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HYDROGEOLOGICAL INVESTIGATIONS OF THE
PALMERSTON NORTH REGION

A thesis presented in partial fulfilment of the
requirements for the degree of
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ABSTRACT

The Lower Manawatu River Valley and its major tributary the Pohangina River Valley are incised within the marine strata of the South Wanganui Basin. Lining each valley are a flight of both aggradational and degradational terraces. Three aggradational terraces are identified and correlated with the Ohakea, Rata, and Porewa terraces of the Rangitikei River Valley which aggraded during stadial periods of the Last (Otiran) Glaciation. The distribution of these terraces in the Lower Manawatu River Valley is discussed and their cover beds described. Previous river channels of the Manawatu River are identified by means of bore-log information.

The nature and history of the Manawatu River has resulted in a sequence of clay, silt, sand, and gravel deposits which is exceedingly complex in detail. Cross-sections are presented which show this complexity. This has been the main factor influencing the distribution and nature of the aquifers in the region. Water is normally extracted from the coarsest deposits with 75% of the bores in the region obtaining water from gravel layers, 15% from sand layers, and 10% from sand/gravel mixtures. The aquifer system is considered to be "leaky" due to the complex arrangement of lithologies allowing water to flow both vertically and horizontally without much impedance. Depth ranges of 0-60 m, 60-120 m, and >120 m below the ground surface are considered to be the closest resemblance to separate aquifers. Piezometric contour maps are presented which show an overall groundwater flow direction for all the depth ranges from east to west along the Manawatu River Valley with additional water influx from the Pohangina and Oroua River catchments. Transmissivities of the aquifer system ranges between 150-2000 m²/day and storativity between 1.1×10^{-4} and 3.2×10^{-4} . Static water levels and discharge rates increase with depth and decrease from east to west. Nearly all the bores in the area are naturally flowing artesian, making the entire area a discharge zone. Recharge of the aquifer system is from two sources. Firstly, direct percolation of atmospheric precipitation, the main source areas being the Tararua Range, the Ruahine Range, and both the eastern and western flanks of the Pohangina Anticline, and secondly, river recharge.

There is a significant loss (6,500 l/s) of water as the Manawatu River flows through the Manawatu Gorge which is identified as occurring in the vicinity of White Horse Rapids. This water loss is attributed to groundwater river recharge of shallow aquifers. Groundwater accounts for nearly 90% of total water use within this area and the estimated water extraction from the aquifer system is 120,000 m³/day (43 x 10⁶ m³/year.)

The hydrochemistry of the area is presented by way of isoconcentration contour maps. Total alkalinity, calcium, magnesium, chloride, electrical conductivity, potassium, manganese, sodium, and total dissolved solids increase from east to west within the research area. Free carbon dioxide, fluorine, and iron show no trend but have local "highs". Only sulphate shows an increase from west to east. The average concentrations for the various chemical parameters are: total alkalinity - 157 ppm, Ca - 104 ppm, Cl - 36 ppm, free CO₂ - 11 ppm, conductivity - 43 mS/m, F - 0.16 ppm, Fe-2.1 ppm, Mg - 55 ppm, Mn - 0.38 ppm, nitrate - 0.02 ppm, Na - 23 ppm, SO₄²⁻ - 10 ppm, and total dissolved solids - 256 ppm. Concentrations increase with depth for all the chemical parameters. Conductivity diagrams are presented which show extremely good linear relationships when plotted against all the major cations and anions. These diagrams have practical significance because conductivity is easy to measure in the field.

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CHAPTER ONE - INTRODUCTION

1.1 DESCRIPTION OF RESEARCH AREA

1.1.1 LOCATION

The area investigated in this study is located in the south-western part of the North Island with Palmerston North City located approximately in the centre. The area is approximately triangular in shape with the Tararua Range forming the south-eastern boundary, the Oroua River the western boundary, and the Ashhurst-Bunnythorpe Road forming the northern boundary (see figure 1.1). The area covers 32 km along the Manawatu River from the Manawatu Gorge to the confluence of the Manawatu and Oroua Rivers. From the confluence the study area extends 20 km north along the Oroua River to approximately Awahuri township. From Awahuri the study area extends 23 km towards the Manawatu Gorge. The total area covered in this research is approximately 230 km².

1.1.2 SELECTION OF STUDY AREA

The area under investigation was chosen for a number of reasons, listed below.

1) The area is economically important as the land use is very intense. In the area just to the north-east of Palmerston North, known as the Whakarongo-Te Matai area, much horticulture and market gardening takes place. The rest of the study area is pastoral land devoted to dairying, sheep and beef. A lot of these enterprises use bore water for irrigation and stock drinking water which makes a study of the groundwater resources invaluable for future water allocation and location of bores.

