occur in the upper high-permeability layer.

This report reviews the available geological and hydraulic evidence to assess if this two-layer model is realistic or geographically prevalent across the Wairau plain. All bore log data used for this review are available on the MDC online GIS database.

1.2 BACKGROUND

This study focusses on the unconfined Wairau Aquifer located between the Wairau River and Old Renwick Road (Figure 1). This area is the subject of a distributed groundwater flow model that has been developed (Wilson & Wöhling, 2015) and is currently being refined.

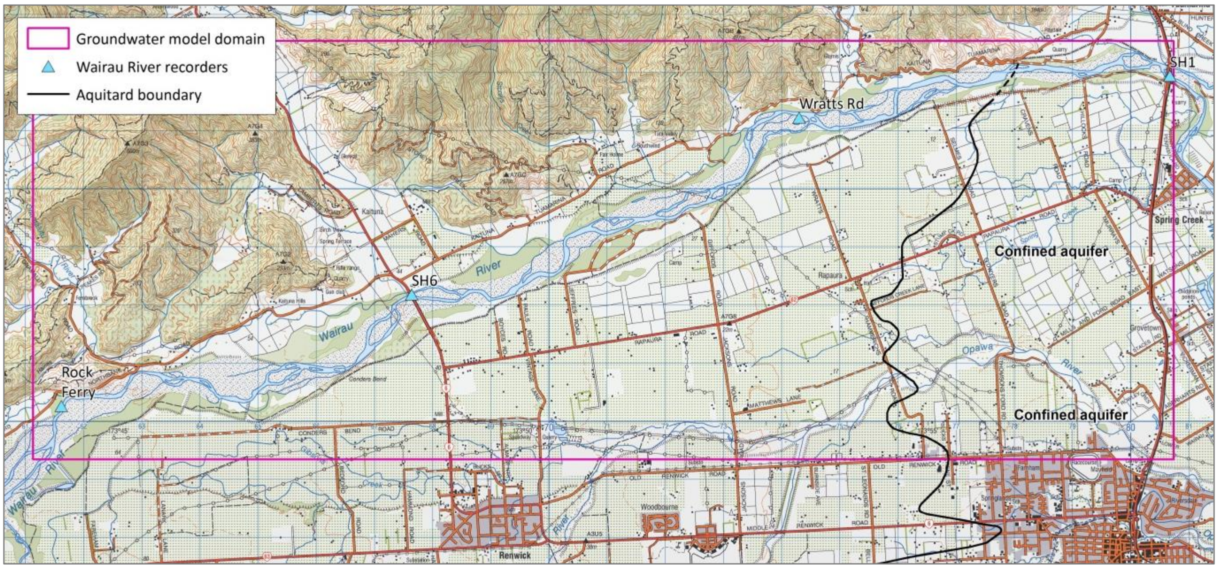

Figure 1 Location map for the stratigraphy review

A previous review of the lithology of the Wairau Plain as a whole has been undertaken by White and Tschritter (2009). This report is not intended to duplicate that report, but to specifically review the lithological structure of the unconfined gravels of the Rapaura Formation, particularly in their relationship to the present day Wairau River.

The Wairau Aquifer is hosted by the Rapaura Formation, which was deposited during the Holocene period of the last 11,700 years (11.7 ka). Several studies (e.g. Brown 1981, Brown 1981a, PDP 2001, PDP 2009 PDP 2014, Wilson & Wöhling 2015) have suggested the possibility that the Wairau Aquifer consists of two main permeable 'layers' deposited during the Holocene period. The lower layer is thought to have been formed by erosion, reworking, and re-deposition of the Speargrass Formation following warming of the climate in the wake of the last glacial maximum about 14,000 years ago. The upper layer is thought to have formed after the sea level stabilised about 6,500 years ago, and therefore post-dates the marine Dillons Point Formation.

The stratigraphy of the Wairau Aquifer was developed and written by Len Brown of the DSIR (Brown, 1981, 1981a). Len noted that the Rapaura Formation could be divided into an upper and lower unit on the basis of depth, lithology, permeability and ease of drilling. However, the two horizons were not clearly defined or identified on any of his maps or wells logs, presumably because of the difficulty in doing so with little data. Since the publication of Len Brown's benchmark paper there has been a substantial amount of drilling and aquifer testing on the Wairau Plain. The current evidence leans towards the presence of a two-layered aquifer system. These layers have been identified in well logs and subsequent correlation of the layer's properties in aquifer test analyses (e.g. PDP 2001, 2009 and 2014).

More recently Wilson & Wöhling (2015) reviewed groundwater monitoring records and aquifer test data, and concluded that the permeability of the aquifer is highly anisotropic. This anisotropy can be can be explained by depositional processes in a braided river environment, which results in imbrication (overlapping of particles and cobbles) and stratification (inter-bedding of fine and coarse sediments). A two-layered system was also proposed as a possibility by Wilson & Wöhling (2015), which has prompted this review of the aquifer stratigraphy.

I have observed that there is a tendency in stratigraphic reviews to lean towards one of two extreme viewpoints:

- that the sequence is a single unit of (anisotropic) gravels with no clear internal structure
- that the sequence is composed of definite layers that can be identified in every borehole

While a two-layered system has been indicated or suggested by previous studies, it is not expected that the contact between upper and lower layers will be immediately obvious in bore logs. The Wairau Valley is filled with gravel material deposited by braided rivers after all, and these types of deposits are inherently heterogeneous on a metre scale.

At the same time, we know that the bedload and gradient of the braided river system has changed radically since the last glacial maxima, a change largely driven by climate and changes in sediment supply. It would therefore be unusual for there to not be some variation manifest in the sediments resulting from changes in the depositional environment. Accordingly, the intention of this study is to take a middle path between the two extreme viewpoints as exemplified in the following objective:

To identify general patterns of deposition informed by basin-scale changes in the energy of the river environment

2 METHODOLOGY

The stratigraphy review has followed a three-step process involving:

1. A preliminary data scan of deeper well logs
2. 3D visualisation using GMS version 9.2 (Groundwater Modelling System) software
3. Final delineation of stratigraphic members/facies in Arc GIS

Drillers' well logs were referred to throughout this three-tiered approach.

The main data source that is available for reviewing the stratigraphy of the Wairau Aquifer is the drillers' well logs recorded in the MDC database. However, in the absence of marine marker-beds such as the Dillons Point Formation, it is genuinely difficult to identify distinct stratigraphic layers within the aquifer based on the lithological descriptions in drillers' logs. The reason for this is that the most common lithology recorded on the Wairau Plain is grey or brown sandy gravels regardless of the borehole depth, or the stratigraphic unit being logged. As a result, a typical drillers' log consists of variations on "brown sandy gravels" with qualifiers such as "silty", or "clay-bound". Furthermore, lithologies that are recorded appear to vary considerably between drillers and there is little consistency in logging practice between one driller and another.

An additional data source is the comments made by the drillers on the water-bearing nature of the sediments encountered. The use of these data for informing the internal structure of the aquifer is investigated in this review.

2.1 PRELIMINARY DATA SCAN

The drillers' logs were initially assessed by looking for layering within the deeper wells (>18m). The logs were followed from west to east to see if any consistent patterns of layering are evident within the Rapaura Formation. This preliminary assessment indicated that the gravels are highly stratified southwards of a line about 500m south of Rapaura Road, from Conders Bend to Giffords Creek Lane.

To the north of this line demarking stratification, two-layered system could be consistently identified. The base of the upper layer was typically found at a depth of 13.4 ± 4m. A low-permeability area could be seen in this layer along Rapaura Road from SH6 and Jeffries Road.

The upper and lower layers are normally separated by 3.5-4m of lower permeability material, sometimes described as 'tight', sometimes as 'loess'.

The second deeper layer of the Rapaura Formation appeared to be more consistently water-bearing across the aquifer. This layer could be more readily detected in well logs, even if the upper layer was not clearly identifiable or highly stratified. The lower layer was consistently present at a depth of 17.2 ± 4.7m. There are few intercepts available for the base of the Rapaura Formation since the drillers don't tend to drill into the Speargrass Formation. Based on the available data, the thickness of the lower layer was found to be typically 7-13m.

2.2 3D VISUALISATION

To assess the variability between drillers' logs at a preliminary level, lithological data from the logs were plotted in GMS, which enabled the data to be viewed in 3D.

To aid visualisation, the stratigraphic descriptions were been lumped into four alluvial depositional environments:

- High-energy deposits (sandy-gravel and sand)
- Proximal flood deposits (silty-gravel or coarse clayey-gravel)
- Distal flood deposits (clay-bound gravel, clayey-sand or silt)
- Low-energy (organics, clay, silty-clay)

The results are plotted in Figure 2 with a grey wireframe to represent the land surface and a 20x vertical exaggeration. The prominent escarpment which extends westwards from the town of Renwick can be seen in the top left of the plot, and the edge of the Richmond Range is apparent on the right hand side.

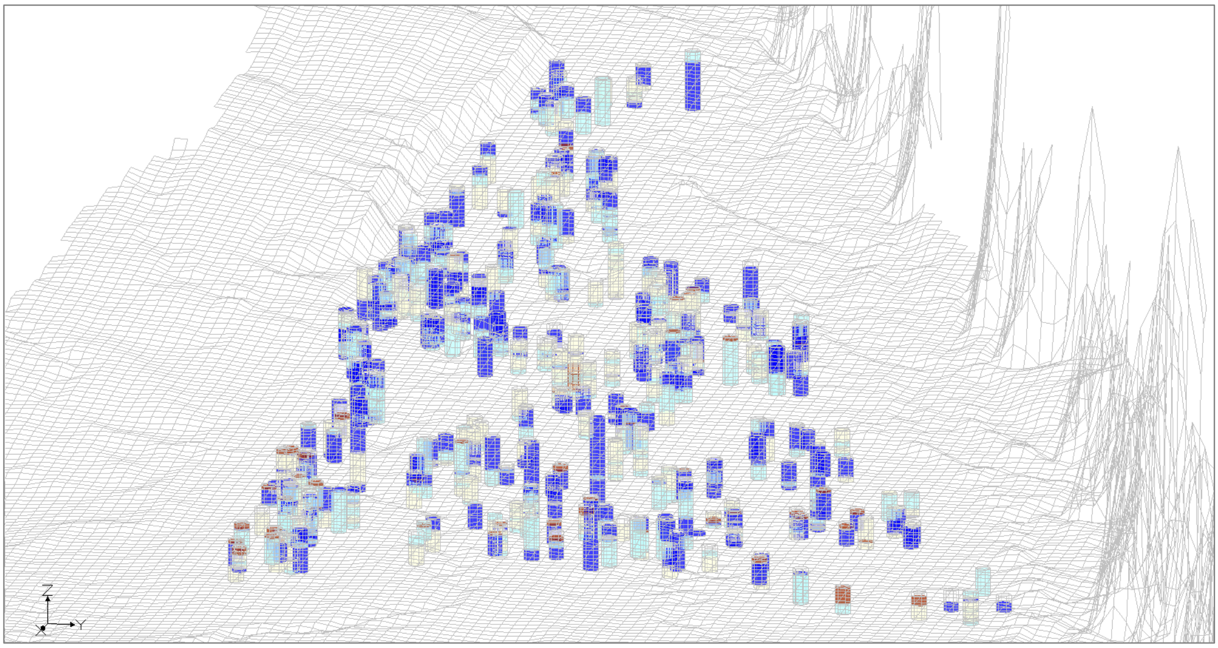

Figure 2 3D plot of lithological data looking up-valley from above the edge of the aquitard

Figure 2 indicates that there is very little consistency between drillers' logs, except for perhaps a dominance of low-energy lithologies in the middle of the Wairau Plain in the Vintage Lane area.

An alternative approach for data visualisation was trialled by assuming that the remarks made by drillers on the water-bearing nature of the sediments are an indicator of permeability. A three-fold classification was used:

Water-bearing, or good water-bearing

Poor water-bearing

No remarks on water, or no water

The results of this approach were also plotted in GMS (Figure 3). Examination of the results suggests that the designation of water-bearing horizons also varies between drillers. However, this approach does provide more lateral consistency than a purely lithological approach. In particular we can start to perceive distinct horizons of more permeable material which are laterally continuous.

