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Groundwater-surface water interaction in a coastal aquifer system, Wairau Plain, Marlborough, New Zealand

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Abstract

The groundwater system and spring-fed streams are key water resources of the Wairau Plain, Marlborough, New Zealand. Current pressures on these resources include an increase in groundwater extraction over time and a rise in nitrogen concentrations in shallow groundwater, due to land use. The spring-fed streams originate within the transition zone, which spans fluviatile Rapaura Formation gravel in the west and Dillons Point Formation sediments (mostly sands, silts and clays) in the east that were deposited in the Holocene marine incursion.

The hydraulic links between land and water were demonstrated by groundwater budgets and three-dimensional (3D) models of shallow sediments and static groundwater pressure (SGP), developed from observations in a large number of wells. Groundwater recharge, sourced principally from the Wairau River but also from rainfall on the Wairau Plain, enters the unconfined gravel aquifer in the west as depicted by downwards vertical SGP gradients. Most of this recharge flows to the spring-fed streams, e.g., groundwater recharge from the Wairau River (7.0 m^3/s) was similar to baseflow in the streams (7.1 m^3/s) and was much larger than groundwater outflow across the eastern boundary of the zone (0.9 m^3/s). The locations of spring-fed streams were commonly associated with: shallow Rapaura Formation gravels, i.e., within 4 m of the ground surface as calculated by a contiguous gravel surface derived from the 3D gravel lithology model; the boundaries between shallow gravel and shallow palaeochannels, which were typically in-filled by silts and clays; and upwards vertical SGP gradients that showed the potential for groundwater to flow to the ground surface.

Co-management of land and water on the Wairau Plain is required to ensure the sustainability of the water resource in the long term and this approach is relevant to similar coastal aquifer systems in New Zealand.

Keywords

Wairau Plain groundwater, three-dimensional geological models, three-dimensional static groundwater level models, spring-fed streams, coastal groundwater systems.

Introduction

Groundwater is a very important resource in the approximately 380 km^2 Wairau Plain located in the Marlborough region, South Island, New Zealand (Fig. 1). Agricultural users are almost totally reliant on groundwater, principally for vineyard irrigation, and groundwater is the sole supply for the urban population in the main towns of Blenheim and Renwick (Cunliffe, 1988; Davidson, 2001; Davidson and Wilson, 2011). The Wairau Plain groundwater system supplies flow to spring-fed streams in the Spring Creek and Blenheim urban

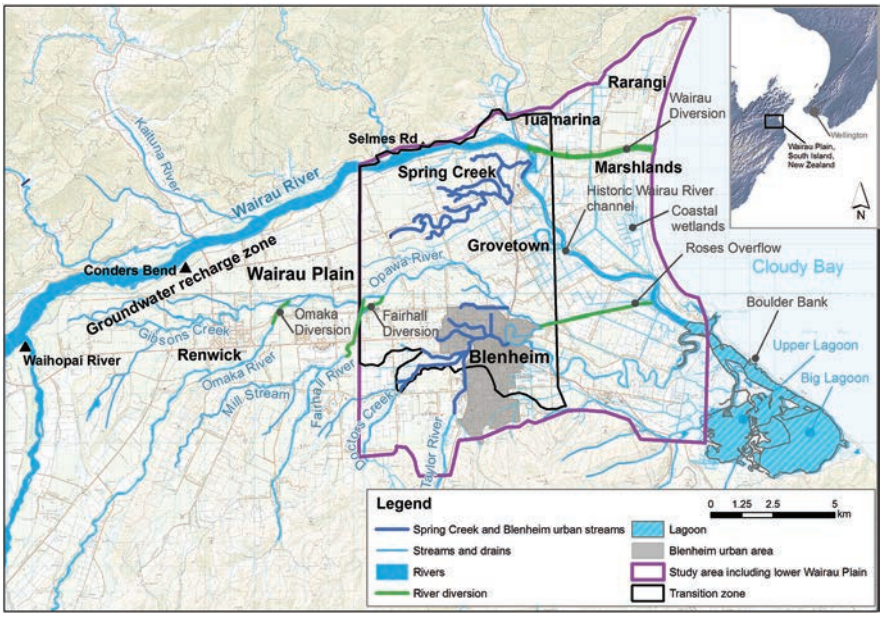


Figure 1 – The Wairau Plain, South Island, New Zealand, showing the study area and the transition zone.

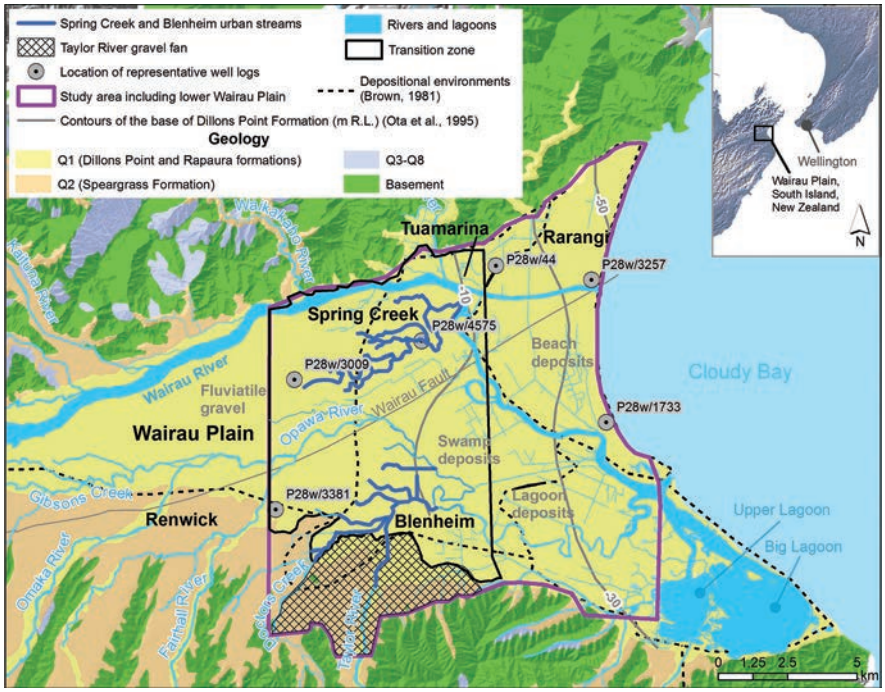


Figure 2 – Geological map of Wairau Plain and environs (after Begg and Johnston, 2000), depositional environments (after Brown, 1981) and the location of present-day rivers and lagoons. This map also shows the locations of representative well logs and contours of the base of Dillons Point Formation (after Ota *et al.*, 1995).

areas. In Blenheim, these streams are popular amenities that are widely used for recreation and are navigable in part.

Much is known about the hydrogeology of this coastal aquifer system (Davidson and Wilson, 2011). For example, surface geology in the Wairau Plain has been mapped and the general three-dimensional (3D) formation boundaries of geological units have been estimated (Brown, 1981; Begg and Johnston, 2000; White and Tschritter, 2009) (Fig. 2). Groundwater recharge, mostly sourced from the Wairau River, flows to the unconfined Holocene Rapaura Formation gravel aquifer to discharge in spring-fed streams (Taylor *et al.*, 1992).

Current water management challenges include an increase in water use over time and degradation of groundwater quality that has been linked to land use (Davidson and Wilson, 2011). Already, groundwater quality in the Rapaura Formation is impacted by land use (Davidson and Wilson, 2011). The clarity of water in spring-fed streams is currently excellent, and the community aims to keep it this way (Davidson and Wilson, 2011). However, early signs of a decline in surface water quality are occurring with nuisance weed growth that requires control, e.g., in Spring Creek. These challenges require better characterisation of the system's hydrogeology and hydrology.