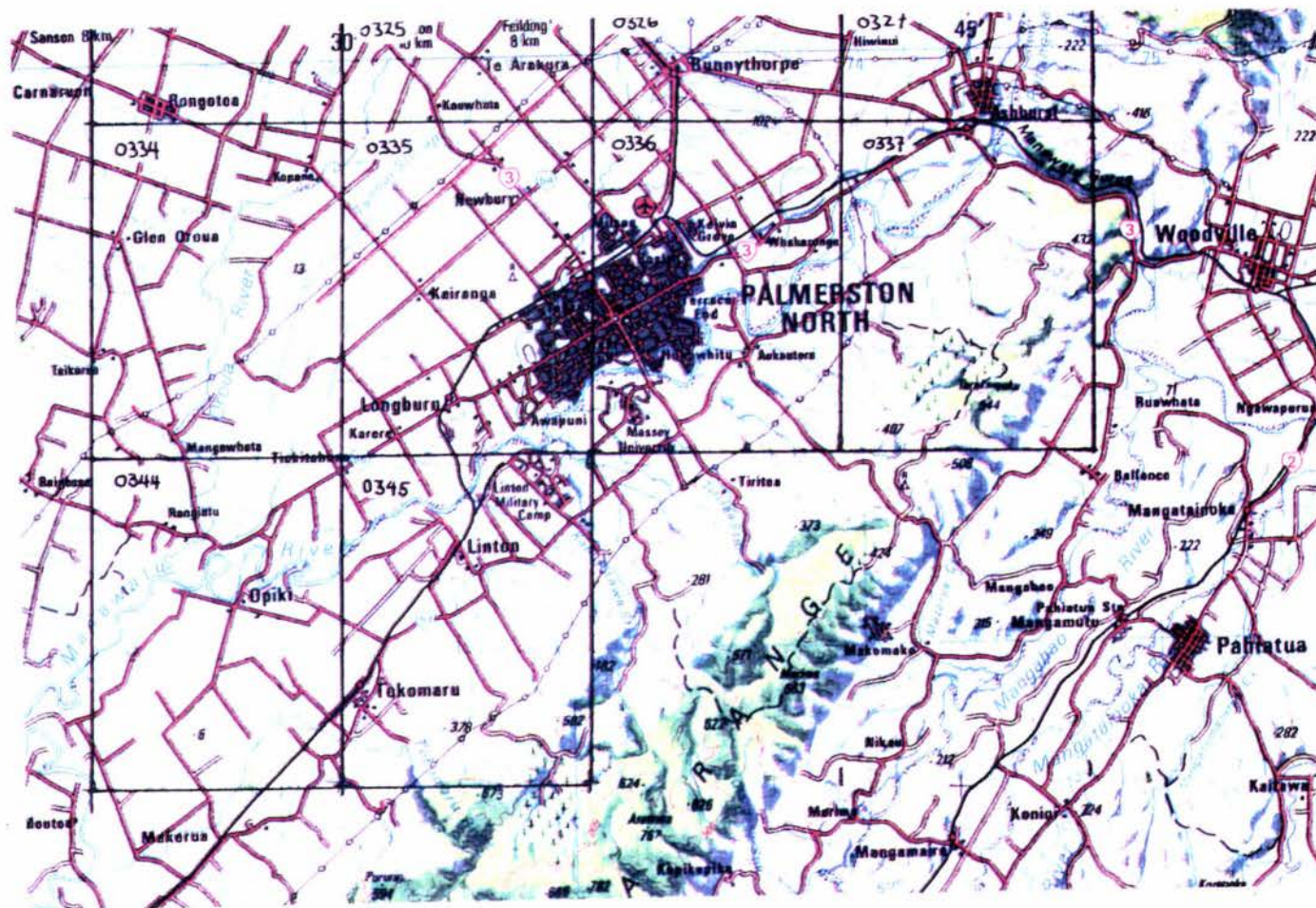
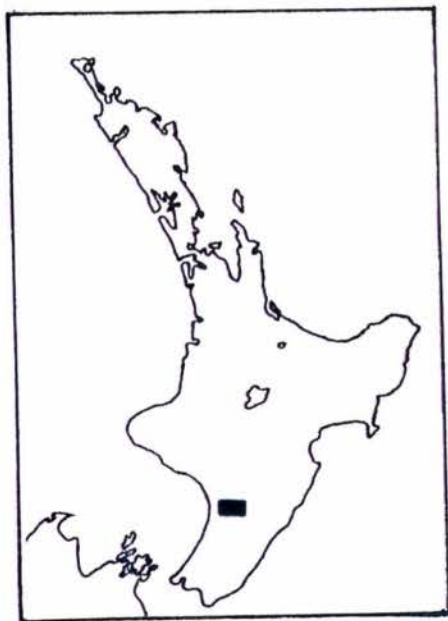


Figure 1.1 Location of study area showing bore grids.

2) The area contains many water bores, many of which have been logged by the well drillers involved in the drilling of the bores: these bore-logs were made available by the Manawatu-Wanganui Regional Council (previously known as the Manawatu-Rangitikei Catchment Boards). Some 250 bore-logs were available for the study and are a necessary part of any hydrogeological investigation.

3) The Manawatu-Wanganui Regional Council has an ongoing groundwater research program of which this area forms a small part. The Council was keen to have this research undertaken and made any pertinent information available.

4) The Manawatu-Wanganui Regional Council conducted a water quality survey in February-April 1989 which included many bores in the study area. The author assisted in this survey and the results obtained were made available for this study.

5) The area was readily accessible for the author which made fieldwork very convenient and constant contact with the Regional Council and well drillers allowed up to date information to be collected constantly.

1.1.3 CLIMATE

The Palmerston North area enjoys a mild climate with moderate rainfall. July is normally the coolest month with an average temperature of 8.5 °C for the last three years; January and February are normally the warmest months with average temperatures usually exceeding 17 °C. Temperature ranges are usually about 9 °C during each month. Rainfall is fairly constant throughout the year with no real rainy season, total rainfall for a year averages around 900 mm. Total sunshine hours in the Manawatu are relatively low for New Zealand standards, normally between 1700 and 1800 sunshine hours are recorded. Table 1.1 shows the climatic data for the Palmerston North region for the last three years (1987-1989).