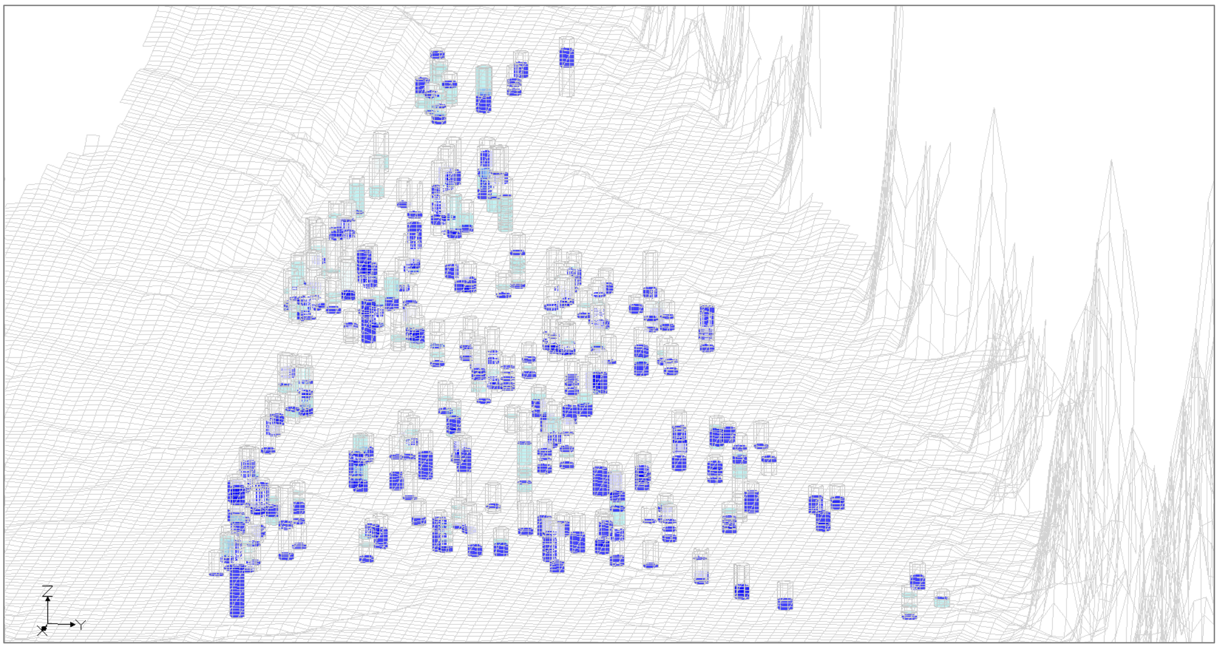

Figure 3 3D plot of water-bearing data looking up-valley from above the edge of the aquitard

Visualisation of the water-bearing intercepts in GMS accord with observations made in the preliminary data scan. In particular, a number of bore logs in the region north of Rapaura Road indicate the presence of a two-layered system with less-permeable material in between.

To the south of Rapaura Road, the deeper permeable layer is usually distinctive, although there is no distinct water-bearing horizon in the shallow sediments. The lithology of these shallow gavels is highly stratified, indicating that these sediments were most likely deposited as flood debris rather than channel gravels. As a consequence of lower water yields from stratified gravels, boreholes in these areas are typically drilled to a depth of 12-15m or more in order to provide sufficient productivity.

An exception to stratification in the shallow sediments does occur within the old Opawa channel of the Wairau River and its associated flood terrace. Shallow water-bearing strata have been recorded in many boreholes throughout this area, however their distribution is inconsistent. Despite this inconsistency, it is more common for boreholes in this area to be less than 10m deep, since the shallow gravels are often of sufficient yield to not drill any deeper.

The old Opawa River channel was blocked by Conders Groyne in 1914-1926, but was mapped by Brown (1981, 1981a). The channel and its associated flood terrace is evident in soil maps (e.g. Basher et al. 1995), but is not distinguished in the Q-Map database geological mapping.

2.3 GIS INTERPOLATION

The final step in the stratigraphic review was to spatially delineate areas or packages showing similar lithological characteristics by collating a set of intercepts of interpreted stratigraphic sub-units. To do this, the water-bearing intercepts from the preliminary data scan were imported to GIS, and supplemented with intercepts of the shallow water-bearing layers that were observed in the GMS 3D visualisation. A process of interpolation and refinement was carried out to generate representative surfaces for distinct layer boundaries. In some areas, this was done on a bore by bore basis for the purpose of delineating lithological boundaries (e.g. west of SH6).

3 SPEARGRASS FORMATION

The remaining chapters in this review describe the Pleistocene geology of the ‘unconfined’ gravels on the Wairau Plain and the features discovered by the methodology applied. In keeping with geological protocol, the oldest unit is reviewed first, which is the Speargrass Formation (Suggate, 1965).

The Speargrass formation is assumed to represent the base of the Wairau Aquifer in most groundwater studies undertaken on the Wairau Plain. The reason for this is that well yields are usually at least an order of magnitude lower than those of the Rapaura Formation. Despite this, the Speargrass Formation is an important groundwater resource to the south of Old Renwick Road. Also, there are some bores located to the west of SH6 which have been drilled through the Rapaura Formation and screened in the Speargrass Formation. This suggests that yields in this area may be equivalent to or higher than those in the lower Rapaura Formation, at least locally.

Gravels of the Speargrass Formation are distinguished from those of the overlying Rapaura Formation by more clay and silt in the matrix, lower permeability, and harder drilling (Brown, 1981). Bore logs also indicate the clasts to be angular, although this condition is not unique since angular clasts can also be found in the Rapaura Formation. The overall colour of the Speargrass Formation is blue-grey, suggesting the gravels have been subject to little surface weathering.

The Speargrass Formation was deposited during an aggradation phase in response to warming following the last glacial period. Rapid and sustained sea level rise occurred during this period (Lambeck et al., 2002). At the onset of deposition, the sea level was 130 m below its current level, and the coast was about 40 km to the east (Ota et al., 1995).

Deposition of the Speargrass Formation occurred between >20 and 14 ka (Brown, 1981). The dating of river terraces in the Awatere Valley (Eden, 1989) indicates that the late-glacial aggradation phase finished at 17 ± 2 ka. This age was been more recently constrained by optically stimulated luminescence dating in the Saxton River catchment to 14.5 ± 1.5 ka (Mason et al., 2006).

A table of known intercepts of the Speargrass Formation is included in the Appendix to this report. A total number of 23 intercepts were identified within the study area, 12 of which were identified by Brown (1981). The intercepts were supplemented by elevations on the top of the Renwick escarpment to generate structure contours of the Speargrass Formation surface (Figure 4).

To the west of SH6 the contact between the Speargrass Formation and overlying Rapaura Formation is not easy to identify, mainly because the yield of the lower Rapaura Formation lowers towards the upper Conders area. The Speargrass Formation contact was identified by Len Brown (1981) in a line of exploration bores located just west of SH6 (P28w/0292,373,426 and 548), and at P28w/0903, which is located at the western end of Conders Bend Road. These intercepts have been used as control points for guiding the identification of Speargrass Formation intercepts in this area. It has been assumed that bores to the west of SH6 will intercept the Speargrass Formation at a shallower depth than the exploration bore intercepts (17.6 to 18.6m depth). As a result of this review, some bores which were previously thought to intercept the Rapaura Formation, have been interpreted to be screened in the Speargrass Formation (e.g. P28w/3449, P28w/4723). In support of this interpretation, water levels in the Speargrass Formation tend to be higher than those in the overlying Rapaura Formation, which can be attributed to their greater induration (tightness) and stratification.

Structure contours for the top of the Speargrass Formation indicate a fairly steady slope from the coast towards the Wairau Valley. The contours reveal a valley axis, or paleo-channel, which represents post-depositional erosion into the Speargrass Surface by the Wairau River during the early Holocene (cut and fill). This valley axis feature is also evident as an incision in the structure contours of the lower Rapaura Formation (Figure 6).

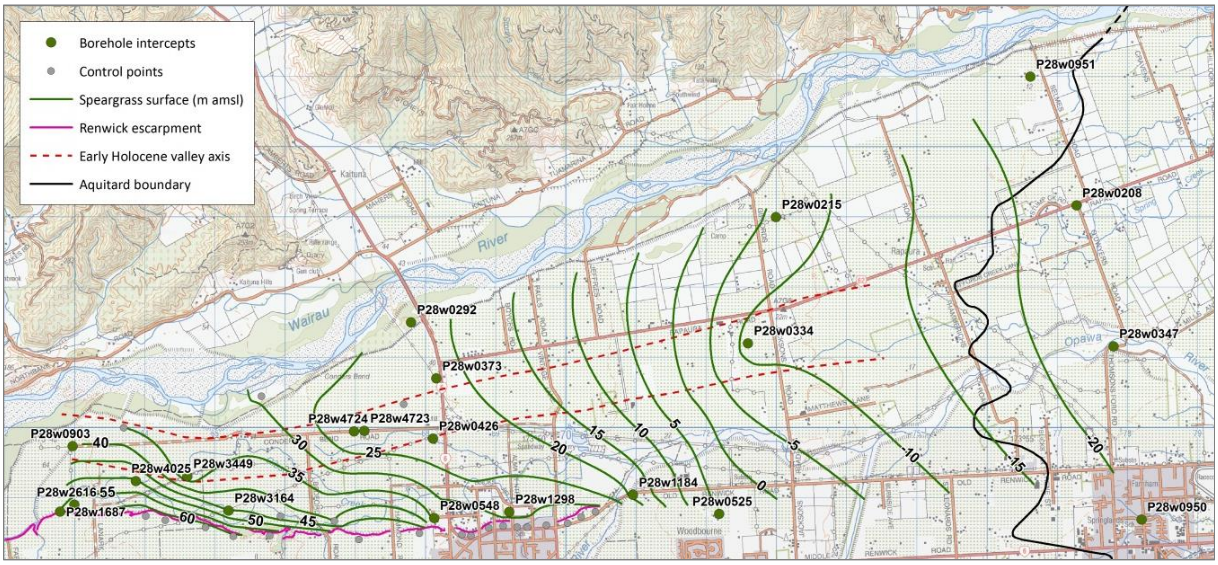

Figure 4 Map showing Speargrass Formation intercepts and structure contours

4 RAPAURA FORMATION

The Rapaura Formation was separated by Brown (1980) into an upper and lower unit on the basis of depth, lithology, permeability, and ease of drilling. The preliminary data scan and 3D visualisation both confirm the presence of system that can be generally considered as two distinct layers. These two layers will be referred to as members of the Rapaura Formation in accordance with stratigraphic nomenclature.

This section describes the two members of the Rapaura Formation that can be identified, the lower and upper members. The older, lower member appears to be relatively uniform in appearance and yield. In the upper member, more lateral variability in depositional environment is evident, and we can therefore identify different facies (lithological packages). A high-permeability facies of the upper Rapaura Formation member can be identified to the north of Rapaura Road, and a low-permeability facies is evident around the intersection of SH6 and Rapaura Road.

To the south of Rapaura Road the sediments are considerably more stratified, and a stratified facies of the upper Rapaura Formation member can be identified. Within this facies some high-yielding gravel associated with the historical Opawa channel of the Wairau River is also apparent. A map of the surface distribution different lithological packages within the Rapaura Formation is shown in Figure 5.

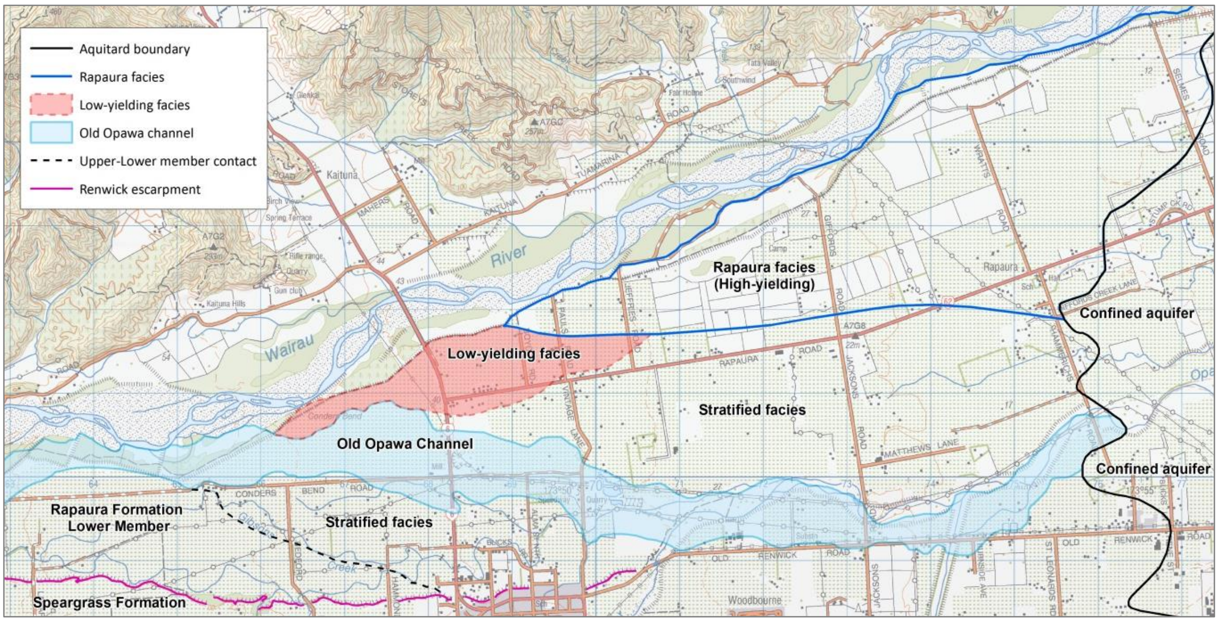

Figure 5 Surface distribution of key lithological packages in the Rapaura Formation

4.1 LOWER MEMBER

The lower member of the Rapaura Formation formed during the early Holocene when the Wairau River eroded into the Speargrass Formation and re-deposited the reworked material towards the coast. The Renwick escarpment, which extends west from Renwick to the Waihopai River valley, is evidence of this early erosional episode. Sediments which form the escarpment and upper Terrace consist of Speargrass Formation, whereas the lower Terrace north of the escarpment is comprised of Rapaura Formation (Figure 5).