This paper provides greater understanding of hydrogeology in the Wairau Plain with 3D models of sediment distributions and static groundwater pressure head from observations in many wells, some of which were drilled as early as 1866 (Davidson and Wilson, 2011). These models represent two developments in the use of 3D models to assess groundwater systems in New Zealand. Models of three sediment types (gravels, sands and silts and clay) were calculated for this study, while previously 3D models have calculated the distribution of gravel (only) to understand the 3D geometry of aquifers (White and Reeves, 1999) and to identify groundwater pathways between spring-fed streams and their recharge sources (White, 2009). The second development is 3D modelling of observed static groundwater pressure head; this has much to offer to the understanding of complex hydrogeological systems, including detailed mapping of 3D groundwater flow paths.

The 3D models of the Wairau Plain are used to introduce the hydrogeological features of the study area with a general summary of lithology and static groundwater pressure head across the Wairau Plain. Then, features of the 77 km^2 transition zone, which include a change in lithology from fluviatile gravel in the west to swamp and lagoon deposits in the east, are described with particular reference to the controls on the locations and flows of the spring-fed streams. The paper includes a discussion that suggests future research to further improve characterisation of groundwater and surface water in the Wairau Plain and considers some implications of this research for land and water management.

Geology and groundwater

Surface geology in the Wairau Plain predominantly includes Q1 (Holocene) sediments and Q2 (Late Pleistocene) fan gravel deposits (Begg and Johnston, 2000) (Fig. 2). Q1 sediments were subdivided into fluviatile gravel (Q1a), typically mapped in the west, with swamp deposits (Q1a), estuarine deposits (Q1a) and beach deposits (Q1b) mostly mapped in the lower Wairau Plain. Brown (1981) described the geology of Wairau Plain including three late Quaternary formations that are relevant to groundwater flow: Rapaura Formation, Dillons Point Formation and Speargrass Formation. These formation names are currently used to classify aquifers and aquicludes in the area (Davidson and Wilson, 2011). Therefore, the formation nomenclature of Brown (1981), rather than

that of Begg and Johnston (2000), was used in this paper to describe geological units relevant to the groundwater system.

The Rapaura Formation gravel is the main aquifer in the Wairau Plain and these gravels are the most permeable sediments in the area, e.g., transmissivities were calculated in the range 20,000 to 30,000 m^2/day (Davidson and Wilson, 2011). These sediments are mostly Holocene greywacke gravels and include interbedded sand lenses sourced from the Wairau River and from reworked Speargrass Formation gravels (Brown, 1981). Rapaura Formation is divided into two geological units on the basis of 'depth, lithology, permeability and ease of drilling' (Brown, 1981). The upper unit was deposited in the Holocene (e.g., well P28w/3009, Fig. 3); the lower unit (e.g., well P28w/1733) was deposited in the period 14,000 to 7,000 years before present (B.P.) and is therefore partly Late Pleistocene in age.

Dillons Point Formation includes 'marine, estuarine, lagoonal and eolian deposits of the coastal Wairau Plain' (Brown, 1981), formed during the Holocene marine incursion, mostly after sea level stabilised about 6,000 to 8,000 years B.P. Grey sands and shells are common in the palaeoestuary (e.g., well P28w/44). The permeability of Dillons Point Formation sands is unmeasured in aquifer tests. An estimate of the transmissivity of these sands, 50 m^2/day (calculated from Thorpe, 1991), is provided by tests of Christchurch Formation sands, which are a similar lithology to Dillons Point Formation sands because they were both deposited with the Holocene marine incursion (White, 2007). Dillons Point Formation sediments include extensive gravel beach deposits located between Rarangi and Marshlands (Pickrill, 1976; Brown, 1981; Ota *et al.*, 1995). These gravels began formation as the Boulder Bank in south Cloudy Bay, an estimated 6,000 to 7,000 years B.P., and developed north of the lagoon from about 5,300 years B.P.

The Speargrass Formation, a glacial-outwash gravel, crops out in the southern Wairau Plain and includes the Taylor River gravel fan (Fig. 2). Clay and silt are common in the matrix of this formation (Brown, 1981). Therefore, the median transmissivity of Speargrass Formation (37 m^2/day), calculated from aquifer tests in 41 wells, is relatively low. Older Pleistocene gravel formations (Q3–Q8) mapped to the south of the Wairau Plain are minor in surface extent and are difficult to subdivide in the subsurface on the evidence of drillers' well logs.

Basement to the Wairau Plain aquifer system includes Pliocene and Miocene sediments and Tertiary Awatere Group greywacke conglomerate, south of the Wairau Plain, with Marlborough Schist and Triassic Torlesse Supergroup greywacke to the north. The Wairau Fault crosses the Wairau Plain (Fig. 2). Fault offsets are visible at the ground surface west of the study area and the northern side of the Wairau Fault is upthrown by 2 m at Marshlands (Begg and Johnston, 2000; Zachariasen *et al.*, 2006; Grapes and Wellman, 1986).

Hydrology and groundwater

The Wairau River is the largest source of groundwater recharge to Wairau Plain aquifers. Groundwater recharge from the river is 7 m^3/s in the reach between the Waihopai River confluence and Selmes Road (Davidson and Wilson, 2011), which is approximately 18 km in length. Engineering works, e.g., the Wairau River Diversion, have modified the channel of the Wairau River to control floods (Fig. 1). Groundwater recharge from surface water in the area west of the transition zone is an estimated 1.0 m^3/s. This recharge was measured after river engineering restored surface flows (i.e., Gibsons Creek in 1960 and Opawa River in 2004; Williman, 2014,