Table 1.1 **Climatic Data For Palmerston North Region**

Station: Grasslands Division DSIR

YEAR MONTH		MEAN TEMP.	TEMPERATURE RANGE	RAINFALL	SUNSHINE
		(°C)	(°C)	(mm)	(Hrs)
1987	January	18.5	9.8	73.8	230.0
	February	17.0	9.3	62.9	200.3
	March	15.4	9.0	122.6	153.3
	April	13.9	8.0	123.9	143.1
	May	11.4	7.7	54.1	74.7
	June	9.5	7.1	67.8	64.5
	July	8.4	8.3	32.8	88.6
	August	11.0	8.3	32.0	131.5
	September	11.2	8.1	67.1	122.5
	October	13.0	8.8	93.1	159.0
	November	15.5	8.3	62.3	198.3
	December	16.8	8.4	95.8	148.3
YEAR :				888.2	1714.1
1988	January	17.6	9.7	5.2	239.6
	February	18.8	8.3	149.9	135.1
	March	15.6	9.2	37.1	136.5
	April	13.0	9.8	46.2	163.5
	May	11.4	8.7	110.3	114.3
	June	9.9	7.7	119.2	67.2
	July	9.5	7.5	163.0	99.0
	August	9.8	8.1	93.8	140.5
	September	12.5	6.2	144.0	67.9
	October	13.7	6.9	98.0	137.6
	November	15.4	8.9	63.3	181.5
	December	18.1	9.5	57.0	224.9
YEAR :				1087.0	1707.6
1989	January	19.6	8.2	92.4	223.1
	February	18.0	10.2	75.3	192.5
	March	17.2	9.6	89.2	171.7
	April	14.5	9.4	43.8	175.0
	May	11.9	7.0	111.1	64.1
	June	8.8	7.6	88.2	73.0
	July	7.7	9.2	53.4	142.3
	August	9.3	8.9	53.1	124.1
	September	9.9	13.2	25.3	150.9
	October	13.8	8.4	123.1	129.9
	November	16.0	8.0	23.0	191.5
	December	15.7	8.8	58.8	157.8
YEAR :				836.7	1795.9

1.2 OBJECTIVES

The main aim of this research project was to collect and analyse all the appropriate data and information available and along with field work to make a summary report on the hydrogeology of the Palmerston North region. The six main objectives are listed below.

- 1) To determine the geology and geological history of the area.
- 2) To establish the aquifer systems of the area.
- 3) Find the direction of groundwater flow.
- 4) Investigate the hydraulic properties of the aquifers from pump test data.
- 5) Locate possible recharge zones.
- 6) Analyse and interpret the water quality data from the water quality survey.

CHAPTER TWO - GEOLOGY

2.0 INTRODUCTION

The lower Manawatu River Valley is composed entirely of sedimentary rocks varying in age from Triassic-Jurassic to Holocene which can be divided into three groups: (1) the Mesozoic greywacke of the Ruahine-Tararua axial ranges, (2) the poorly consolidated, mainly marine sediments of the South Wanganui Basin which are Pliocene and Pleistocene in age, and (3) recent unconsolidated non-marine deposits of Pleistocene and Holocene age.

2.1 THE GEOLOGY OF THE STUDY AREA

2.1.1 THE AXIAL RANGES

The Ruahine Range which runs north-east from the Manawatu Gorge and the Tararua Range which runs south-west from the Manawatu Gorge, form a major part of the axial range of the southern North Island. The rocks which make up both the Ruahine and Tararua Ranges belong to a set of rocks known as the Torlesse Supergroup. Large areas of both the North and South Island of New Zealand are underlain by basement rock of Carboniferous to Jurassic age comprising the Rangitata Orogen (New Zealand Geosyncline of earlier writers) (Marden 1984). These rocks are divided into an eastern and western province (Landis & Coomb 1967). The Torlesse rocks belong to the eastern province along with the Maitai, Murihiku, Brook Street, the Caples-Pelorous, Waipapa and the Otago Schist terranes. All the terranes of the eastern province except the Torlesse were derived principally from a volcanic island-arc source, whereas the Torlesse rocks, being quartzofeldspathic, were derived from a tectonically active continental-margin source (Marden 1984). The Eastern Province terranes are thought to have been part of an extensive largely Mesozoic belt of clastic rocks deposited along the Austral-Antarctic margin of Gondwanaland (Fleming 1974). The Torlesse terrane has long been regarded as of dominantly deep-water marine facies, with some shallow water shelf facies

and even deltaic facies having been described for some Torlesse rocks in the South Island. Haast (1865) first used the name Torlesse and this name was revived by Suggate (1961) who proposed the name Torlesse Group for a heterogeneous assortment of structurally complex, poorly fossiliferous, relatively quartz-rich, flysch-like, non-schistose rocks of the New Zealand Geosyncline forming the ranges of the South Island of New Zealand. Stevens (1963) extended the application of the name Torlesse to include the axial ranges of the North Island where it now applies to structurally and lithologically similar rocks. Warren (1967) raised the rank to Supergroup.

Work done by Marden (1984) concentrated on the structure and lithology of the Mesozoic greywacke comprising the Torlesse terrane within the southern Ruahine Range. Prior to this work very little had been done to unravel the lithological and structural relationships of the rocks that make up the Ruahine and Tararua Ranges (Sporli & Barter 1973; Zutelija 1974; Sporli & Bell 1976; Munday 1977). The Torlesse Supergroup is essentially made up of greywacke, here defined as a type of sandstone consisting of a wide range of grain-sizes, with a fine-grained detrital and usually recrystallised matrix with a mixed mineral and rock fragment composition (Reed 1957b). The Torlesse greywackes of the southern Ruahine and northern Tararua Ranges are divided into three lithotypes which occur, from east to west, as 1) Tamaki Lithotype, 2) Wharite Lithotype, and 3) Western Lithotype (Marden 1984). All the lithotypes strike parallel with the general northeast-southwest trend of the axial ranges. The Tamaki and Western Lithotypes are structurally very similar in that each consists of a relatively undeformed sequence of predominantly graded sandstone, siltstone, and argillite lithologies. The main difference between the two is that the Tamaki Lithotype contains additional pebbly mudstone, calcareous siltstone, and intraformational conglomerate lithologies (Marden 1984). The Wharite Lithotype separates the Tamaki from the Western Lithotypes and is structurally very different from both neighbouring lithotypes. The Wharite Lithotype consists of a strongly deformed succession of lens-shaped clasts or blocks of competent lithologies including sandstone, conglomerate, breccia, limestone, chert, and volcanics set in a black, green, or red coloured pervasively sheared argillaceous matrix (Marden 1984).