The lower member of the Rapaura Formation was initially confirmed during the preliminary data scan by a large number of deeper bores that have been drilled along the western end of Rapaura Road. Boreholes in this area have tended to be drilled deeper 15m since the more shallow gravels tend to be lower-yielding. Visualisation and the identification of contacts for the top surface of the lower member confirmed that this member has lateral continuity beyond the Rapaura Road area, and can be traced from the upper Conders area into the confined aquifer.

Structure contours for the top surface of the lower member are drawn in Figure 6. The Early Holocene valley axis identified on the Speargrass Formation surface is still apparent in the upper Conders area.

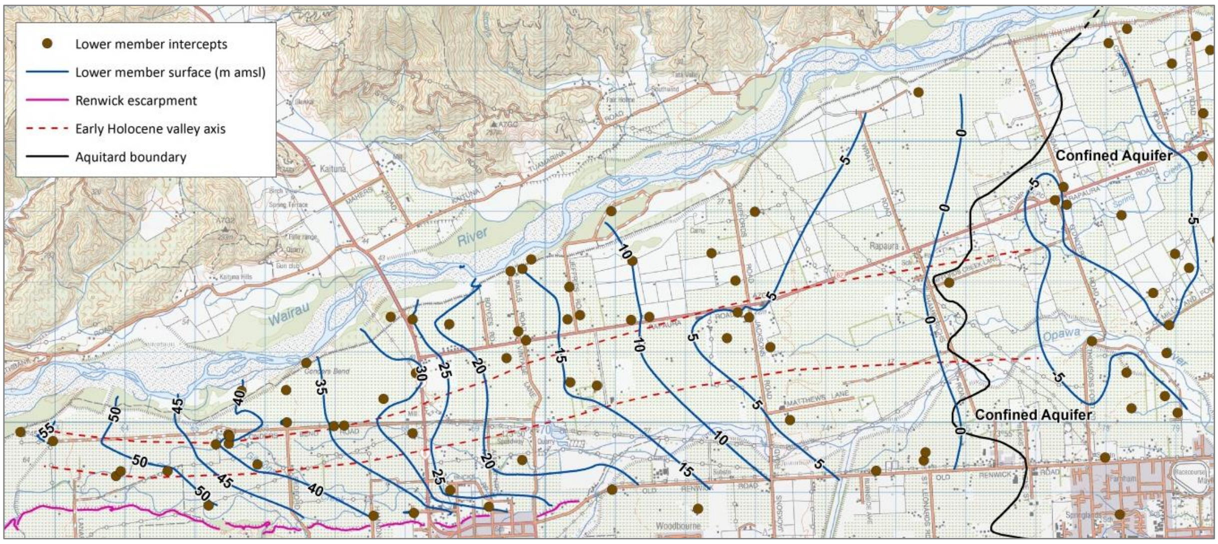

Figure 6 Intercepts and structure contours for the top of the Rapaura Fm lower member

The mean sea level structure contour coincides with the edge of the aquitard, which is represented by the presence of estuarine clay and silt deposits overlying gravels of the Lower member. The base of the aquitard, and therefore the top of the lower member, is found at around 11m to 14m depth along the aquitard boundary margin.

Structure contours for the depth to the lower member below ground level are shown in Figure 7.

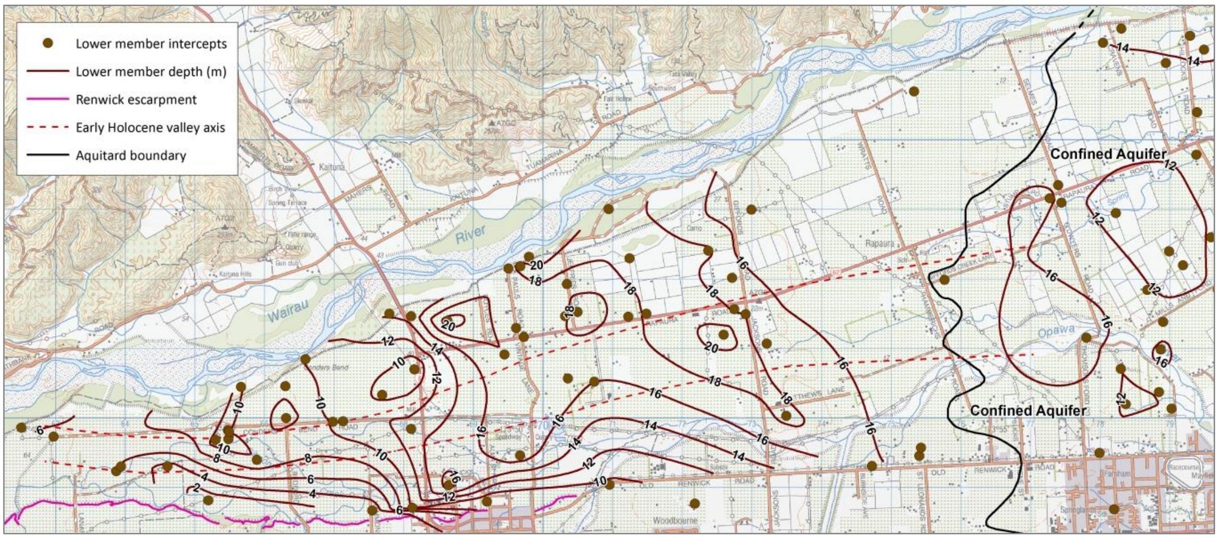

Figure 7 Intercepts and structure contours of the depth to the Rapaura Fm lower member

4.2 LOW-PERMEABILITY HORIZON

In boreholes where the upper and lower members can be distinguished on the drillers' log, a 3-9m horizon of lower permeability material is evident. This horizon is typically described as "grey coarse gravel, yellow clay-bound", sometimes with sand, and is often remarked as being poorly water bearing. Examples of bore logs in which the upper and lower members can be readily identifiable and separated by an intervening horizon are: P28w/3049, P28w/3877, and P28w/3950.

The ubiquitous presence of clay within the intervening horizon suggests that the gravels are unlikely to be clast-supported and most likely to have a clay matrix. This horizon therefore represents a prolonged period of relatively low river sediment load (not quite a depositional hiatus) combined with a low river gradient, most likely after sea level stabilisation. The reported presence of clay in this horizon suggests that deposition primarily occurred during over-bank flow events.

4.3 UPPER MEMBER

The shallow sediments of the Rapaura Formation form the present day Wairau alluvial fan. Within this fan, which forms the upper member of the Rapaura formation, four distinct lithologies can be recognised:

- **Rapaura facies**: highly permeable shallow gravels located close to the Wairau River
- **Old Opawa channel**: locally higher-yielding shallow gravels formed as over-bank channel deposits
- **Low-yielding facies**: an area of relatively low permeability material in the vicinity of Rapaura Road and SH6.
- **Stratified facies**: relatively low-yielding stratified over-bank flow and channel deposits

All of the upper member deposits are draped over the gravels of the lower member or the intervening low-permeability horizon. Some incision into the lower member has occurred at the apex of the fan, and the current river channel is approximately 4m below the level of the terrace at Lanark Lane. This means that gravels of the upper member tend to thin towards the apex of the fan. A line showing the approximate surface contact between the lower member and gravels of the lower member has been drawn on Figure 5. A thin layer of brown silt can be seen in driller's logs up-gradient of this contact. This silt is interpreted to represent over-bank deposits that have settled following flood events, and are contemporaneous with the upper member.

4.3.1 RAPAURA FACIES

The Rapaura facies of the upper member of the Rapaura Formation was identified during both the preliminary data scan and 3D visualisation phases of the review as a shallow lens of high-permeability gravels. The presence of the Rapaura facies is distinguished by clearly identifiable upper and lower layers of water-bearing gravels. In bore logs the lithology is described as "grey coarse gravels, to coarse sand". There is an absence of clay in most bore logs, although this varies between drillers. It is not known if the gravels are clast or matrix supported. Examples of bore logs where both the shallow Rapaura facies and lower member can be distinguished are P28w/0951, P28w/3882, and P28w/3950.

The Figure 8 shows the structure contours for the base of the Rapaura facies and its approximate spatial distribution. The structure contours west of Gifford Road dip to the northeast, indicating that the position of the river channel has progressively moved northwards over time to its present day location. Some incision and reworking of gravel by the river may have also occurred to the west of Giffords Road. To the east of Giffords Road, the contours change shape and strike in a northerly direction, indicating aggradation (deposition) at the fan terminus up-gradient of the aquitard boundary.

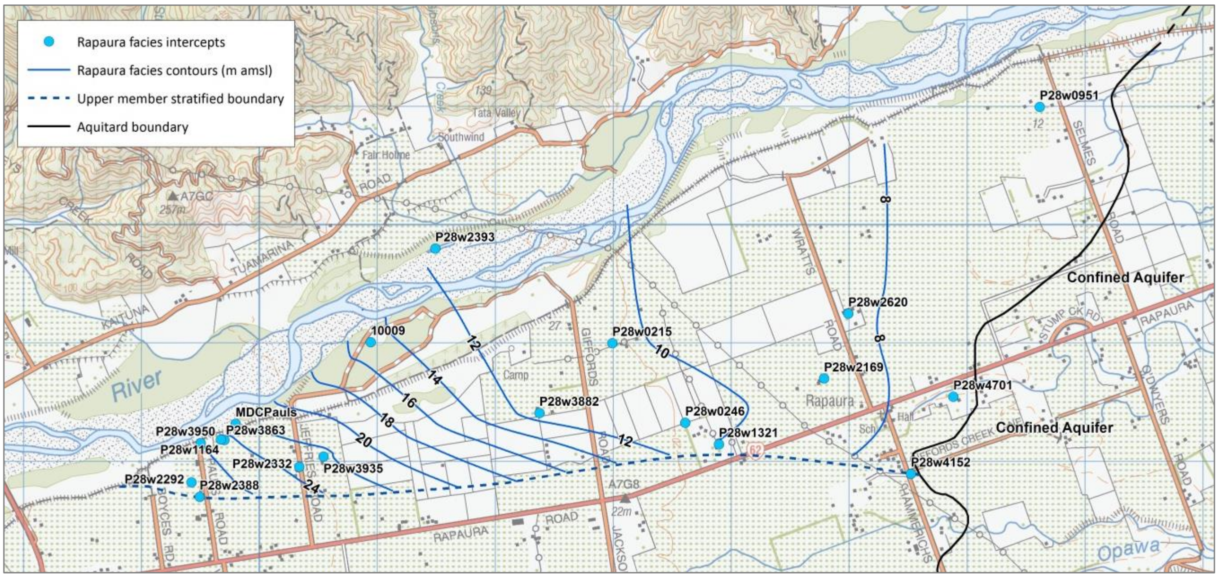

Figure 8 Structure contours for the base of the Rapaura facies of the upper Rapaura Formation

The shallow Rapaura Formation gravels situated to the south and west of the Rapaura facies have a relatively low permeability. The spatial distribution of the Rapaura facies is interpreted to represent the reach of river over which the rate of recharge to the Wairau Aquifer is greatest (see Wilson & Wöhling, 2015). This is a 6km reach of river between Boyces Road and Wratts Road. River losses are expected to peak across the initial 3km of this reach since the Rapaura facies begins to thin to east of Giffords Road.

Figure 9 shows the thickness of the Rapaura facies, which is thickest near the river between Jeffries and Giffords roads, and showing a gradual thinning from Gifford road eastwards towards the aquitard. The Rapaura facies gravels thin rapidly southwards towards Rapaura Road. This rapid thinning, combined with a relatively high permeability, suggests that the Rapaura facies represent the reworking of previously deposited gravels by the river in recent times.

The distribution of the Rapaura facies gravels aligns with the headwaters of Spring Creek. It is likely that most discharge from Spring Creek is derived from groundwater that has been recharged by the river and has travelled exclusively within the Rapaura facies. The groundwater residence time is expected to be considerably more rapid in this facies compared to other parts of the aquifer. This may also manifest in distinctly different tracer chemistry due to lesser groundwater contact time with the host sediments.