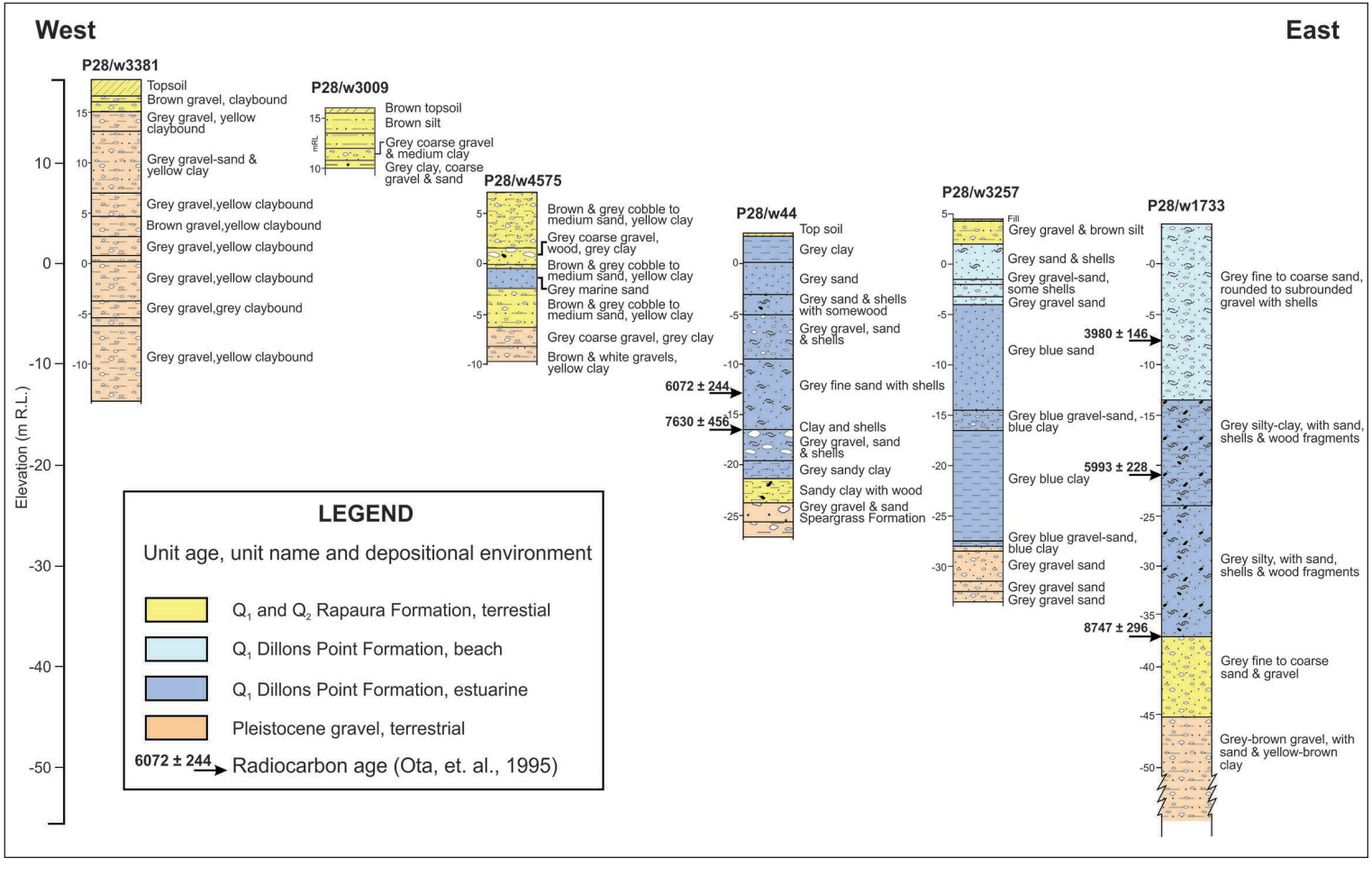
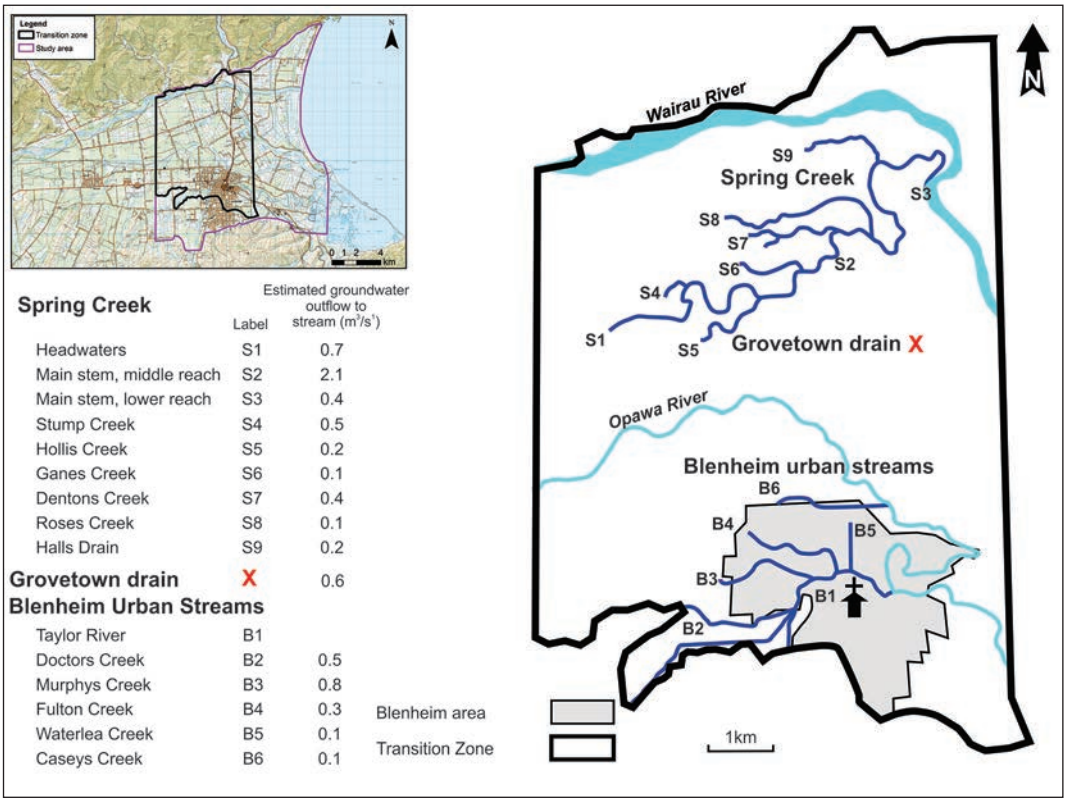


Figure 3 – Geological logs of representative wells with selected radiocarbon dates (Ota *et al.* 1995). The locations of these wells are plotted on Figure 2. Units are named for well P28w/44 and well P28w/1733 by Brown (1981) and Ota *et al.* (1995), respectively, with units in other wells named in this paper.

pers. comm.) to increase groundwater levels and boost flows in spring-fed streams. Earlier river engineering works in the area included: blocking Waihopai River flow into Gibsons Creek (1911); blocking Wairau River flow into the Opawa River (1914); and diversion of the Omaka River and the Fairhall River into the Opawa River (Cunliffe, 1988; Williman, 2014, pers. comm.). Other sources of groundwater recharge to Wairau Plain include rainfall recharge and inflow from the valleys and gravel fans located to the south and west of Blenheim.

Spring Creek is the largest spring-fed stream in the Wairau Plain and has largely remained in its natural course since European settlement. Flow is closely related to groundwater elevation in the Wairau aquifer and to baseflow in the Wairau River (Davidson and Wilson, 2011). The average baseflow gain in Spring Creek is approximately 4.7 m^3/s and most of this flow enters the creek in the middle reach of the main stem between Stump Creek and Roses Creek (Fig. 4). Blenheim urban streams provide baseflow to the Taylor River and the Opawa River. Baseflow in these streams is an estimated 1.8 m^3/s and most of this flows in three creeks (Doctors Creek, Murphys Creek and Fulton Creek) to the Taylor River. Swamps were significant features of the historic hydrology of the Wairau Plain, including the area surrounding the Taylor River gravel fan (Cunliffe, 1988). In the last



Spring Creek	Label	Estimated groundwater outflow to stream (m^3/s^1)
Headwaters	S1	0.7
Main stem, middle reach	S2	2.1
Main stem, lower reach	S3	0.4
Stump Creek	S4	0.5
Hollis Creek	S5	0.2
Ganes Creek	S6	0.1
Dentons Creek	S7	0.4
Roses Creek	S8	0.1
Halls Drain	S9	0.2
Grovetown drain	X	0.6
Blenheim Urban Streams		
Taylor River	B1	
Doctors Creek	B2	0.5
Murphys Creek	B3	0.8
Fulton Creek	B4	0.3
Waterlea Creek	B5	0.1
Caseys Creek	B6	0.1

Figure 4 – Estimated groundwater inflow to spring-fed streams and drains. Reach-by-reach flows were derived from measured flows (Davidson and Wilson, 2011) for all streams and drains except Caseys Creek, which was reported by Kuta (2013, pers. comm.). Flows are rounded to one decimal place.

150 years, the swamps were drained to allow settlement and agricultural development; drainage networks are now common in the transition zone and east of Blenheim (Fig. 1). For example, the Grovetown drain and associated drainage field takes water from the area between Grovetown and Spring Creek (Davidson and Wilson, 2011).