The Kaikoura Orogeny in Pleistocene times resulted in rapid uplift of the axial ranges in the southern North Island. These periods of tectonic activity have resulted in the Torlesse greywacke rocks being a complexly deformed, highly shattered, crushed, and closely jointed group of rocks. The uplift of the axial ranges occurred along numerous faults and the resultant Ruahine-Tararua Ranges are a horst structure, the associated graben and fault angle depression structures on both sides of the horst being the site of accumulation the marine sedimentation in Waitotaran-Castlecliffian time.

2.1.2 WANGANUI BASIN SEDIMENTS

The greywacke forms the undermass of New Zealand. To the west of the Ruahine-Tararua Ranges it is downthrown to form the underlying bedrock for the South Wanganui Basin in which approximately four kilometres of mainly marine sediments accumulated during the Pliocene and Pleistocene. The area covered by the present South Wanganui Basin was largely emergent prior to the end of the Miocene with development of the basin taking place during the Plio-Pleistocene. Regional tilting has involved progressive subsidence to the south and emergence to the north (Anderton 1981). The origin of the sediments was originally from the south-west but shifted increasingly from the north and north-east as the North Wanganui Basin emerged, followed later by the northern part of the South Wanganui Basin. During the Pleistocene a new source of sediments was provided by the uplifted axial ranges (Anderton 1981). The South Wanganui Basin was connected with the Hawkes Bay and Wairarapa Basins to the east by the "Manawatu Strait" during the early Pliocene; this seaway persisted until the late Pliocene-early Pleistocene. The Manawatu Strait was located at the low point which separates the present Ruahine and Tararua Ranges known locally as the "Manawatu Saddle".

The lower Manawatu Valley lies on the south-eastern margin of the South Wanganui Basin and this location has been a dominant factor influencing the stratigraphy of the covering strata. In general the covering strata dip off and strike parallel to the axial ranges, but because of the marginal position there are many incomplete sections, variations in the thickness, and marked lateral and vertical lithological variations (Rich 1959). The sequence of Wanganui

sediments in this area is compressed as well as incomplete due to low rates of sedimentation, or even non-deposition with bypassing of sediment to deeper water during periods of marine transgression. The upper three stages of the Wanganui series are represented but the presence of the lower most Opoitian stage is doubtful (Rich 1959).

The Wanganui strata overlie the Torlesse Supergroup with strong angular unconformity. Rich (1959) made a detailed study of these beds and recognized and described four formations of Wanganui age, separated into two groups on the bases of age, lithology, and distribution. The first and oldest group is called the Raukawa Group.

The Raukawa Group is made up of two formations, the Totara Sandstone and the Quarry Stream Formation. The Totara Sandstone is the oldest of the covering strata, its basal member being nearly parallel to the eroded greywacke surface. The Totara Sandstone is about 100 m thick and contains very few fossils but what meagre fossil evidence is present indicates Waipipian age but the basal member may be older (Opoitian). The sandstone is thought to have accumulated in a shallow water environment with some shifting currents in the vicinity of the "Manawatu Strait". The source of detritus is likely to be the higher parts of the Ruahine-Tararua Ranges which may have been peninsulas or large islands at the time of deposition. The Totara Sandstone may be equivalent to the basal portion of the Te Aute Formation (Lillie 1953) and was mapped as the Waitotaran Formation by the Superior Oil Company (Feldmeyer *et al.* 1943). The second member of the Raukawa Group was named the Quarry Stream Formation by Rich (1959). A brief marine transgression during the Mangapanian is thought to be responsible for the accumulation of the conglomerates within the Quarry Stream Formation which lie unconformably on the gently dipping Totara Sandstone. Also within the formation is a limestone member. The total thickness of the formation is about 75 m. The source of the sediment is local, probably the northern Tararuas. Due to the absence of *Chlamys delicatula* the Quarry Stream Formation is considered to be Mangapanian, and is thought to be equivalent to the Okiwa Group in the Wanganui area (Fleming 1953). The Raukawa Group can be thought of as representing the Waitotaran Stage with the possibility that the lowest beds may be slightly older and the uppermost beds may be

slightly younger than at the Waitotaran (Ww) type locality (Fleming 1953). However the unconformity between the two members of the Raukawa Group in this area must represent much of Waitotaran time (Rich 1959).

The second group of Wanganui Series sediments recognized and described by Rich (1959) was named the Fitzherbert Group and also consists of two formations, the Centre Road Formation and the Tua Paka Formation. The Centre Road Formation consists of about 80 m of poorly consolidated conglomerates, sands, and silts lying unconformably on all the older lithologies. Faunal evidence indicates deposition in the upper Nukumaruan and correlates with the Maxwell Group of Wanganui (Fleming 1953). Volcanic glass shards, which may be suggestive of Castlecliffian age, occur in the silts - the source being the central North Island volcanic district. Muscovite is also found in these sediments and its origin has been a matter of debate for some time but the most probable source is the granites of the north-west Nelson area. If this is the source of the muscovite then this may also indicate that Cook Strait must have been closed and a continuous beach extended from the north-west South Island to the Wanganui region. Alternatively they could be derived from the Otago schists. The sediments of the Centre Road Formation were laid down in shallow to moderate water depth increasing from south to north with current action still present near the "Manawatu Strait". Deposition was continuous between the Centre Road Formation and the second member of the Fitzherbert Group, the Tua Paka Formation.