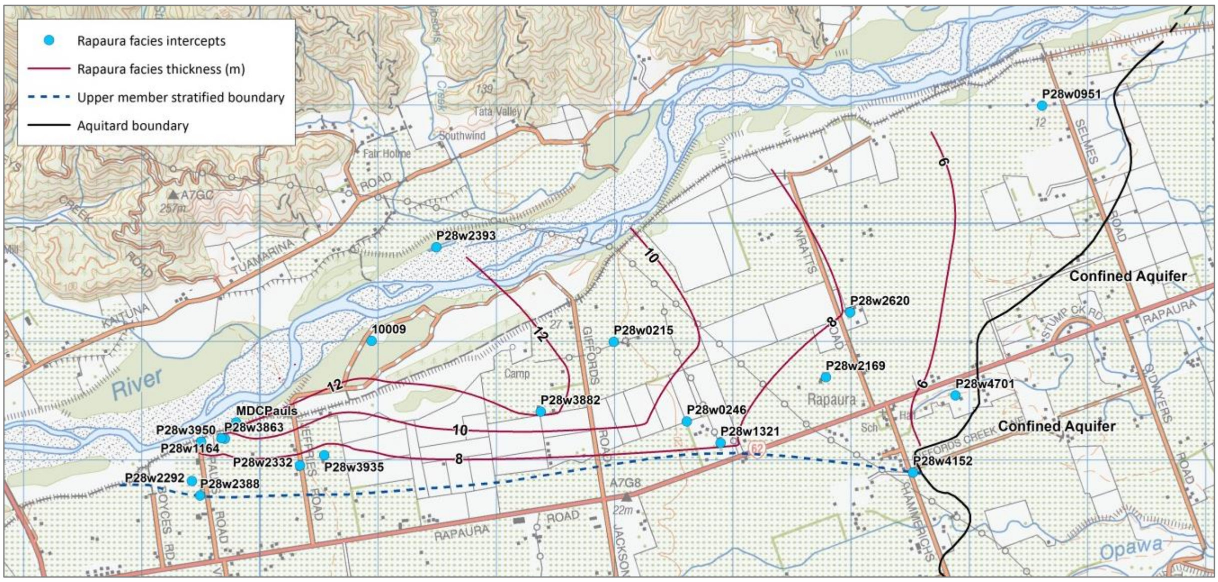

Figure 9 Thickness of the Rapaura facies of the upper Rapaura Formation

4.3.2 LOW-YIELDING FACIES

During the preliminary data scan, a shallow low-permeability zone was identified at Rapaura Road-SH6 junction. This low-yielding zone is located between the old Opawa River channel and the Rapaura facies, and its approximate distribution is shown in Figure 5.

Driller's logs in this area record that the shallow sediments consist of coarse gravels with yellow clay, often described as being 'claybound'. Some poor water-bearing gravel is normally intercepted between 9 and 12m depth. The static water level in this area is approximately 7m deep, so there is little available drawdown for pumping.

The poor yields found in this area require most bores to be drilled deeper into the lower member. Good examples of drillers' logs from this area are P28w/3838, P28w/3772, and 10224

4.3.3 STRATIFIED FACIES

The most widespread facies in the upper member of the Rapaura Formation is a stratified or interbedded sequence of alluvium. This stratified facies is characterised by its absence of consistent water-bearing gravels in wells logs. Instead, the bore logs record lenses that alternate between water-bearing or poor water-bearing shingle with sand and yellow clay; and yellow clay with shingle.

Descriptions of the higher-yielding horizons suggest they consist of clast-supported or sandy matrix-supported gravel. Both of these lithologies are representative of braided river channel fill deposits. The lower-yielding horizons in the stratified facies are likely to be clay, silt, or sand matrix-supported gravels.

The alternation between coarse and fine fractions normally represents deposition during a period when the river channel was highly mobile. This type of deposition is found in rapidly aggrading alluvial fans, which can be subject to frequent channel avulsions. An abundance of sand, silt and clay within an aggrading alluvial deposit usually signifies over-bank sheet-flow deposits, or the infilling of abandoned channels following avulsion events. The Wairau River is likely to have been the most dominant of source material for the stratified facies. However, there may also have been a significant contribution of finer material from the southern valleys rivers.

Good examples of drill logs from the stratified facies are P28w/4724 (Renwick town supply), P28w/4746, P28w/4537 and 10094. The scale of inter-bedding between poor and high yielding lenses is typically 0.5 to 2m. Water levels tend to rise with depth, which can be attributed to a decreasing storage coefficient with increasing hydraulic confinement.

4.3.4 OLD OPAWA CHANNEL

Until 1861, the Wairau River overflowed at Conders Bend during high flows and spilled into the Omaka River channel near present day Renwick. The construction of Conders Groyne between 1914 and 1926 ensured that this channel was no longer flooded by the river. The historical river channel was drawn by Brown (1981a) and this has been digitised in Figure 10 and extended westwards to the Waihopai River channel. The distribution of recent river channel gravel deposits is also evident in Landcare Research's soil mapping database, S-Map.

The old Opawa channel position manifests as a topographic low on the Wairau Plain which is evident when driving south on SH6 between Rapaura Road and Renwick. Incision into the Wairau Plain indicates that degradation has been the prevalent river process during the channel's occupancy. This is a shift from the rapid period of aggradation which has formed the adjacent slightly elevated terraces of the stratified facies.

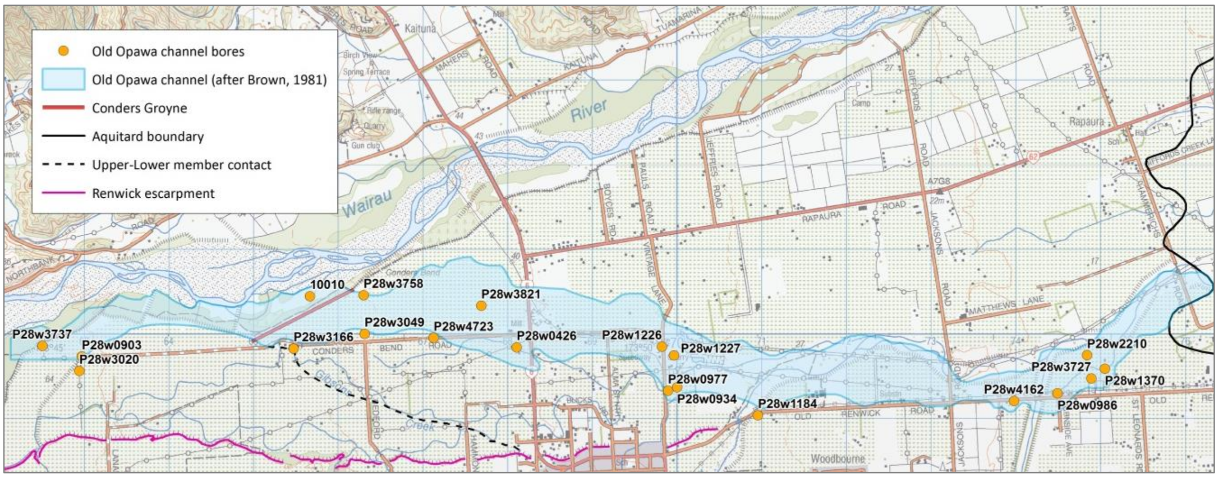

Figure 10 Map of the old Opawa channel of the Wairau River

Gravels of the old Opawa channel were described as the type section for the Rapaura Formation by Brown (1981). Photographs taken of gravel pit faces near the intersection of SH6 and Rapaura Road show that the sediments are highly stratified at a macro and micro scale. Brown (1981) records the sediments as predominantly poorly sorted gravel with rounded to sub-angular clasts up to cobble in size. Grey-brown sand dominates the matrix with minor fraction of clay and silt and rare sand lenses. The parent material is almost exclusively greywacke, indicating that the parent material has been mainly sourced from erosion in the southern hills. The presence of schist clasts would indicate the influence of sediment from the north side of the catchment.

A good example of a bore log in the old Omaka channel is the MDC monitoring bore P28w/3821. The log for this bore records shallow water-bearing gravels from 6.9 to 8.5m depth, but the sediments otherwise stratified until the water-bearing gravels are encountered at the base of the lower member.

Gravels from beneath the old Opawa channel cannot be definitively classed as a facies which is separate from the adjacent stratified alluvium. Well logs along the southern margin of the Rapaura Formation do tend to be more water-bearing at shallow depths than those located north of the Opawa channel, but the observations are not consistent.

It is most likely that some shallow reworking of gravels has occurred during the most recent degradation phase of the river. However, it is more likely that these channels are near-surface features embedded within the more ubiquitous stratified facies.

4.4 AQUIFER THICKNESS

The total thickness of the Rapaura Formation can be estimated by the difference between surface topography and the Speargrass Formation structure contours. The estimated total Rapaura Formation thickness, which constitutes the whole Wairau Aquifer, is mapped in Figure 11.

In general, the Rapaura Formation is thickest in the centre of the early Holocene valley axis located just south of Rapaura Road. Between Giffords Road and Wratts Road the Rapaura Formation is 30m thick. Between Wratts Road and Selmes Road the river has incised slightly into the aquitard, forming a maximum thickness of 35m in this area. To the South of Rapaura Road, the unit thickness doesn't reach its 35m maximum because of the presence of the Dillons Point Formation.

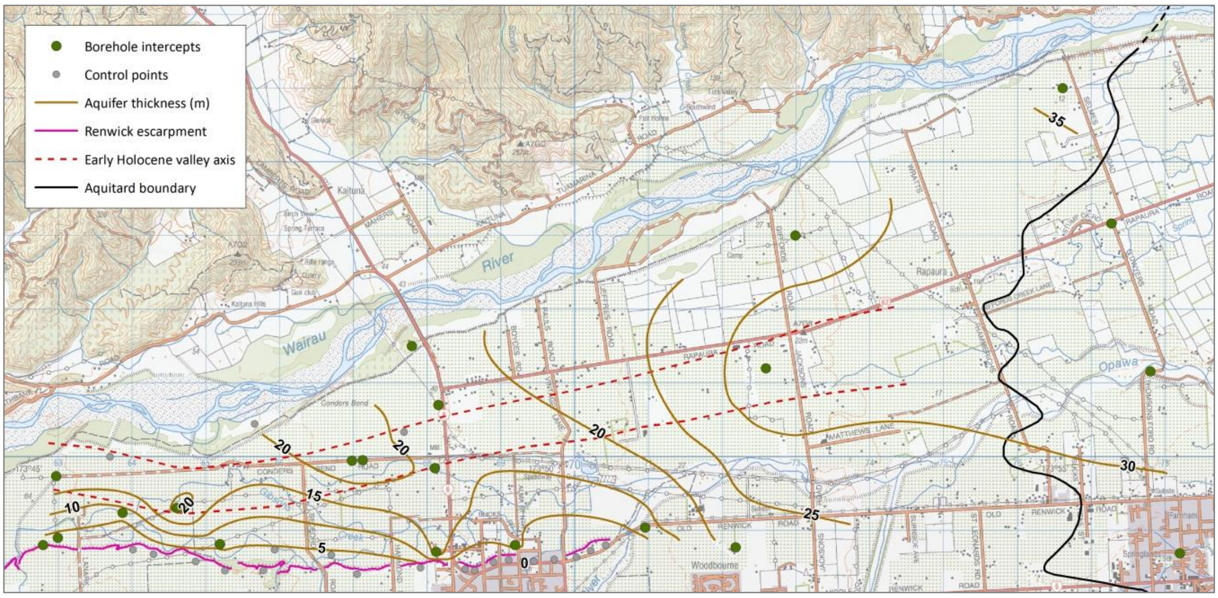

Figure 11 Total thickness of the Rapaura Formation based on Speargrass Formation intercepts

The thickness of the lower member is diffcult to gauge because the surface of the Speargrass formation is only constrained by a few intercepts. The thickness does increase eastwards from about 5m thick in the upper Conders area to reach a maximum of 30-35m between Jacksons and O'Dwyers roads near the edge of the aquitard.

A representative bore log for the central Wairau Plain is the DSIR exploration bore P28w/0334, which is shown in Table 1. This bore is interpreted to comprise 11.6m of upper member, 9.8m of intervening clay-bound material, and 13.3m of lower member before intercepting the Speargrass Formation at 34.6m depth. Note that this bore logindicates the upper member to be quite high-yielding (water-beraing) despite it being located within the stratified facies.

Another exploration bore, P28w/0208 at O'Dwyers Road is interpreted to have a lower member thickness of 15.2m. The lower member thins towards the coast from O'Dwyers Road eastwards due to the on-lapping of the marine Dillons Point Formation and associated estuarine sediments. The Lower member is interpreted to be 7.6m thick in MDC monitoring bore P28w/1733 at the coastline.