Groundwater in the Rapaura Formation is commonly oxidised in the unconfined aquifer with elevated nitrate concentrations indicating that land use affects groundwater quality (Raiber *et al.*, 2012; Davidson and Wilson, 2011). In the east, Rapaura Formation is confined and anoxic conditions are demonstrated by dissolved oxygen and nitrate concentrations that are 'zero or near-zero' (Taylor *et al.*, 1992). Groundwater in the Dillons Point Formation near Grovetown is oxic with low nitrate concentrations, indicating that it is mostly recharged from the Wairau River (Raiber *et al.*, 2012).

Method

Digital terrain models

Two digital terrain models (DTMs) of the Wairau Plain were developed in this study. The first DTM represented present-day ground elevation. Contour lines at 1 m intervals were derived from point data captured by aerial orthophotography and matched to ground topography using multiple aerial flight control points and Land Information New Zealand geodetic survey locations as ground truth (Sigmund, 2012, pers. comm.). The data were checked for coverage and completeness, with the relative fit of the data classified using automated routines to remove errors and non-ground surface returns. The second DTM estimated surface topography before the construction of drainage features by: interpolating the present-day DTM with a 5 m by 5 m grid; removing the elevation points associated with the drainage features; and then recalculating the surface.

Three-dimensional lithological models

Marlborough District Council (MDC) provided observations of lithology for 1,165 wells in the study area, with a total of approximately 22 km of lithologies logged, as of August 2012 (Fig. 5). Data quality checks were completed prior to 3D lithological model calculation, which resulted in the removal of poor-quality well logs from the database. Three-dimensional lithological models were calculated for three classes of sediment between the ground surface and –50 m R.L. (i.e., 50 m below mean sea level):

1) gravel, which is the predominant coarse sediment described by drillers (other coarse sediment that was included with the gravel model were described by drillers as stones, cobbles, shingle and boulders);
2) sand; and
3) silt and clay, either singularly or together.

These classes were not exclusive. For example, lithologies that were described in a well log as a mix of 'gravel and sand' were represented by each of the 3D models of gravel and sand. The 3D models were generated following the method of White and Reeves (1999). In summary, EarthVision® software (Dynamic Graphics Inc., USA) was used to calculate continuous (3D) distributions of de-facto probabilities for the occurrences of the three sediment classes by 3D gridding and 3D contouring of lithology property codes.

A 2D surface that maps the top of the Speargrass Formation was calculated in two parts. The surface was represented by the DTM where the formation crops out. Below ground level, the surface was approximated by well-base elevations supplemented with sediment descriptions. Well-base elevations were used because many wells intersect Rapaura Formation sediments located immediately above the top of the Speargrass Formation (e.g., well P28/w44, Fig. 3). Sediment descriptions were used because the base of Dillons Point Formation can be identified by distinct palaeoenvironmental

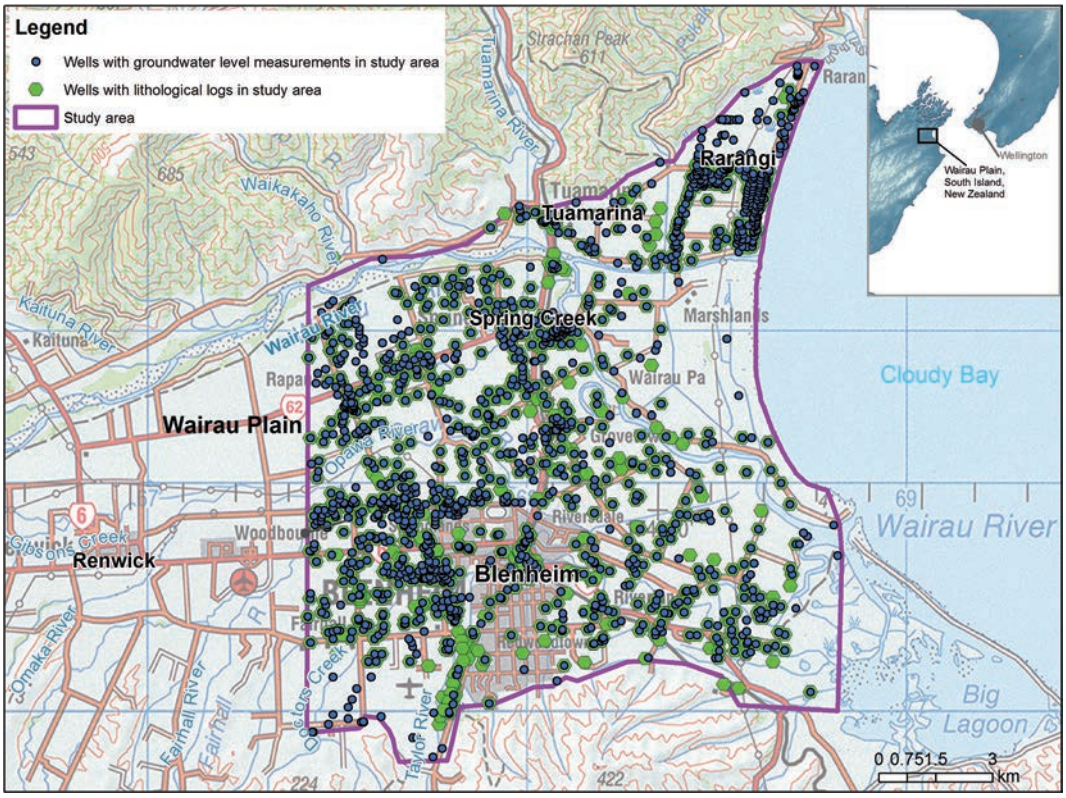


Figure 5 – Location of wells used for 3D models of lithology and static groundwater pressure.

indicators (e.g., shells in well P28/w1733) (White and Tschritter, 2009). However, the elevation of the Speargrass Formation surface may be overestimated where wells partly penetrate the Rapaura Formation and where the base of Dillons Point Formation is above the top of the Speargrass Formation. Therefore, well-base elevations were selected from clusters of wells with the aim of reducing the uncertainty in the surface. The top surface of basement was estimated from the DTM and from the few drill holes that intercepted this unit (White and Tschritter, 2009).

The 2D surfaces identified that bases of most wells were in the Rapaura Formation (31% of all wells with groundwater level measurements in the study area), Speargrass Formation (28%) or Dillons Point Formation (21%). The Wairau Fault was not described as a 2D surface because a detailed analysis of well logs targeting fault offsets has not been completed for Dillons Point Formation sediments near the fault trace (see Discussion).

Three-dimensional SGP model

A 3D model of static groundwater pressure head (SGP) was derived from observations of groundwater level at 1,505 wells in the study area (Fig. 5). The model represented SGP in the saturated zone. Therefore, the top surface of the saturated zone, represented by the water table elevation, was also calculated.

Groundwater pressure head was calculated from observations of groundwater level and estimates of ground elevation at the well head, interpolated from the DTM.

MDC groundwater level data commonly included depth measurements; height measurements were also recorded by MDC with stand pipes in flowing artesian wells. Data quality checks identified wells where SGP data may not represent static conditions in the formation due to the influence of drilling, or pumping, on groundwater level measurements. Mostly, SGP calculations were representative of static hydraulic conditions in the wells because most measurements were recorded by contractors during drilling and most wells were drilled with the cable-tool method, which does not require the use of drilling fluids, such as water, to remove sediment from the wells. More recently, the rotary drilling method has been used, either using air or water to remove cuttings (Davidson and Wilson, 2011), which may result in groundwater depth, or height, data that is not representative of static groundwater level.