The Tua Paka Formation is made up of poorly consolidated micaceous sands, siltstones, and greywacke conglomerates. A feature of this formation is the abundance of pumiceous material which originated from the Taupo Volcanic Zone. There is great lateral and vertical lithological variation and the thickness increases from about 30 m near the ranges to several hundred metres towards the centre of deposition making the Tua Paka Formation the thickest of the covering strata in this area. Varying conditions of both shallow to estuarine and non-marine resulted in a great range of sediments being deposited. The absence of the genus *Pecten*, which is one of the most important forms of the upper Castlecliffian, has lead to the hypothesis by Rich (1959) that the sea appears to have withdrawn from the "Manawatu Strait" and the northern flank of the Tararua Range by the middle of the

Castlecliffian although basinward sedimentation continued until the end of the stage. The basal pumice sands of the Tua Paka Formation are thought to correlate with the richly fossiliferous Butler Shell Conglomerate of the Wanganui Subdivision (Fleming 1953) and represent the first major volcanic activity in the Castlecliffian. The whole Tua Paka Formation is thought to correlate to the Okehu Group and the lowest member of the Kai Iwi group at Wanganui (Rich 1959). The Tararua Range was well established by this time as seen by relict marine cliffs cut along the western flank.

During the Haweran stage the sea again reached the mouth of the Manawatu Gorge for a brief period and cliffed the Tararua Range from Mt. Bryant south. The gravels, silts, and sands that were subsequently deposited were called the Tiritea Formation by Rich (1959). These sediments are poorly consolidated greywacke conglomerates, cross-bedded sands, and massive to thinly bedded siltstones with much vertical and lateral variation. They unconformably overlie the older Wanganui strata. The source of sediments was local, mainly from the axial ranges and from older covering strata. Some pumice is present but most of this is thought to have been derived from pumice already blanketing much of the central North Island. The environment of deposition was shallow to littoral and even subaerial in response to frequent shifting of the strandline. The Tiritea Formation is correlated by Rich (1959) with the Otaki Sandstone described in detail by Oliver (1948 in Rich 1959).

The extensive marine bench exposed following the Oturian Interglacial reveals that the surface has been warped into a number of broad gentle folds related to upthrust fault blocks of greywacke undermass (Te Punga 1957). As the blocks were pushed upward the covering strata, being soft and pliable, behaved like plasticine and gently buckled, arching upward to form domes. Where the blocks subsided or were not uplifted so the sediments formed depressions (Stevens 1974). Dome structures in geologically suitable rocks sometimes provide natural storage areas for oil and natural gas and a number of the domes in the Manawatu have been drilled (Superior Oil Company 1943). All the anticlines are asymmetrical with a sharp eastern scarp and a long gentle western slope. The anticlines along with the associated synclines have controlled the drainage system of the Manawatu region and dictated the

course of all the main rivers. Where the Manawatu River crosses the axial ranges through the Manawatu Gorge, south of the structurally low "Manawatu Saddle", it encounters one of the largest anticlines in the region, the Pohangina Anticline which parallels the axial ranges to the west. Between the Pohangina Anticline and the axial ranges is the associated Pohangina Syncline formed where the Plio-Pleistocene strata dipping off the western flank of the ranges are warped to form the steep eastern limb of the anticline. The Pohangina River flows south along the Pohangina Syncline to join the Manawatu River at the western end of the Manawatu Gorge. Both the Pohangina Anticline and Syncline lie at right angles to the path of the Manawatu River and appear to be responsible for the abrupt bend in the river forcing it to flow southwards in the Pohangina synclinal trough. Further downstream the Himatangi and Levin anticlines have also affected the courses of both the Manawatu and Oroua Rivers. The Oroua River most probably once flowed straight out to sea reaching the coast just north of Foxton while the Manawatu River apparently flowed parallel to the axial ranges entering the sea just to the west of Lake Horowhenua. The doming of the Himatangi Anticline appears to have forced the Oroua River to the south-east where it joins the Manawatu River near Rangiotu and has removed a large portion of the Tokomaru Marine Bench. Active fault scarplets are associated with the Manawatu domes and movement has occurred very recently with the domes probably still growing today (Brown 1978).

2.1.3 PREVIOUS WORK - TERRACES OF THE LOWER MANAWATU VALLEY

The Manawatu River and to a lesser extent the Pohangina River, have become incised within the marine strata of the South Wanganui Basin. Their vallies are now entrenched within a flight of terraces formed by both aggradation and degradation during the Pleistocene. The climate of the Last Interglacial and glacial periods of the Pleistocene has been an especially significant controlling factor in the evolution of the present day landforms (Fair 1968).

During the Otiran Glaciation ice fields were present on the summits of both the Tararua and Ruahine Ranges (Willett 1950) although actual glaciers were restricted to small areas near the summit of the Tararua Range during this glaciation and perhaps the Penultimate Glaciation (Adkin 1912). The main constructional feature of the North Island mountains and adjacent lowlands during the Otiran Glaciation was deposition of extensive aggradational gravels and not moraines as in widely glaciated areas of the South Island.