Table 1 Drillers' log for exploration bore P28w/0334

Top	Bottom	Thickness	Lithology	Remarks[a]	Interpretation
0.0	0.9	0.9	Brown & grey silty gravel		
0.9	6.1	5.2	Grey clean round well sorted medium gravel	GWB	Upper member
6.1	7.0	0.9	Grey clean medium & large gravel, much grey sand		
7.0	7.9	0.9	Grey clean medium well sorted gravels	GWB	
7.9	11.6	3.7	Grey clean medium & large gravel	GWB	Base upper member
11.6	12.5	0.9	Grey medium to large gravel partly clay-bound		Interveneing clay-bound
12.5	13.1	0.6	Grey small gravels & sand	WB	
13.1	21.3	8.2	Grey medium, some large gravel, partly clay-bound	PWB	Interveneing clay-bound
21.3	23.2	1.8	Grey brown stained medium gravel	GWB	Top lower member
23.2	24.1	0.9	Grey large gravel, some clay	PWB	
24.1	24.7	0.6	Grey medium, small gravel, brown stained	GWB	
24.7	26.5	1.8	Grey medium large gravel & sand	PWB	
26.5	28.0	1.5	Grey medium, small gravel, brown stained	GWB	
28.0	28.2	0.2	Grey brown stained, larger gravel, brown sand	PWB	
28.2	28.5	0.3	Yellow & grey clay-bound, medium gravel, small angular pieces		
28.5	29.3	0.8	Grey small gravel	GWB	
29.3	29.9	0.6	Grey medium to large gravel, sand, part clay-bound	PWB	
29.9	31.4	1.5	Grey small, some medium gravel, brown sand	PWB	
31.4	32.3	0.9	Grey medium & larger gravel, abundant brown sand	PWB	
32.3	32.6	0.3	Grey medium & larger gravel, abundant brown some clay-bound		
32.6	33.5	0.9	Brown stained medium & small gravel	GWB	
33.5	34.0	0.5	Grey small gravels, brown sand, some clay		
34.0	34.6	0.6	Brown stained small gravel, some medium brown sand	GWB	Base lower member
34.6	35.4	0.8	Grey small gravel, grey sand, some sticky clay		Speargrass Formation
35.4	36.3	0.9	Grey small gravel some medium, grey sand, some sticky clay		
36.3	37.8	1.5	Grey small gravel some medium, grey sand, sticky clay increasing		
37.8	39.6	1.8	Grey small gravel as above, clay decreasing, formation tightening		

a. 'GWB' = good water-bearing, 'PWB' = poor water-bearing

Profiles through the aquifer have been drawn as an alternative means for visualising the lithology. Intercepts for the upper member (Rapuara facies), lower member, and Speargrass Formation have been projected onto south-north and west-east planes in Figure 12 and Figure 13 respectively.

The west-east profile (Figure 13) shows the Speargrass Formation steadily dipping toward the coastline. The thickness of the Rapaura facies of the upper member can be seen to reach its maximum to the west of Jeffries road.

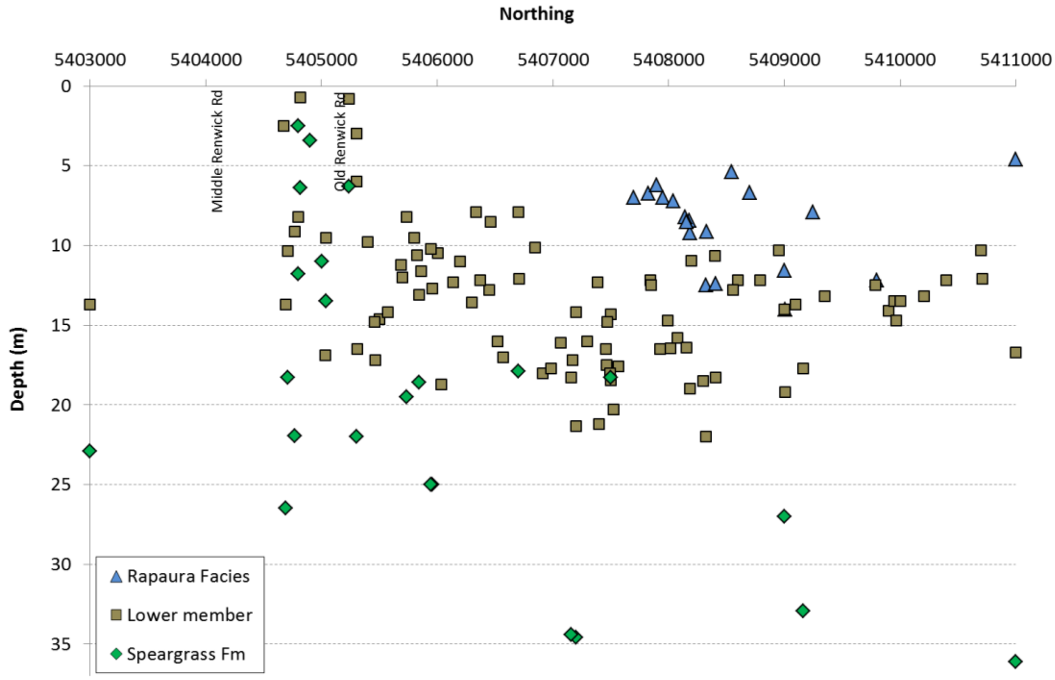

Figure 12 Plot of unit thickness vs northing

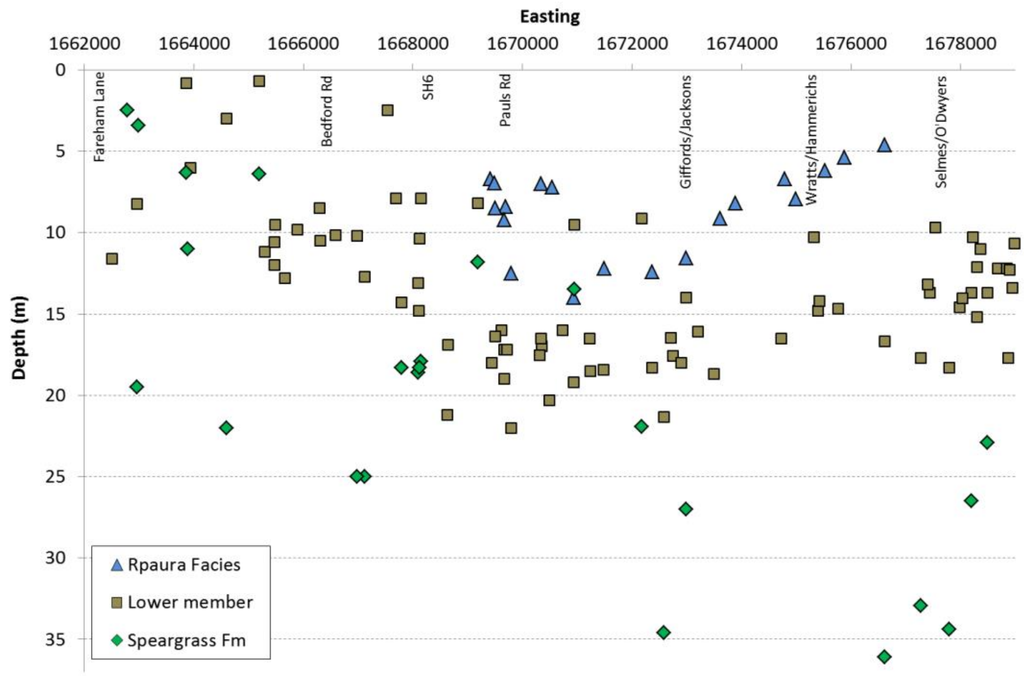

Figure 13 Plot of unit thickness vs easting

5 DEPOSITIONAL HISTORY

The stratigraphy of the Rapaura Formation represents the depositional history of the Wairau River during the Holocene. This section uses the new information gained by this review combined with work from previous authors to derive an interpretation of how the Rapaura Formation may have formed over time. The main drivers of deposition are considered to be climate, sea level, and river sediment supply or bed-load (related to vegetation).

The Wairau Valley has been formed by block rotation along the Alpine Fault, so it is expected that there will be a tectonic influence on rates of deposition. While, it is genuinely difficult to distinguish tectonic influences from other depositional drivers in a gravel setting, it is reasonable to assume that subsidence on the south side of the Alpine Fault would tend to move the river northwards towards the Richmond Range. Basher et al. (1995) consider that northwest tilting of the Wairau block has maintained the river on the northern side of the Plain since the Last Glacial. Structure contours for the top and base of the lower member of the Rapaura Formation confirm that the river channel has moved northwards during the Holocene from south of Rapaura Road to its present position.

5.1 EARLY HOLOCENE (LOWER MEMBER)

Deposition of the Speargrass Formation outwash gravels ceased at end of the Pleistocene (11.7 ka). The climate at this time was a brief period of rapid cooling with stable sea level (Lambeck et al. 2002) known as the Younger Dryas (12.9ka to 11.7ka). Conditions of rapid cooling are conducive to a reduction in sedimentations rates.

The end of the Younger Dryas period of relatively stable climate marks the onset of the Holocene period (11.7 ka). The Holocene represents the beginning of a prolonged period of warmer global temperatures, resulting in vegetation growth in the Wairau catchment and a reduced sediment load in the river. The reduction in sediment supply caused the Wairau River to eventually erode into the Speargrass Formation surface, and re-deposit the reworked material further down-gradient. This reworked gravel constitutes the lower unit of the Rapaura Formation defined by Brown (1981), which has been called the ‘lower member’ in this review.

Dating carried out in Marlborough indicates that there was delay of around 2,000 years in catchment responses to a rapid increase in temperatures after the Younger Dryas. The timing of the transition from aggradation (Speargrass Formation) to degradation (Rapaura Formation) has been constrained by radiocarbon ages of 9.85 ± 0.35 ka from the last glacial advance in the upper Wairau Valley (McCalpin, 1992), and 9.4 ± 1.6 from pebble weathering rinds (Kneupfer, 1992).

The subsequent period of incision into and reworking of the Speargrass Formation was coincident with rapidly rising sea levels (Lambeck et al., 2002). Thus, there was degradation occurring in the mid to upper part of the Wairau Fan (c.f. the Holocene valley axis), and a locus of aggradation occurring towards the coast as an alluvial fan. New structure contours for the Speargrass Formation surface indicate that incision has occurred at least as far eastward as the Jacksons-Hammerichs road area.

Long-term changes in the gradient of the Wairau River occurred during deposition of the Rapaura Formation because of changes in the relative elevation of downstream and upstream control points (Basher et al. 1995). These control points are sea level and the height of aggradation terraces respectively. Because of the rise in sea level and progressive flattening of the outwash surface over time, the Rapaura gravels were deposited in a sequential manner from east (gravels of the confined aquifer) to west (unconfined gravels). The position of the alluvial fan toe would have therefore migrated inland in response to sea level rise and marine transgression over this period.

The lower member of the Rapaura Formation is interpreted to have formed over a ~3,000 year period, starting around 9.85ka to 9.4ka, and ending when sea level stabilised around 6.5ka. If we assume the maximum thickness of the lower member to be 15m, we can calculate a deposition rate of around 5-6 mm per year. This is slightly lower than the rate of deposition that can be estimated at the coast. The contact between the lower member of the Rapaura Formation and the overlying marine Dillons Point formation in MDC bore P28w/1733 has been constrained by carbon dating as 8.75 ± 0.3 ka (Ota et al, 1995). We can calculate that the 7.6m thick gravel at the coast in P28w/1733 was deposited over a period of 650 to 1,100 years at a rate of 7-11mm per year.

5.2 MID HOLOCENE (LOW-PERMEABILITY HORIZON)

Sea level reached its present-day level around 6.5ka following the stabilisation of global temperatures. The rising and stabilisation of sea level would have lowered the gradient of the river, thereby reducing its bed-load capacity. At the same time, the catchment had become equilibrated to stable external conditions such as temperature and vegetation.

It is most likely that the 3-9m of poor water-bearing, clay-rich sediments found between the upper and lower members were deposited during this period of stability as over-bank flow deposits. This would have occurred from around 7ka onwards, although the timing of the transition to deposition of the upper member has not been confirmed. Clay-rich soils found to the east of SH1 have been ^{14}C dated at 1.7 to 2.5 ka (Basher et al. 1995), which may represent the timing of this transition. This would constrain the deposition rate of the low permeability horizon to 0.6 to 2 mm/year.

5.3 LATE HOLOCENE (UPPER MEMBER)

The upper member of the Rapaura Formation (up to 14m thick) was deposited as a predominantly aggradation surface (Brown, 1981). Minor degradation would have continued to occur near the apex of the fan towards the Waihopai confluence. This is evident as a 4m elevation difference between the terrace and river channel at Larnarks Lane.

If we assume that deposition of the upper member of the Rapaura Formation commenced around 6.5 ka, then the rate of deposition would have been extremely slow (around 2mm/year). It is most likely that the rate of deposition of the lower member commenced after 1.7 to 2.5 ka, and accelerated in recent times.

Evidence for accelerated aggradation is the presence of buried former forests which were identified and ^{14}C dated by Brown (1980). A Kahikatea sample from the Rapaura Formation in P28w/0208 at

10.5m depth was dated at less than 200 years. Another sample in P28w/0714, taken from buried totara at 9m below the former Fairhall Swamp was dated at 240 ± 60 years. These ages are taken from sample depths that represent most of the upper member thickness. They both indicate extremely rapid deposition rates of 40 to 50mm per year during the last 250 years.

Since climate and sea level conditions have been very stable over the last 6,500 years, rapid increase in deposition rates could only be triggered by tectonic activity, and/or a change in vegetation. One hypothesis is that erosion was accelerated by burning of forest on the southern hills after the arrival of humans in the Wairau Valley. The buried forest ages predate European exploration and settlement in the valley. Maori settlement at Wairau bar has been carbon dated by Higham et al. (1999) to be 1288-1300 AD. It is feasible that burning of forest on the dry southern hills occurred at some stage over the last 700 years, resulting in rapid hillside erosion and sediment input to the Wairau fan.

6 HYDRAULIC PROPERTIES

6.1 SPECIFIC CAPACITY

The best dataset to assess aquifer productivity is the specific capacity data recorded on drillers' logs. These values are routinely obtained by pumping the developed bore at a constant rate, normally for two hours, and measuring the drawdown. Specific capacity is normally expressed on the drillers' log in $m^3/h/m$.