Twenty-nine wells were removed from the data set where pumping reduced groundwater level to below sea level (24 wells) or drillers' logs indicated uncertainty in static groundwater conditions (5 wells). Seasonal and long-term corrections were not applied to SGP estimates because the pattern of seasonal variation is variable over the Wairau Plain and long-term monitoring data was only available for a small number of the wells in the MDC dataset. In addition, the 3D SGP model calculation included 3D smoothing, which reduced the effects of 'outliers' in the model.

The model calculation used EarthVision® conformal 3D gridding and 3D contouring with a cell size that was 50 m by 50 m by approximately 1 m in the easting, northing and vertical directions, respectively. This model did not use SGP control points so as not to impact the assessment of groundwater pressure gradients.

The top surface of the saturated zone was calculated from SGP data in shallow wells, i.e., the 545 wells that were less than 10 m deep. Control points were used where shallow wells were not present, i.e., SGP was set at 0 m R.L. between Marshlands and the lagoons and set at the Wairau River bed elevation within the groundwater recharge zone (Fig. 1). However, control points were not used in the vicinity of the spring-fed streams because identification of groundwater gradients near the streams was an aim of this paper and these points could bias calculation of SGP contours.

Groundwater budget of the transition zone

A general water budget equation describes the relationships between water inflow, water outflow and water storage within a defined area of a catchment (Scanlon *et al.*, 2002):

$$\text{inflow} = \text{outflow} + \Delta S \qquad (1)$$

Water inflows are the sum of: precipitation (P); surface water inflow (Q^{SW}_{IN}), which is quickflow and baseflow; and groundwater inflow (Q^{GW}_{IN}). Water outflows are the sum of: actual evapotranspiration (AET); surface water outflow, which is the sum of Q^{SW}_{IN}, Q^{SW}_{QF} (surface water quick flow generated in the area), Q^{SW}_{BF} (surface water base flow generated in the area, which is discharge to surface water from the saturated portion of the groundwater system) and consumptive surface water use (U^{SW}); groundwater outflow from the area, which comprises consumptive groundwater use (U^{GW}) and groundwater discharge across the boundary (Q^{GW}_{OUT}); and change in water storage (ΔS). Flows were calculated to the nearest 0.1 m^3/s.

Expanding Equation 1 and assuming that three components are zero in the transition zone has:

$$P + Q^{GW}_{IN} = AET + Q^{SW}_{BF} + U^{GW} + Q^{GW}_{OUT} \qquad (2)$$

The water budget components assumed as zero were: U^{SW}, because little, or no, surface water is used; Q^{SW}_{QF}, as it is probably a small component of total surface flow in the study

area, e.g., quick flow was an estimated 0–10% in spring-fed streams (Davidson, 2012); and ΔS, as the water budget aimed to represent steady-state conditions.

The components of the transition zone groundwater budget are described in the following text. These include Q^{GW}_{IN} through the western boundary of the transition zone, which is calculated with a groundwater budget of the west-transition area that is also described. This area includes Holocene sediments on Wairau Plain between the transition zone and the main Waihopai River terrace (Davidson and Wilson, 2011) and the Wairau River.

- P was calculated from the National Institute of Water and Atmospheric Research (NIWA) nationwide map of average rainfall (mm/year) based on the rainfall measurements at individual climate stations, interpolated and averaged for the period 1960 – 2006 (Tait *et al.*, 2006).
- AET was estimated from the NIWA nationwide map of average actual evapotranspiration (mm/year) for the period 1960–2006 without specific consideration of land use, land cover or soil type (Woods *et al.*, 2006).
- Q^{GW}_{IN} from the Wairau River through the northern boundary of the transition zone was 1.0 m^3/s, i.e., the length of the reach (2.5 km) between the western boundary of the zone and Selmes Road multiplied by the average Wairau River flow loss to groundwater (0.4 m^3/s/km) between the Waihopai River confluence and Selmes Road (Fig. 1); therefore, Q^{GW}_{IN} from the Wairau River to the west-transition area was 6.0 m^3/s to balance the total groundwater outflow from the Wairau River (i.e., 7.0 m^3/s, see earlier).
- Q^{GW}_{IN} through southern boundary was the difference between P and AET, including: inflow to the transition zone from the Taylor River gravel fan and the Pleistocene sediments in the Doctors Creek catchment; and inflow to the west-transition area from the Omaka River valley and Fairhall River valley including Mill Stream.
- Q^{GW}_{IN} through the western boundary of the transition zone was the groundwater outflow from the west-transition area.
- Q^{GW}_{IN} (other streams) included groundwater recharge of 1.0 m^3/s from Gibsons Creek and the Opawa River to the west-transition area.
- Q^{SW}_{BF} was 7.1 m^3/s, which is the sum of 4.7 m^3/s from Spring Creek, 1.8 m^3/s from Blenheim urban streams and 0.6 m^3/s from Grovetown drain (Davidson and Wilson, 2011; Kuta, 2013, pers. comm.).
- U^{GW} included: 1) irrigation of grapes. The irrigated area is 34 km^2 in the transition zone and 27 km^2 in the west-transition area; estimated average irrigation was 1 mm/day over a four-month irrigation season. Irrigation return to groundwater was assumed as zero because irrigation is provided by micro-sprinklers; and 2) Blenheim municipal use, calculated from usage records.
- Q^{GW}_{OUT} was calculated to balance the groundwater budget.

Flow in spring-fed streams is relatively stable over time (Davidson and Wilson, 2011) but the measurements used to calculate Q^{SW}_{BF} may not represent steady-state conditions. For example, Q^{SW}_{BF} in Blenheim urban streams, calculated using mean flows from the period 2002 and 2009, was greater than the Taylor River flow gain through Blenheim measured in March 2013 (approximately 1.2 m^3/s), Davidson (2013). Therefore, further stream gaugings are recommended (see Discussion).

Results

General description

Rapaura Formation gravels were common at the ground surface in the western transition zone (e.g., features 'A' and 'B', Fig. 6). In the subsurface, these gravels generally dipped towards the east and were shallow in four areas through the middle of the transition zone (features 'C' to 'F'). Dillons Point Formation sediments thicken towards the east; sands, silts and clays were prominent at the southern coast with gravels and sands, deposited in a beach environment, at Rarangi.

A large decrease in SGP occurred across the study area. For example, maximum SGP was 17 m R.L. in the west (section W–W') and was 2 m R.L. at the coast (Fig. 7). Generally, vertical SGP gradients were downwards in the west ('A' and 'B' on section W–W') indicating the potential for rainfall and rivers to recharge the unconfined aquifer. Vertical SGP gradients were generally upwards at section Y–Y', and features 'C', to 'F', which is consistent with the occurrence of spring-fed streams and historic swamps. Gradients were mostly upwards in the eastern transition zone (section Z–Z') and at the coast. Also, the potential for groundwater to flow from the Taylor River gravel fan into the transition zone was shown by the SGP contours.

Transition zone and spring-fed streams

Factors within the transition zone that were relevant to the locations and flows of spring-fed streams include: topography; the groundwater budget; the distribution of Holocene gravel sediments; and vertical SGP gradients across Holocene sediments (VGHS).

Spring-fed streams occupied general topographic lows in the transition zone (Fig. 8). Historic swamps, now drained, occupied the area of Blenheim urban streams and three historic surface water channels (i.e., Omaka River, Fairhall River and Doctors Creek) discharged to these swamps. Topographic gradients, in the area west of the streams, were broadly in the directions of Spring Creek and Blenheim. For example, the directions of gradients in the general area of 'G' were towards Spring Creek and Blenheim urban streams. Groundwater probably flows in these directions because gravels were common in the area and the directions were coincident with groundwater level gradients indicated by SGP contours (Figs 6 and 7).