Fair (1968) made a detailed study of the terraces of the lower Manawatu Valley and recognized four aggradation surfaces and attempted to correlate them with the known ice advances of the Otiran glaciation in New Zealand.

During glacial times when the aggradational surfaces were being constructed, the river took on the form of a wide braided flood plain, providing the fine silt-sized particles that were picked up by the wind and deposited on the higher surfaces. This resultant blanket of loess is thus an indicator of cold climates. A detailed study of the distribution and nature of loess in the Manawatu was conducted by Cowie (1964b). It is reasonable to assume the wind direction in the glacial periods was predominately from the north-west as they are today. Evidence of this is that greater thicknesses of loess occur on the terraces south-east of the Manawatu River. Cowie (1964b) noted the same trend for the other major rivers in the Wanganui Basin. One of the best Pleistocene marker beds (time horizons) in New Zealand is the 22,500 year old Aokautere Ash. This Ash originated from a centre just to the north of the present Lake Taupo and fell during the accumulation of the Ohakean loess in which it is preserved as a distinct pinky-white layer (Cowie 1964a).

All the aggradational terraces in the lower Manawatu River catchment are younger than the late Oturian marine bench deposits, which have been named the Otaki Sandstone (Oliver 1948 in Rich 1959), the Tiritea Formation (Rich 1959), and the Tokomaru Marine Terrace (Cowie 1961 in Fair 1968).

When the sea retreated from the Tokomaru Marine Bench the Manawatu River cut down into the marine sediments establishing a new gradient as it flowed towards the new lower sea-level. The highest aggradational terrace described by Fair (1968) was termed the Forest Hill Terrace. According to Fair (1968)

the Forest Hill Terrace was formed during the later part of the Oturian Interglacial. Further work conducted in this study however, suggests that the Forest Hill Terrace can be correlated with the Porewan terrace in the Rangitikei described by Milne (1973) (see section 2.2.3). Fair (1968) paid attention to the presence of "buckshot gravels" in the profile of the Forest Hill Terrace. These "buckshot gravels" are iron nodules formed by leaching of iron salts. Te Punga (1954) suggested these "gravels" represent a lengthy period of uninterrupted soil formation and warm humid climate. So Fair (1968) suggested that the Forest Hill Terrace and the Tokomaru Marine Bench must have been emergent for a considerable time at the end of the Last Interglacial for the "buckshot gravels" to have formed.

Fair (1968) suggested that the first advance of the Otiran Glaciation resulted in a lowering of sea-level and forced the Manawatu River to degrade thus removing most of the Forest Hill Terrace, remnants of which only occur on the east side of the present river. An associated aggradational terrace was named the Milson Terrace by Fair (1968), dated by Brodie (1957) as occurring in the Wellington region about 37,000 years B.P. with terrace aggradation being greatest between 32,000 - 35,000 years B.P.. The present author disagrees with this interpretation and suggests that the first advance of the Otiran Glaciation resulted in the formation of the Forest Hill Terrace (see section 2.2.3).

Fair (1968) then proposed a second advance which caused the Manawatu River to downcut, this time into the Milson Terrace, leaving only remnants on the west side of the present river. The associated aggradational phase, produced a terrace named the Ashhurst Terrace by Fair (1968), which is dated in the South Island as occurring between 18,000 - 21,000 years B.P. (Suggate 1965). The loess deposits on this terrace do not contain the Aokautere Ash, implying that this terrace continued to form subsequent to the ash shower.

Fair (1968) interpreted a short return to glacial conditions about 14,800 years B.P. with most aggradation ceasing by 14,100 years B.P. (Suggate 1965) which produced the youngest of the aggradation surfaces in the lower Manawatu Valley, named the Raukawa Terrace. Fair (1968) suggests a slow return to warmer conditions because of a 1 m layer of loess overlying the

gravels of this terrace. Steady warming of the climate in the last 10,000 years reached a peak at the Climatic Optimum of 6,500 years B.P.. Evidence in the Wanganui Basin suggests that cliffing of the seaward edge of the Tokomaru Marine Bench occurred during the Holocene (Fair 1968). This may account for the lack of aggradation surfaces on the river between Palmerston North and the coast. Three Holocene river terraces have been described by Cowie (1978) and there is very little height difference between them. Fair (1968) identified a surface just south of Ashhurst which was initially thought to be a river terrace but this turned out to be lacustrine and postulates the presence of a lake in the vicinity of the Manawatu Gorge at some time between the deposition of the Milson Terrace and before the deposition of the Aokautere Ash (Fair 1968).

2.2 PRESENT WORK - TERRACES OF THE LOWER MANAWATU VALLEY

2.2.1 INTRODUCTION

The only major detailed work done on the terraces of the Lower Manawatu River Valley was by Fair (1968). This work is reviewed in section 2.1.3. Work in this study involved remapping the extent of the aggradational terraces and additional profile descriptions were made on both sides of the Manawatu River Valley as far south-west as the Tiritea Stream.

2.2.2 FIELD METHODS

The initial stage of this part of the study was the field reconnaissance phase which involved tracing the terrace edges on NZMS 260 topographic maps around the study area. Numerous road cuttings were examined and chosen for future profile descriptions.

Where the terrace edges were not able to be mapped in the field due to inaccessibility, aerial photographs were used to complete the picture as much as was reasonably possible.

The second part of this work involved the description of the profiles which were chosen to best represent the various terraces. A profile for each major terrace on each side of the river was described where possible. Eight profiles were described and photographed (see Appendix A) to positively establish the position of the terraces in the known terrace sequence.