Data from the MDC database are plotted against the top of the bore screen in (Figure 14). The data have been grouped into their lithologies based on their bore logs.

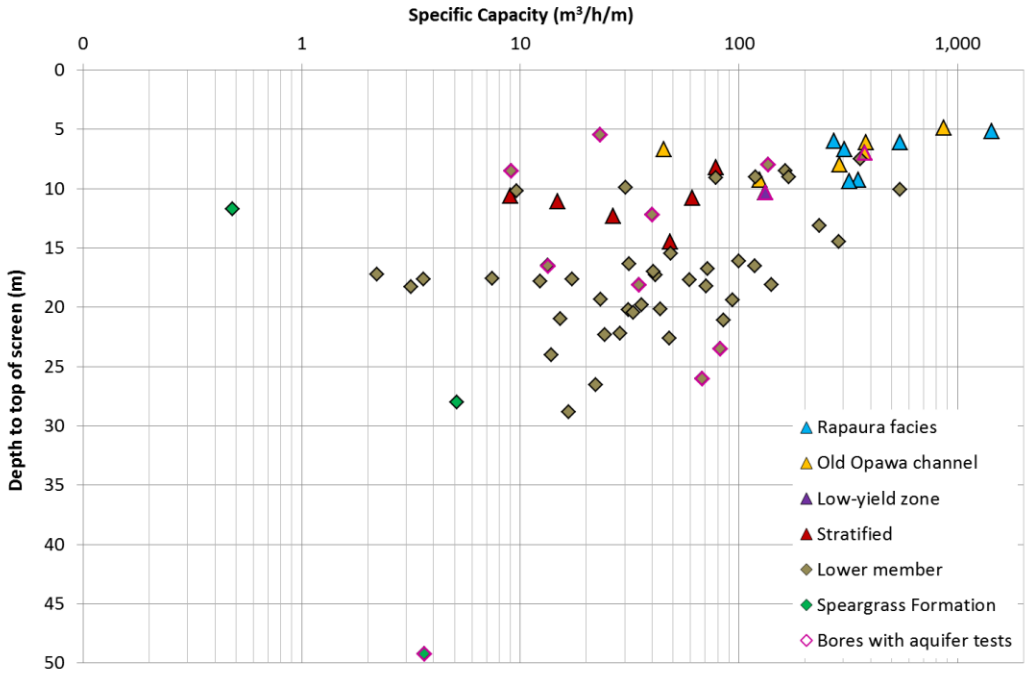

Figure 14 Relationship between screen depth and specific capacity for different lithologies

The data show a general trend of decreasing specific capacity with depth. The upper member of the Rapaura Formation tends to provide higher specific capacity results than the deeper layer. The exception is for bores screened within the highly stratified and low-yielding areas of the upper facies, which have specific capacities comparable to the lower member.

In the lower Rapaura Formation, bore screens to the north of Rapaura Road are set at around 15m depth. Bore screens in the stratified, southern part of the aquifer are set at depths of 20m or more. Some exceptions of shallower screens do occur in areas where the bores are located closer to the Speargrass Formation contact, up-gradient of Bedford Road and along Old Renwick Road.

The specific capacity data indicates a general decline in specific capacity with depth. This may be due to an increase in finer material in the aquifer with depth and/or a decrease in the storage coefficient with depth. Because the aquifer is known to be highly anisotropic due to imbrication and stratification (Wilson and Wöhling 2015), it is interpreted that the decrease in specific capacity is mostly due a reduction in the storage coefficient with depth. This manifests in specific capacity data because the tests are only run for about two hours, and the early drawdown response of a pumped bore is primarily controlled by the aquifer storage coefficient.

Low specific capacity values in the lower member in the Jeffries-Pauls Road area could be due to lower hydraulic conductivity in this area, or a lower storage coefficient imparted by stratification and/or overburden. The latter is the most likely case since the overlying upper member sediments are thickest in the area between Pauls Road and Giffords Road (8-12m). By contrast the area of higher specific capacity values found in the Wratts Road area is associated with an area of thinner sediments in the upper member (5-8m).

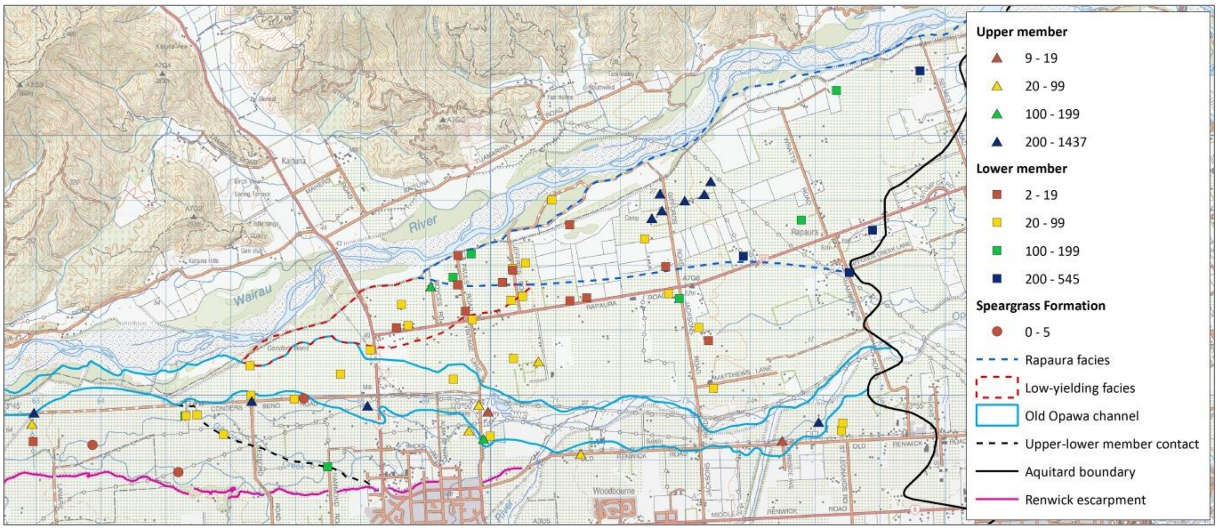

Figure 15 Specific capacity values obtained from drillers' drawdown tests

6.2 TRANSMISSIVITY

There are less transmissivity data available for the Wairau Aquifer than specific capacity values. Transmissivity values for the unconfined Wairau Aquifer obtained from the MDC database are listed in Table 2. One bore has been interpreted to be screened in Speargrass Formation.

Table 2 Summary of transmissivity values from aquifer tests unconfined Wairau Aquifer

Source	Pumped Bore	Easting	Northing	Depth (m)	Screen Top (m)	Specific Capacity ($m^3/d/m$)	Transmissivity (m^2/d)
Upper	P28w0903	1662970	5405735	21.64	4.88	20,786	13,023
Member	P28w1113	1671390	5405100	14.3	8.2	1,877	2,374
	P28w1188	1669081	5407680	14.6	10.3	3,160	3,765
	P28w3020	1662939	5405564	10.2	6.7	1,086	575
	P28w3044	1666323	5405916	13	7	9,000	6,000
Lower	P28w0373	1668151	5406700	29.3	12.2	960	2,369
Member	P28w0934	1669996	5405372	13	5.46	556	5,694
	P28w0999	1667491	5404901	16.5	8	3,269	8,000
	P28w1684	1669425	5406249	21.2	18.1	835	2,711
	P28w3758	1666296	5406461	29.5	23.5	1,966	4,600
	P28w4163	1662959	5405289	14.5	8.5	217	460
	P28w4537	1665313	5405688	29.8	26	1,628	10,250
	P28w4867	1671219	5408627.5	19.2	16.5	321	1,200
Speargrass	P28w4025	1663869	5405238	52.7	49.2	87	98
North Bank	P28w2061	1670190	5409599	15.5	11.5	1,195	5,000
	P28w3792	1668662	5409049	24.1	20.5	188	670
	P28w4059	1669681	5409384	20	8.7	304	4,400

The relationship between transmissivity and specific capacity is plotted in Figure 16. Transmissivity values typically exceed 1,000 m^2/day in both the upper and lower members, but not in all cases. Lower values of transmissivity have been recorded in bores associated with anomalously low specific capacity values. One transmissivity value, P28w/4537, is anomalously high (10,250 m^2/d) and may be influenced by stream depletion although the screen is set from 26m depth.

The corresponding trends in Figure 16 could be used to estimate transmissivity values from specific capacity if the screened lithology is known, although the sample dataset is rather small.

Figure 16 shows that specific capacity values for the upper member are consistently greater than those of the lower member. Variation in transmissivity is less clearly evident between the two datasets. The resulting trend slope (exponent) for the upper and lower member data is almost identical, the offset being explained by specific capacity, and hence the difference in storage coefficient of the two members. Based on distinctive difference between the trends for the upper and lower members, it is likely that the tests carried out on the north bank are from boreholes screened within the lower member.

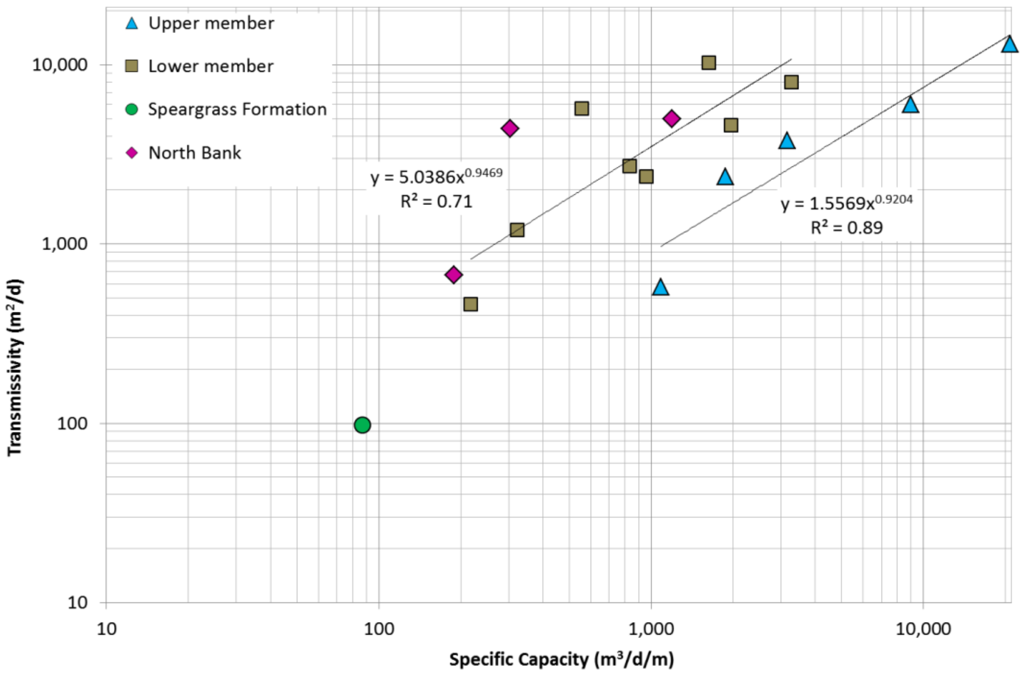

Figure 16 Relationship between transmissivity and specific capacity values

The spatial distribution of transmissivity values is mapped in Figure 17. There does not appear to be any clear pattern to the distribution of transmissivities, and high and low values can occur in close proximity to each other within the same lithological body. To some extent this variability is also evident in the specific capacity distribution (Figure 15), although there is sufficient consistency evident in that dataset to enable the identification of higher and lower yielding zones. Based on the trends seen in Figure 16, zones of higher and lower transmissivity should also be present within the aquifer, although there is insufficient aquifer test data to confirm this.

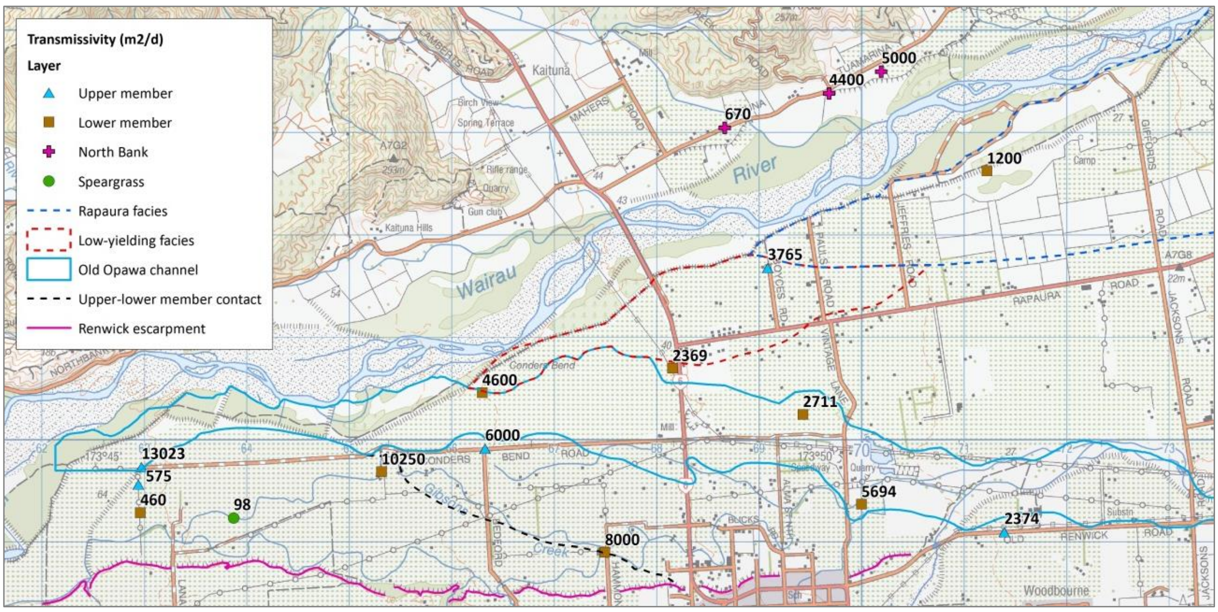

Figure 17 Transmissivity values obtained from aquifer test reports

7 INTERPRETAIONS

7.1 WAIRAU RIVER RECHARGE

The review of the stratigraphy has given a new appreciation of the near-surface distribution of different lithologies. The near-surface geology enables an estimation to be made of locations where the Wairau River will preferentially recharge the Wairau Aquifer.