The groundwater budget showed that most groundwater inflow to the transition zone flows to spring-fed streams, in agreement with Taylor *et al.* (1992), i.e., Q^{GW}_{IN} through the western boundary of the transition zone and Q^{SW}_{BF} were both 7.1 m^3/s (Table 1). Therefore, groundwater flow rates were relatively low through the eastern boundary of the transition zone, i.e., Q^{SW}_{BF} was much larger than Q^{GW}_{OUT} (0.9 m^3/s). This conclusion was supported by two other results: most of the SGP decrease in the study area occurred across the transition zone as the maximum SGP was 17 m R.L. and 5 m R.L. at the western and eastern boundaries of the zone, respectively; and VGSH was typically upwards in the vicinity of spring-fed streams.

The distribution of Holocene gravel sediments was represented by a 'contiguous' gravel surface in the transition zone that was derived from the gravel sediment model, following White and Reeves (1999). The surface was a statistical representation of the distribution of gravel; below this surface, the gravel property value indicated that gravel deposition was contiguous, whereas above the surface, the gravel property value indicated that gravels were not common. Some gravels were recorded by well logs above this surface, but these were typically not continuous between adjacent wells. VGHS indicates the potential for vertical groundwater flow, e.g., groundwater may flow to spring-fed streams where VGHS is upwards. However,

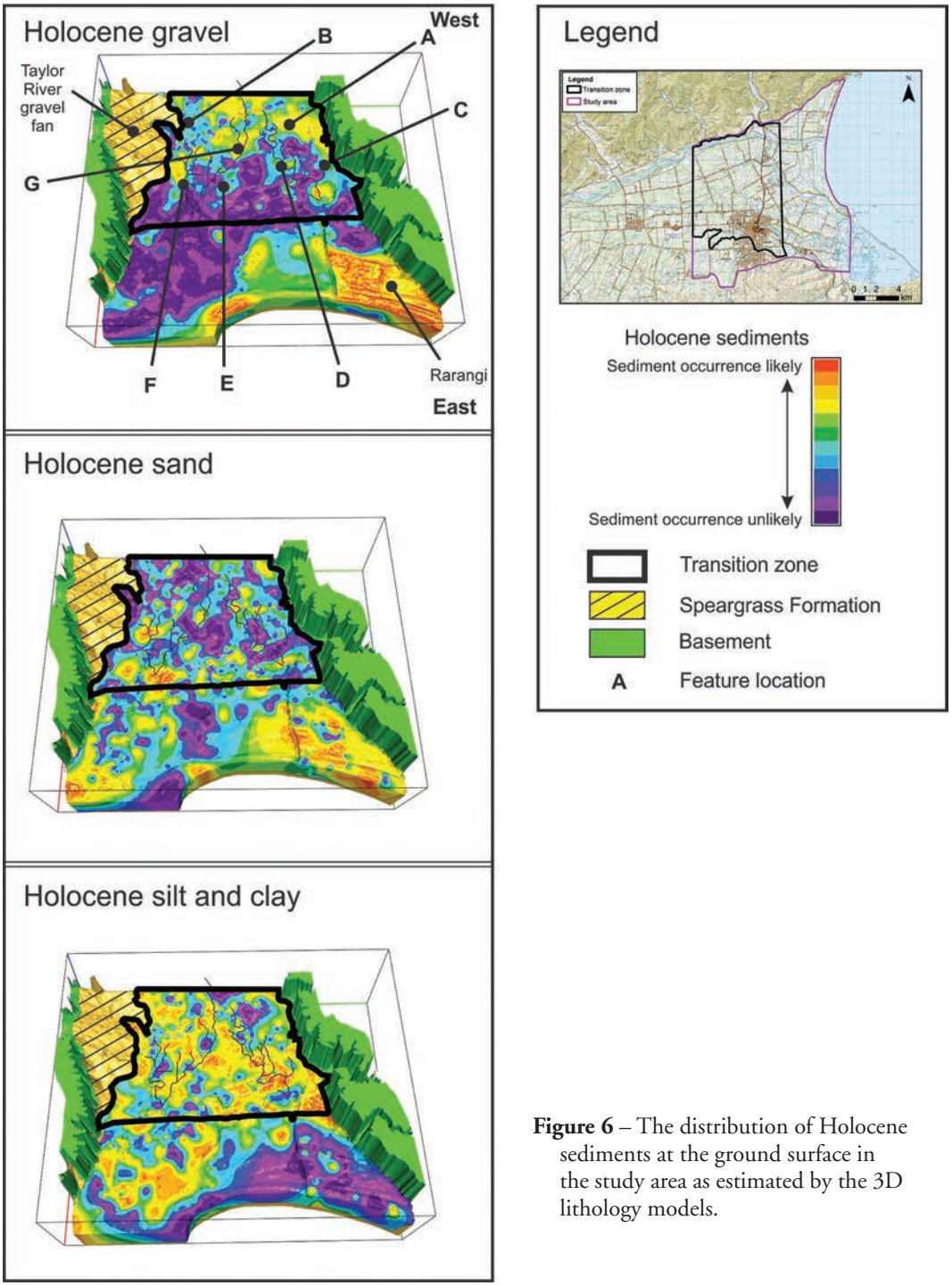


Figure 6 – The distribution of Holocene sediments at the ground surface in the study area as estimated by the 3D lithology models.

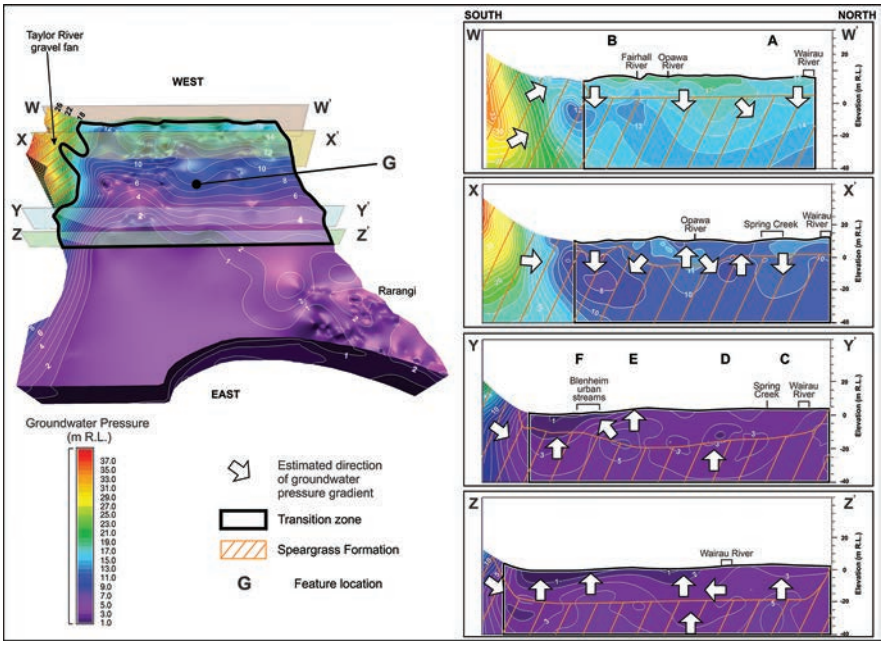


Figure 7 – The SGP model in the study area and SGP contours at four cross sections in the transition zone and Taylor River gravel fan. The arrows indicate, schematically, the general direction of groundwater pressure gradient estimated from the SGP contours.