2.2.3 DISCUSSION

Work on the Holocene terraces by Cowie (1978) mainly looked at the soils on these terrace but nonetheless describes three distinct zones of alluvial accumulation between the Manawatu River and the first aggradational terrace, the Ohakean terrace. The first grouping of soils are those which are subjected to numerous floods and thus are termed rapidly accumulating recent and gley recent soils. These comprise Rangitikei series which are well drained and Parewanui series which are poorly drained. The second grouping of soils are the slowly accumulating recent, gley recent, and organic soils. These soils are subjected to occasional flooding and are made up of the Manawatu, Kairanga, Opiki, and Makerua series (Cowie 1978). Finally there are the non-accumulating recent and gley soils of the Karapoti and Te Arakura series which are not subjected to any flooding as they are elevated enough to be out of range of flood waters.

The first aggradational terrace is the Ohakean terrace, locally known and often referred to as the Ashhurst Terrace. The Ohakean terrace forms an extensive surface throughout the Lower Manawatu River Valley (see figure 2.1). On the north-western side of the present Manawatu River the Ohakean terrace forms much of the area on which Palmerston North is situated. There is a small remnant in the vicinity of Whakarongo and an extensive surface around the township of Ashhurst extending further northwards up the Pohangina River Valley. South-west of Palmerston North City all evidence of

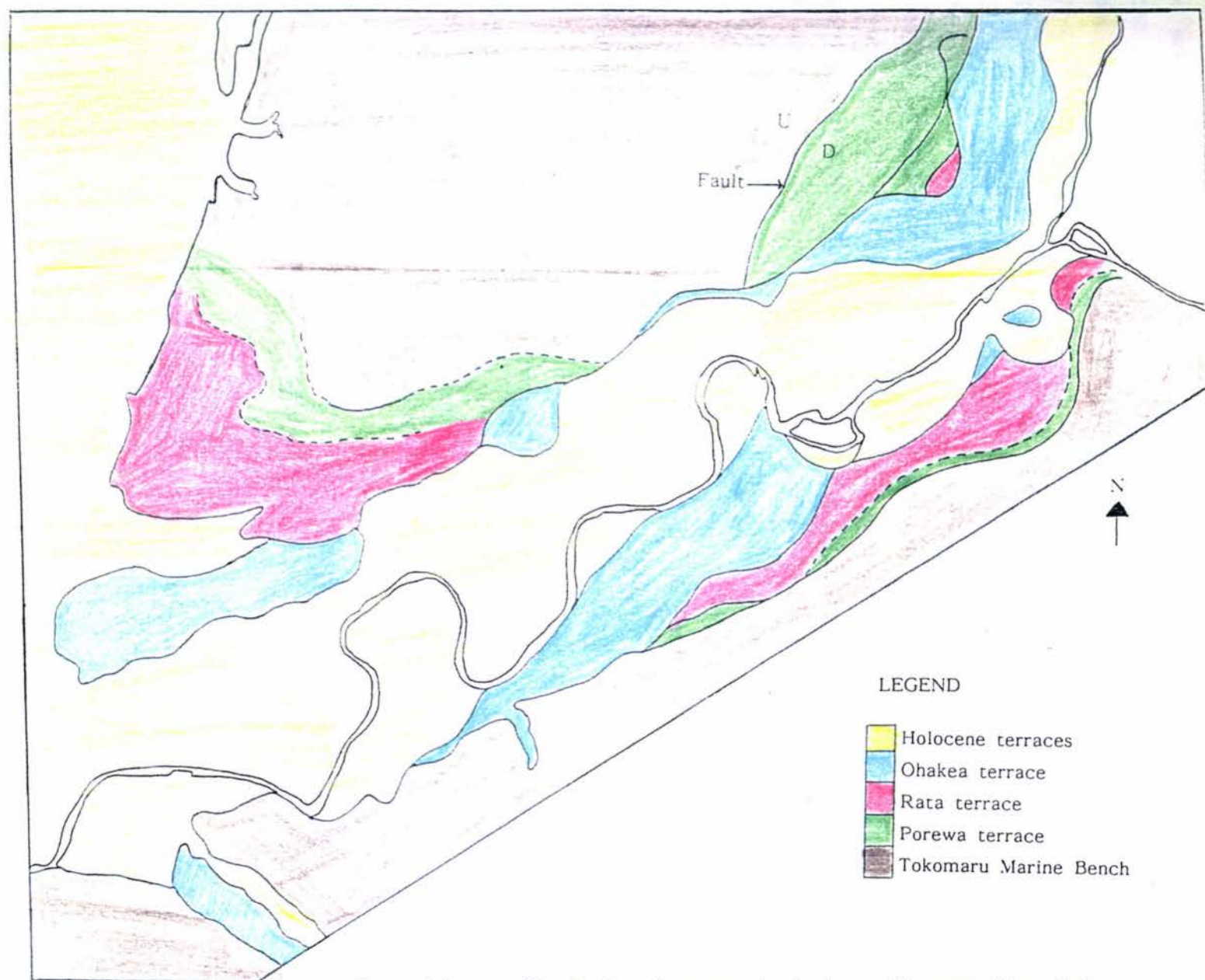


Figure 2.1

Distribution of terraces in the Lower Manawatu River Valley.