The Wairau River is thought to be hydraulically perched above the river for most of its journey across the Wairau Plain (Wilson & Wöhling, 2015). The reason for this disconnection is the hydraulic anisotropy inherent in the aquifer host sediments caused by stratification and imbrication. Despite this anisotropy, areas of overall higher permeability are expected to leak at a higher rate than those of lesser permeability.

Three main areas of recharge can be identified based on the new stratigraphic distribution, which are mapped in Figure 18:

1. *Rock Ferry*. Recharge to the lower member along a 3km reach of the Wairau River downstream of Rock Ferry. The upper surface of the lower member is very close to ground level in this area. The upper ~5m of drillers logs between Rock Ferry and Conders Bend shows that a relatively low permeability horizon of over-bank flow deposits mantles the Lower Member terrace surface (e.g. P28w/3737). However, the Wairau River has incised into the lower member terrace surface by up to 4m elevation in the upper Conders area. This means that the river bed has the potential to be in direct contact with gravels of the lower member.
2. *The Old Opawa channel.* Recent channel gravels of the Wairau River are connected to the Old Opawa River channel. This channel was blocked in 1914-1924 by the Conders Groyne in an effort to stop the Wairau River from flooding the Wairau Plain.
3. *Rapaura facies.* The upper member is highly permeable downstream of Boyces Road. River recharge to the aquifer is expected to peak over a 3-4km reach downstream of Boyces Road, an area which coincides with the thickening of the Rapaura facies.

An area of river where very little groundwater recharge is expected to occur extends from Conders Bend to Boyces Road. This area is where the low-yielding near-surface deposits occur, which extend to a depth of around 10m. MDC monitoring bore 10485 was drilled adjacent to the river in this area, and was screened in water-bearing gravels of the upper member beneath the overlying low-permeability sediments.

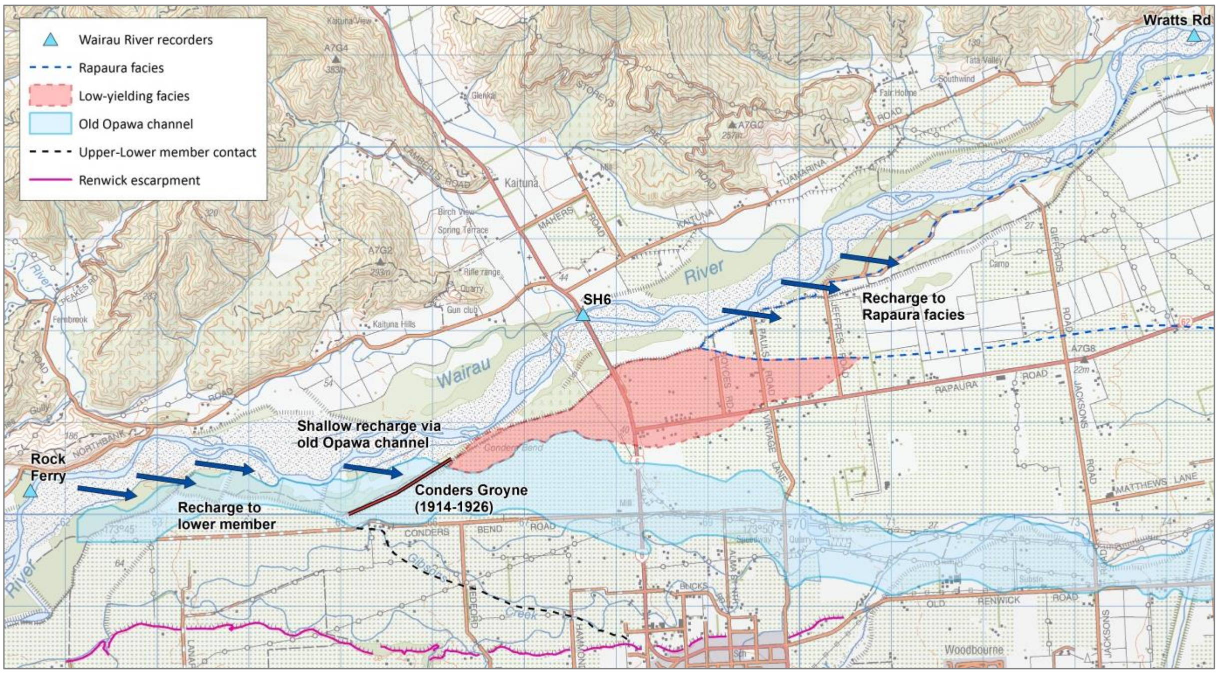

Figure 18 Map showing areas where preferential river recharge to the aquifer is likely to occur

7.2 MDC MONITORING BORES

Table 3 lists the MDC groundwater monitoring sites, and their positions are mapped on Figure 19. The water levels sites are monitored continuously and the quality sites are sampled quarterly. The water quality sites cover the whole range of lithologies apart from the low-yielding area which is only monitored for water level at 10485. Water temperatures within this bore are very slow at responding to changes in river temperature, which supports the concept of a low-permeability horizon restricting aquifer recharge in this area.

Table 3 MDC monitoring bores and their intercepted source lithologies

Bore number	Site name	Screen Top	Screen Base	Specific Cap (m3/h/m)	Interpreted unit	Lithology Top	Lithology Base	Bore purpose
P28w/0398	Conders shallow	5.6	9.7	36.1	U. member (Opawa channel)	6.2	10.9	Quality
Pauls shallow	Pauls Rd shallow	8.8	9.9	60.0	U. member (Rapaura facies)	3.4	12.4	Level
P28w/3009	Wratts	5.0	6.0	-	U. member (Rapaura facies)	5.2	-	Level & Quality
10485	Conders recharge	10.1	13.1	-	U. member (low-yield)	10.1	-	Level
Pauls Deep	Pauls Rd Deep	24.3	25.3	18.7	Lower member	22	25.3	Level
P28w/3821	Conders deep	20.2	21.6	31.2	Lower member	15.1	21.7	Level
P28w/0548	MDC Renwick	11.6	13.4	22.5	Lower member	10.4	18.3	Quality
P28w/1652	MDC Renwick	12.0	15.0	65.8	Lower member	12.2	-	Quality
P28w/2333	MDC Renwick	14.0	18.0	31.8	Lower member	12.8	-	Quality
P28w/4577	Selmes	14.0	15.0	162.2	Lower member (confined)	5.8	-	Level
P28w/4404	Mills & Ford	15.0	-	-	Lower member (confined)	-	-	Quality
P28w/2651	Upper Conders	12.1	14.1	13.0	Speargrass Formation?	11	-	Quality

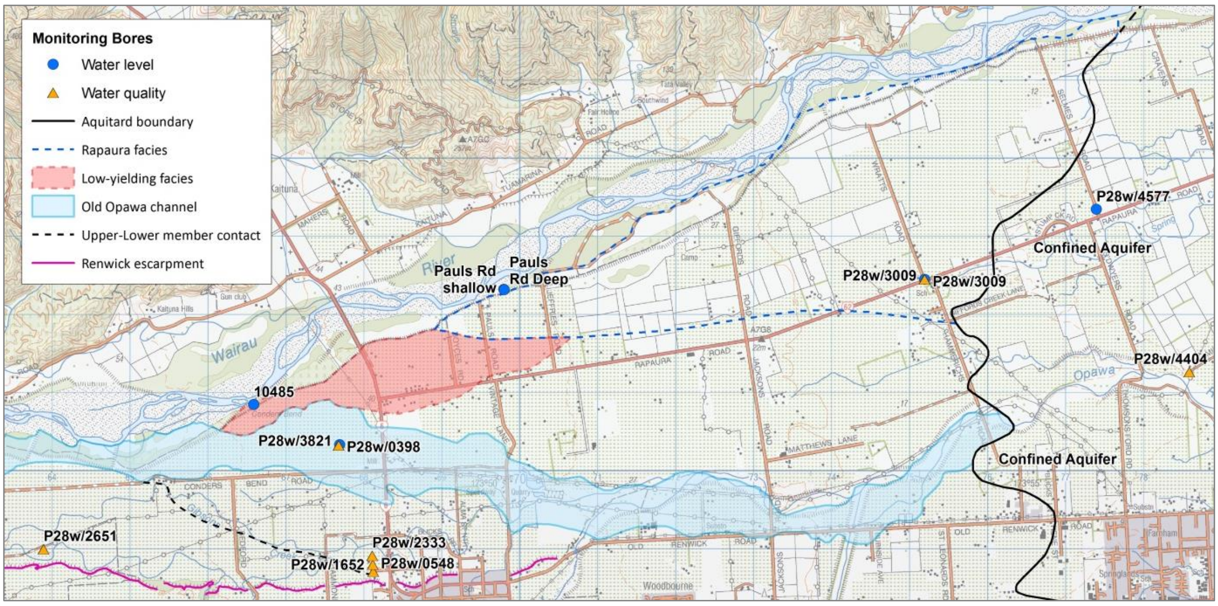

Figure 19 Map showing the location of MDC monitoring sites in relation to lithologies

8 CONCLUSION

A review of the Rapaura Formation lithology has confirmed that the Wairau Aquifer consists of two main productive horizons. The lower member is typically 9.5 ± 5m thick, and the upper member typically 8 ± 3m thick. Well yields in the upper member tend to be highest to the north of Rapaura Road. Outside of this area the shallow aquifer is more stratified and tends to be lower yielding and less predictable as a groundwater supply. Many bores in this highly stratified part of the aquifer are drilled deeper to access the lower member. Preferential flow is expected to occur in the old Opawa River channel gravels which are incised into the stratified upper member deposits.

Transmissivity values typically exceed 2,000 m^2/day in both the upper and lower Wairau Aquifer. The upper member does appear to be slightly more transmissive, although there is very little aquifer test dataset available. It is recommended that more testing be carried out in the Wairau Aquifer to collect additional transmissivity data.

Anomalously low specific capacity values have been observed in both the upper and lower members. These values are interpreted to be symptomatic of locally reduced storage coefficients resulting from low vertical hydraulic conductivity values. This type of hydraulic anisotropy is caused during deposition due to sediment stratification and/or clast imbrication (see Wilson & Wöhling, 2015).

The stratigraphy review identifies three areas where Wairau River recharge to the Wairau Aquifer may preferentially occur. The first of these is the 3km reach of river downstream of Rock Ferry. The lower member of the Rapaura Formation is very close to the surface in the upper Conders area, which allows deep Wairau Aquifer recharge to occur directly.

The second is via shallow gravels associated with the old Opawa River channel just upstream of above Conders Bend. These gravels are mapped by Brown (1981), and are also evident on soil maps.

The third area of preferential recharge is a 3-4 km stretch of river below Boyces Road. In this area the river traverses a thickening section of the Rapaura facies of the upper member of the Rapaura Formation. This is thought to be the most transmissive part of the Wairau Aquifer, and forms a rapid groundwater flow pathway between the Wairau River and Spring Creek.

REFERENCES

Basher, L.R., Lynn, I.H., Whitehouse, I.E., 1995. *Geomorphology of the Wairau Plains: implications for floodplain management planning*. Landcare Research Science Series No. 11, Manaaki Whenua Press, Lincoln, 42p.

Brown, L.J., 1981. Late Quaternary Geology of the Wairau Plain, Marlborough, New Zealand. *New Zealand Journal of Geology and Geophysics 24*, 477-490.

Brown, L.J. 1981a. *Water Well Data Northern Marlborough New Zealand*. Geological Survey, Department of Scientific and Industrial Research, Report N.Z.G.S. 93.

Davidson, P. & Wilson, S., 2011. *Groundwaters of Marlborough*. Marlborough District Council, 302p.

Eden, D.N., 1989. River terraces and their loessal cover beds, Awatere River Valley, South Island, New Zealand. *New Zealand Journal of Geology and Geophysics 32*: 487-497.