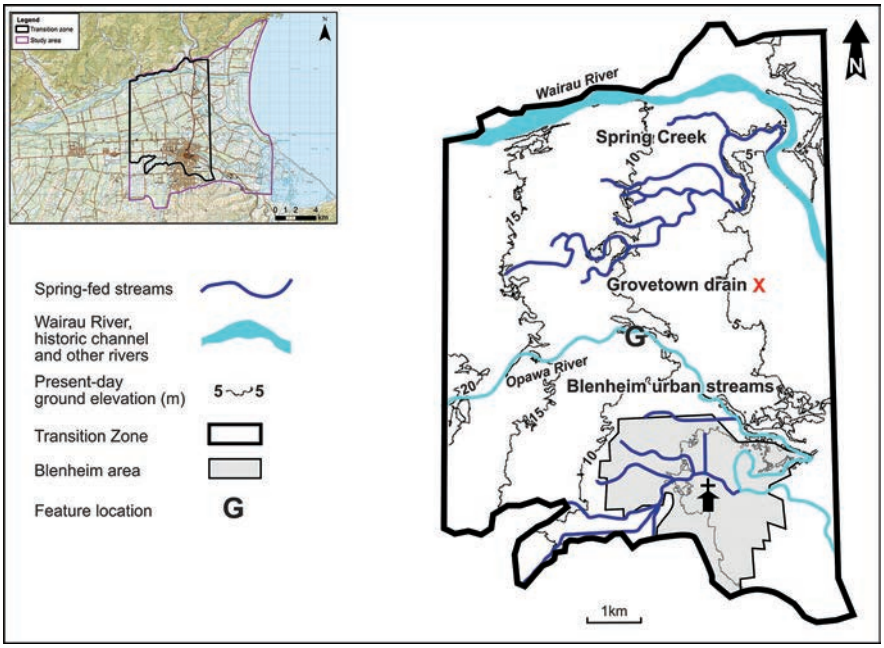


Figure 8 – Present-day ground elevation in the transition zone and channels of spring-fed streams (Davidson and Wilson, 2011).

Table 1 – Groundwater budget components in the transition zone and the west-transition area.

Budget component		West- transition area (m^3/s)	Transition zone (m^3/s)
Inflow	P	1.2	1.7
	Q^{GW}_{IN} (Wairau River) northern boundary	6.0	1.0
	Q^{GW}_{IN} western boundary	0.0	7.1
	Q^{GW}_{IN} southern boundary	0.1	0.0
	Q^{GW}_{IN} (other streams)	1	0.0
Outflow	ET	1.1	1.6
	U^{GW} (irrigation)	0.1	0.1
	U^{GW} (municipal)	0.0	0.1
	Q^{SW}_{BF}	0.0	7.1
	Q^{GW}_{OUT} (boundary)	7.1	0.9

actual groundwater flow will depend on the permeability of flow pathways, e.g., the same pressure gradient will produce a much larger groundwater flow in Rapaura Formation gravels than in finer sediments.

Generally, the locations of spring-fed streams were associated with shallow Rapaura Formation gravels (i.e., the gravel surface was typically less than 4 m deep) and VGHS was upwards (Figs 9 and 10). Sands, silts and clays cover the shallow gravel. These sediments are probably Rapaura Formation, i.e., they were deposited in a terrestrial environment because well logs show that they were associated with organics (e.g., wood) but not with shells (e.g., well P22/w4575, Fig. 3).

Spring Creek was associated with Feature C and Feature D. VGHS was upwards across four Spring Creek reaches (Halls Drain, the main stem middle reach, Dentons Creek and Roses Creek; Fig. 4). These four reaches provided an estimated baseflow (2.8 m^3/s), which was the majority of the total creek baseflow (4.7 m^3/s). However, other reaches (headwaters, Stump Creek and Hollis Creek) were generally located where VGHS was downwards. This lack of a clear association of Spring Creek flows with VGHS suggested that the 3D models could be improved with new data (see Discussion).

To the south, Feature E was not associated with spring-fed streams but historic swamps and swamp deposits that were mapped in the area indicated the potential for groundwater to discharge at the land surface (Davidson and Wilson, 2011; Fig. 2). This feature was possibly associated with Blenheim urban streams as SGP contours indicated a pressure gradient in the direction of the town (Fig. 7). Blenheim urban streams were commonly associated with shallow Holocene gravel (Feature F) which probably included gravel deposited by the historic channels of the Omaka River and the Fairhall River. Three streams that cross these gravels (Doctors Creek, Murphys Creek and Fulton Creek; Fig. 4) provided a baseflow (1.6 m^3/s) to the Taylor River, which was most of the total baseflow in the urban streams (1.8 m^3/s).

The lateral transition in shallow strata from shallow gravel to finer sediments was also an important control on the locations of spring-fed streams as features associated with shallow gravels (C, D, E and F) were adjacent

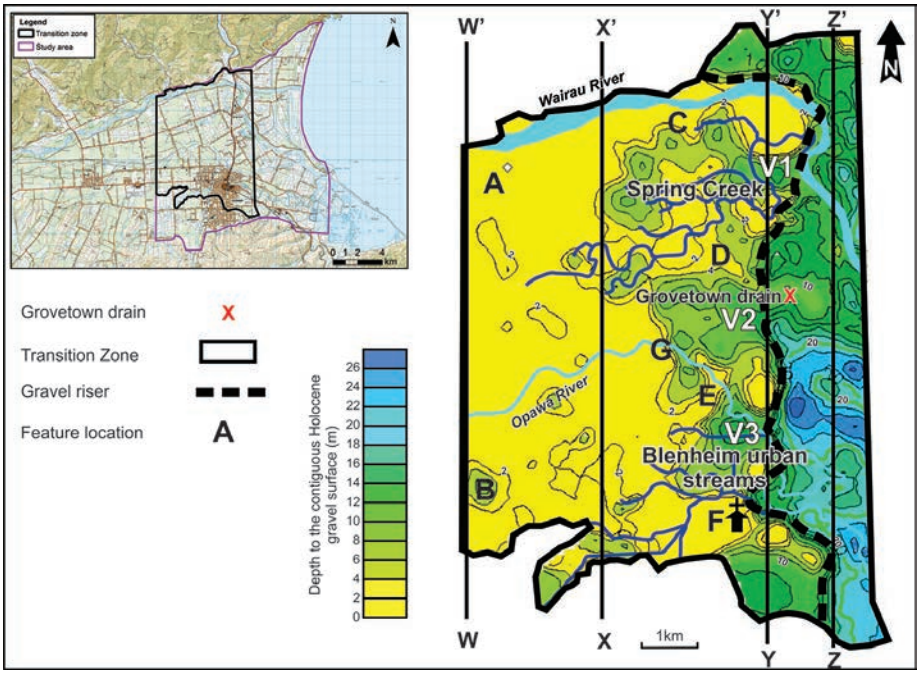


Figure 9 – The contiguous Holocene gravel surface in the transition zone.