Higham, T., Anderson, A., Jacomb, C., 1999. Dating the first New Zealanders: the chronology of Wairau Bar. *Antiquity 73*: 420-427.

Knuepfer, P.L.K., 1992. Temporal variations in latest Quaternary slip across the Australian-Pacific plate boundary, north-eastern South Island, New Zealand. *Tectonics 11*: 449–464.

Laffan, M.D., Vincent, K.W., 1990. Soils of the Blenheim-Renwick district. In: Rae, S.N., Tozer, C.G. (eds), *Water and soil resources of the Wairau. Vol. 3: Land and soil resources*. Nelson-Marlborough Regional Council, Blenheim, pp. 77-93.

Lambeck, K., Yokoyama, Y., Purcell, T., 2002. Into and out of the Last Glacial Maximum: Sea-level change during oxygen isotope stages 3 and 2. *Quaternary Science Reviews 21*: 343–360.

Mason, D.P.M., Little, T.A., Van Dissen, R.J., 2006. Rates of active faulting during late Quaternary fluvial terrace formation at Saxton River, Awatere fault, New Zealand. *Geological Society of America Bulletin 118*: 1431-1446.

McCalpin, J.P., 1992. Glacial geology of the upper Wairau Valley, Marlborough, New Zealand. *New Zealand Journal of Geology and Geophysics 35*: 211-222.

Pattle Delamore Partners, 2001. *Assessment of effects of proposed abstractions at upper Conders Bend*. Report prepared for Montana Wines Ltd Delegat's Wine Estate.

Pattle Delamore Partners, 2009. *Oyster Bay pump test*. Letter to Steve Wilkes, APL Resource Management dated 11 Dec 2009.

Pattle Delamore Partners, 2014. *Assessment of potential drawdown interference effects due to pumping from the Matua Block bore P28w/4867*. Report prepared for Marlborough District Council.

Suggate, R.P., 1965. Late Pleistocene geology of the northern part of the South Island, New Zealand. *New Zealand Geological Survey Bulletin 77*: 91p.

Wilson, S., Wöhling, T., 2015. *Wairau River-Wairau Aquifer Interaction*. Envirolink Report 1514-MLDC96.

APPENDICES

Rapaura Formation Intercepts (upper member)

Rapaura facies base:

Bore number	Easting	Northing	Land surface (m amsl)	Intercept depth (m)	Intercept (m amsl)
10009	1670942	5409007	28.69	14.00	14.69
MDCPauls	1669796	5408321	34.30	12.50	21.80
P28w0215	1672990	5408999	21.79	11.58	10.21
P28w0246	1673608	5408326	19.80	9.14	10.66
P28w0951	1676613	5410997	11.40	4.61	6.79
P28w1164	1669700	5408180	33.48	8.42	25.06
P28w1321	1673893	5408143	18.14	8.20	9.94
P28w2169	1674784	5408699	16.46	6.70	9.76
P28w2292	1669421	5407821	34.58	6.71	27.87
P28w2332	1670336	5407953	30.46	7.01	23.45
P28w2388	1669490	5407700	34.59	6.98	27.61
P28w2393	1671490	5409799	23.68	12.19	11.49
P28w2620	1674989	5409249	16.28	7.92	8.36
P28w3863	1669671	5408183	33.66	9.20	24.46
P28w3882	1672372	5408408	23.37	12.40	10.97
P28w3935	1670540	5408039	29.79	7.20	22.59
P28w3950	1669499	5408154	34.68	8.50	26.18
P28w4152	1675522	5407893	13.12	6.20	6.92
P28w4701	1675882	5408545	12.12	5.40	6.72

Old Opawa channel base:

Bore number	Easting	Northing	Land surface (m amsl)	Intercept depth (m)	Intercept (m amsl)
10010	1665661	5406448	49.83	8.50	41.3
P28w0426	1668104	5405844	40.05	10.37	29.7
P28w0903	1662970	5405735	60.16	8.23	51.9
P28w0934	1669996	5405372	32.88	12	20.9
P28w0977	1669890	5405330	33.22	11.5	21.7
P28w0986	1674489	5405300	19.19	11.5	7.7
P28w1184	1670953	5405040	32.07	6.80	25.3
P28w1226	1669818	5405853	34.04	12.2	21.8
P28w1227	1669962	5405749	32.92	12.4	20.5
P28w1370	1675050	5405590	17.03	12	5.0
P28w2210	1674839	5405750	16.91	12.8	4.1
P28w3049	1666309	5406003	47.09	6.00	41.1
P28w3166	1665471	5405828	50.69	5.90	44.8
P28w3727	1674890	5405476	18.14	10.5	7.6
P28w3737	1662505	5405862	62.35	11.60	50.75
P28w3758	1666296	5406460	47.18	8.00	39.2
P28w3821	1667687	5406335	40.17	7.00	33.2
P28w4162	1673975	5405209	20.55	12	8.6
P28w4723	1667124	5405955	44.26	10.60	33.7

Rapaura Formation Intercepts (lower member)

Bore number	Easting	Northing	Land surface (m amsl)	Intercept depth (m)	Intercept (m amsl)
10004	1680567	5411287	4.1	15.4	-11.3
10009	1670942	5409007	28.7	19.2	9.5
10010	1665661	5406448	49.8	12.8	37.0
10043	1677440	5409099	10.0	13.7	-3.8
10094	1668639	5405035	38.3	16.9	21.4
10099	1675323	5410698	14.4	10.3	4.1
10122	1670493	5407525	31.7	20.3	11.4
10161	1671482	5407502	26.8	18.4	8.4
10226	1680298	5410207	5.5	13.2	-7.7
10426	1672711	5408016	23.5	16.5	7.0
10469	1674722	5405311	18.1	16.5	1.6
10485	1666584	5406847	46.3	10.2	36.2
MDCPauls	1669796	5408321	34.3	22.0	12.3
P28w0075	1679488	5411298	5.7	14.6	-8.9
P28w0086	1678940	5411107	6.7	13.4	-6.8
P28w0123	1679388	5410398	6.3	12.2	-5.9
P28w0208	1677272	5409164	10.3	17.7	-7.4
P28w0215	1672990	5408999	20.9	14.0	6.9
P28w0224	1679888	5408789	5.2	12.2	-7.0
P28w0234	1679588	5408599	5.9	12.2	-6.3
P28w0242	1678988	5408399	6.9	10.7	-3.8
P28w0256	1679188	5408199	6.6	11.0	-4.4
P28w0275	1678675	5407843	7.6	12.2	-4.6
P28w0292	1667791	5407500	41.5	14.3	27.2
P28w0334	1672590	5407200	22.9	21.3	1.5
P28w0347	1677798	5407158	10.4	18.3	-7.9
P28w0373	1668151	5406700	39.9	7.9	32.0
P28w0426	1668104	5405844	40.1	13.1	26.9
P28w0525	1672179	5404770	26.6	9.1	17.5
P28w0548	1668120	5404711	50.8	10.4	40.4
P28w0903	1662970	5405735	60.2	8.2	51.9
P28w0949	1678488	5403000	9.1	13.7	-4.6
P28w0950	1678198	5404690	6.5	13.7	-7.2
P28w0951	1676613	5410997	11.6	16.7	-5.1
P28w1134	1679378	5409788	7.2	12.5	-5.3
P28w1184	1670953	5405040	32.1	9.5	22.6
P28w1298	1669190	5404801	36.3	8.2	28.1
P28w1422	1679788	5406299	6.4	13.6	-7.1
P28w1685	1671240	5408300	28.4	18.5	9.9
P28w1794	1679024	5406135	7.8	12.3	-4.5
P28w2064	1677988	5405500	9.2	14.6	-5.4
P28w2258	1679731	5408557	5.7	12.8	-7.1
P28w2914	1663935	5405303	57.2	6.0	51.2
P28w3028	1678039	5411398	9.0	14.0	-5.0
P28w3049	1666309	5406003	47.1	10.5	36.6
P28w3060	1678843	5406374	8.4	12.2	-3.8
P28w3128	1679288	5411498	7.0	15.8	-8.8
P28w3161	1665479	5405700	50.4	12.0	38.4
P28w3162	1665292	5405687	51.5	11.2	40.3
P28w3163	1665889	5405399	48.4	9.8	38.6
P28w3164	1665191	5404817	51.4	0.7	50.7

Bore number	Easting	Northing	Land surface (m amsl)	Intercept depth (m)	Intercept (m amsl)
P28w3166	1665471	5405828	50.7	10.6	40.1
P28w3184	1680520	5408078	3.4	15.8	-12.4
P28w3199	1665491	5405801	50.4	9.5	40.9
P28w3201	1680538	5407199	5.5	14.2	-8.7
P28w3216	1678366	5406199	9.4	11.0	-1.6
P28w3220	1671223	5407459	28.6	16.5	12.1
P28w3292	1672743	5407567	22.7	17.6	5.1
P28w3343	1678295	5406709	9.9	12.1	-2.3
P28w3356	1670736	5406523	29.7	16.0	13.7
P28w3449	1664603	5405306	54.3	3.0	51.3
P28w3572	1675764	5407990	13.7	14.7	-1.0
P28w3612	1669667	5405463	33.8	17.2	16.6
P28w3618	1678901	5407385	7.8	12.3	-4.5
P28w3725	1680105	5410712	5.7	12.1	-6.5
P28w3730	1679833	5409902	6.3	14.1	-7.9
P28w3737	1662505	5405862	62.3	11.6	50.7
P28w3758	1666296	5406460	47.2	8.5	38.7
P28w3769	1667545	5404672	42.1	2.5	39.6
P28w3820	1669445	5406914	35.0	18.0	17.0
P28w3821	1667687	5406335	40.2	7.9	32.3
P28w3838	1669612	5407296	34.6	16.0	18.6
P28w3849	1679689	5407845	5.4	12.5	-7.1
P28w3863	1669671	5408183	33.7	19.0	14.7
P28w3882	1672372	5408408	23.4	18.3	5.1
P28w3950	1669499	5408154	34.7	16.4	18.3
P28w4025	1663869	5405238	57.1	0.8	56.3
P28w4030	1680103	5411151	5.3	13.4	-8.1
P28w4031	1670353	5406569	31.8	17.0	14.8
P28w4121	1673490	5406034	21.9	18.7	3.2
P28w4131	1668626	5407399	37.5	21.2	16.3
P28w4214	1670341	5407927	31.2	16.5	14.7
P28w4401	1680343	5409946	5.7	13.5	-7.8
P28w4413	1669719	5407169	34.3	17.2	17.1
P28w4432	1668104	5407467	39.8	14.8	25.0
P28w4481	1679964	5409964	6.3	14.7	-8.4
P28w4506	1678302	5411603	8.7	15.2	-6.5
P28w4526	1678866	5406985	8.7	17.7	-9.0
P28w4575	1679706	5409999	6.3	13.5	-7.2
P28w4577	1677396	5409350	9.0	13.2	-4.2
P28w4633	1670314	5407466	31.9	17.5	14.4
P28w4653	1675401	5405458	15.7	14.8	0.9
P28w4713	1677544	5411352	10.3	9.7	0.6
P28w4723	1667124	5405955	44.3	12.7	31.6
P28w4724	1666978	5405947	44.8	10.2	34.6
P28w4728	1678223	5408950	7.4	10.3	-2.9
P28w4746	1672905	5407494	22.2	18.0	4.2
P28w4747	1673208	5407070	21.1	16.1	5.0
P28w4764	1680680	5411769	6.3	15.6	-9.3
P28w4800	1675424	5405576	16.3	14.2	2.1

Speargrass Formation intercepts

Bore number	Easting	Northing	Land surface (m amsl)	Intercept depth (m)	Intercept (m amsl)
P28w0208	1677272	5409164	10.3	32.9	-22.6
P28w0215	1672990	5408999	20.9	27.0	-6.1
P28w0292	1667791	5407500	41.5	18.3	23.2
P28w0334	1672590	5407200	22.9	34.6	-11.7
P28w0347	1677798	5407158	10.4	34.4	-24.0
P28w0373	1668151	5406700	39.9	17.9	22.02
P28w0426	1668104	5405844	40.1	18.6	21.45
P28w0525	1672179	5404770	26.6	22.0	4.7
P28w0548	1668120	5404711	50.8	18.3	32.5
P28w0903	1662970	5405735	60.2	19.5	40.7
P28w0949	1678488	5403000	9.1	22.9	-13.8
P28w0950	1678198	5404690	6.5	26.5	-20.0
P28w0951	1676613	5410997	11.6	36.1	-24.5
P28w1184	1670953	5405040	32.1	13.5	18.6
P28w1298	1669190	5404801	36.3	11.8	24.5
P28w1687	1662792	5404801	61.71	2.50	55.71
P28w2616	1662992	5404901	61.28	3.40	57.88
P28w2651	1663892	5405001	57.21	11.0	46.21
P28w3164	1665191	5404817	51.4	6.4	45.0
P28w3449	1664603	5405306	54.3	22.0	32.3
P28w4025	1663869	5405238	57.1	6.3	50.78
P28w4723	1667124	5405955	44.26	25	19.3
P28w4724	1666978	5405947	44.78	25	19.8