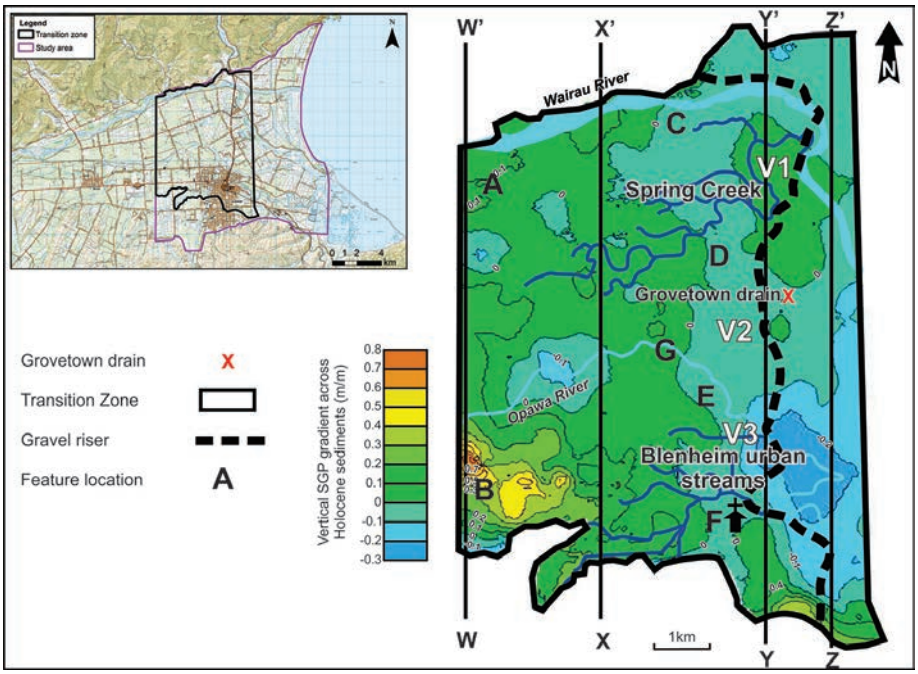


Figure 10 – Vertical hydraulic gradient across Holocene sediments in the transition zone. A positive value indicates that the vertical component of the SGP gradient is downwards and a negative value indicates that it is upwards.

to palaeochannel-like features ('V1', 'V2' and 'V3'). For example, Halls Drain was near the boundary of C and V1; and two Blenheim urban streams (Fulton Creek and Murphy Creek) were located near to the boundary of feature F and V3. Well logs showed that palaeochannels were commonly in-filled with fine sediments (silts and clays); sands were less common in the palaeochannels and gravels were observed but were not generally continuous between wells. The fine sediments were probably Rapaura Formation because they are associated with organics in well logs. Typically, upwards VGHS occurred in the palaeochannels as observed east of Feature G (Figs 9 and 10).

Lastly, stream locations were bounded to the east by Dillons Point Formation sediments that were relatively thick (typically 10 m to 20 m below the ground surface) and an associated buried gravel riser that dipped relatively steeply towards the coast. The gravel riser probably had a marine, or estuarine, origin because shells were commonly associated with these gravels, as described by well logs.

Discussion

Wairau Plain – future characterisation

The 3D models in the transition zone would benefit from additional observations of lithology and groundwater level measurements in the Holocene sediments that cover the Rapaura Formation. Shallow drill holes would be particularly useful in developing an improved representation of lithology in aquifers and aquitards. SGP data collection could include aquitards, because current SGP measurements target aquifers. Ideally, detailed synoptic low-flow gauging surveys should also be undertaken with an aim to identify stream gains and losses at the sub-reach scale. Together, these new measurements could result in more accurate estimates of groundwater flow directions towards the spring-fed streams.

Further characterisation of gravel deposits may explain the relatively complex groundwater flow directions, as indicated by SGP contours, in the area east of the historic Wairau River channel. Drilling is recommended, including collection of detailed logs and measurements of lithology ages, south of Rarangi where little well log information is available (Fig. 5). An analysis of well logs and lithology ages is recommended in the area with the aim of assembling a chronology of Holocene gravel deposition from two sources: the Wairau River and the Boulder Bank. The Wairau River channel has probably migrated in the Holocene, possibly from a position below Rarangi, as indicated by contours on the base of Dillons Point Formation (Fig. 2), to the historic location (Fig. 1). Through the same period, the Boulder Bank migrated north and filled the Rarangi-Marshland area with gravel.

Uncertainty and model sensitivity

Valuable insights to the complexity of lithology and SGP in alluvial systems would come from an uncertainty analysis of the models developed for the study area, which will extend the uncertainty analysis of 3D lithology alone (White and Reeves, 1999). A full assessment of uncertainty was not completed for 3D models of lithology and SGP in the study area. However, model uncertainties were considered by calculating alternative distributions of lithology and SGP with combinations of gridding parameters (including grid size, model depth and contour level). These distributions identified the features that were described in the paper, which gives confidence that the features were not random artefacts of model calculation.

Future research aims to assess the uncertainties of the 3D models including automated identification of poor-quality

lithological logs and questionable SGP measurements. The analyses of uncertainties in the 3D models will extend into uncertainties of model predictions including 3D pressure gradients and groundwater flow estimates based on these gradients.

Groundwater and surface water management

Land use and groundwater pumping from the Rapaura Formation and Pleistocene aquifers have the strong potential to impact on flow rates and water quality in spring-fed streams because of the links between land, the Holocene aquifer and spring-fed streams that were identified in this study. Therefore, co-management of land and water is appropriate in the Wairau Plain to protect the flow and quality of the streams.

In the opinions of the authors, characterisation of groundwater systems is a key component to the implementation of co-management policies. The 3D models have provided significant new information on water resources that is relevant to possible future policies in the Wairau Plain and have shown, with various views and cross sections, the potential of the models as tools to communicate an understanding of complex groundwater systems.

Coastal aquifer systems

Coastal groundwater systems like the Wairau Plain, i.e., sedimentary aquifers deposited in terrestrial environments with a Holocene marine incursion at the coast, are common in New Zealand and are important because they supply large quantities of groundwater to population centres including Christchurch City, Hastings City and Napier City (White, 2001; White *et al.*, 2007). The methods described in this paper are relevant to other coastal aquifer systems. In particular, 3D lithological analyses and 3D SGP models are very useful for assessment of potential groundwater flow paths to the ground surface. Together, these models can also provide the characterisation that is required for scientifically-robust assessments of the effects of water use. However, the development of these models in similar coastal aquifer systems will be limited by data availability because the models require large numbers of well logs and SGP observations.

Some general results may provide a useful contribution to the development of conceptual groundwater models in similar systems. Firstly, spring-fed streams are located across the transition zone between gravels and the marine incursion because the permeability boundary in the zone restricts groundwater flow towards the coast. Secondly, spring-fed streams probably receive most groundwater recharge, sourced from rivers and rainfall inland of spring-fed streams, which results in relatively low groundwater flow rates across the coastal zone.

Conclusions

This paper contributes to addressing current water management challenges in the Wairau Plain, Marlborough by describing hydrogeological features of the area with three-dimensional (3D) models of Holocene lithology (gravels, sands, silts and clays) and static groundwater pressure (SGP) that were developed from observations in a large number of wells. General features of the groundwater system identified by the models were consistent with the literature (Brown, 1981; Taylor *et al.*, 1992; and Davidson and Wilson, 2011). For example, Rapaura Formation gravels, which crop out in the west and dip towards the coast, formed the main aquifer in the area. Dillons Point Formation sediments (typically sands, silts and clays) crop out east of Blemheim and thicken towards the coast.

The models provided important characterisation of groundwater and surface water in the transition zone where the depositional

environments of surface Holocene sediments change from fluviatile gravel in the west to swamp and lagoon deposits in the east and where the spring-fed streams (Spring Creek and Blenheim urban streams) were located. The streams were typically associated with: shallow Rapaura Formation gravels (i.e., a "contiguous" gravel surface, derived from the 3D gravel lithology model, was less than 4 m deep); lateral boundaries between shallow gravel and palaeochannels, which were typically filled with Holocene silts and clays; and upwards vertical SGP gradients across Holocene sediments. In addition, stream locations were bounded to the east by relatively thick Dillons Point Formation sediments and an associated buried gravel riser that dips relatively steeply towards the coast.

Co-management of land and water is required to address current pressures on water resources in the Wairau Plain because hydraulic links between land, the Wairau River, the Holocene aquifer and the spring-fed streams were identified by the groundwater budget and the 3D models. The methods described in this paper are also relevant to the assessment of other coastal aquifer systems. However, their use will be restricted in other systems because these models require large databases of well logs and SGP observations.

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