the Ohakean terrace has been removed by erosion of the Manawatu River. On the south-eastern side of the Manawatu River Valley the Ohakean terrace is present in the Tiritea Stream Valley, and the Kahuterawa Valley. Between the Tiritea Valley and Aokautere there is no evidence of the Ohakean terrace, but from Aokautere to the Manawatu Gorge it forms an extensive surface. The Ohakean terrace is a result of accumulation or aggradation of mainly greywacke gravels during the last phase of the last ice-age, the Otiran Glaciation, when cool climate persisted between 13,000 and 25,000 years B.P. (Milne 1973). This resulted in reduced vegetation in the Ruahine and Tararua Ranges, which in turn resulted in increased erosion of the axial greywacke due to both increased frost action and increased amounts of exposed rocks. This increased erosion lead to the rivers and streams increasing their bedload and to aggrade as the rivers carried more and more gravels. Subsequently during the Holocene some silt sized material has blown from the present river bed up onto the Ohakean terrace forming a thin mantle of loess in some areas. The amount of loess cover is dependent on the predominant wind direction during the time of accumulation, which in the Manawatu is normally from the north-west. Thus it is to be expected that the gravels on the eastern side of the river will have the greatest thickness of loess cover. The profile description for the Ohakean terrace (see profile 1, Appendix A) shows 30 cm of loess on top of predominately greywacke gravels at this location. Being on the eastern side of the river explains the relatively thick loess cover. In many areas the Ohakean terrace has very little or no loess cover. A contour map for the Ohakean surface was constructed using data from NZMS 1:25,000 topographic maps, heights of bores situated on the Ohakean terrace, and the height (+/- mean sea level) of the top of Ohakean gravels which are below the present ground surface (see figure 2.2).

The gradients of the present Oroua River and the Ohakea terrace are shown in figure 2.3. It can be seen from this figure that the present river has a gradient of 1 in 190 as compared to 1 in 150 for the Ohakea terrace. Three parts of the profile are recognised. The first being upstream where the two profiles diverge from each other with the Ohakea terrace having a marked increase in gradient, this can be attributed to tectonic uplift which has occurred over the last 10,000 years. The second part of the profiles shows that the gradients of both the Oroua River and the Ohakea terrace are very

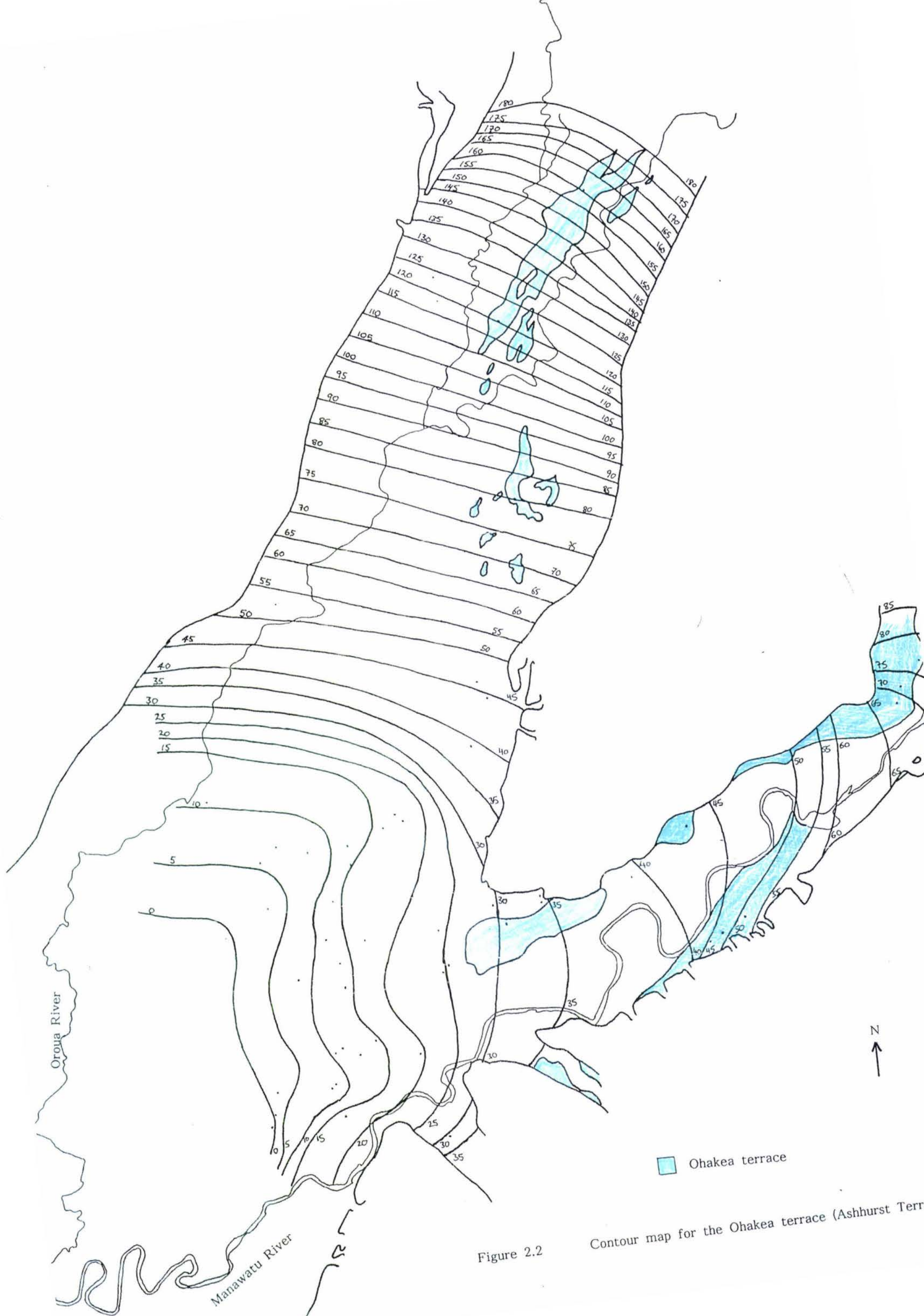


Figure 2.2

Contour map for the Ohakea terrace (Ashhurst Terr)

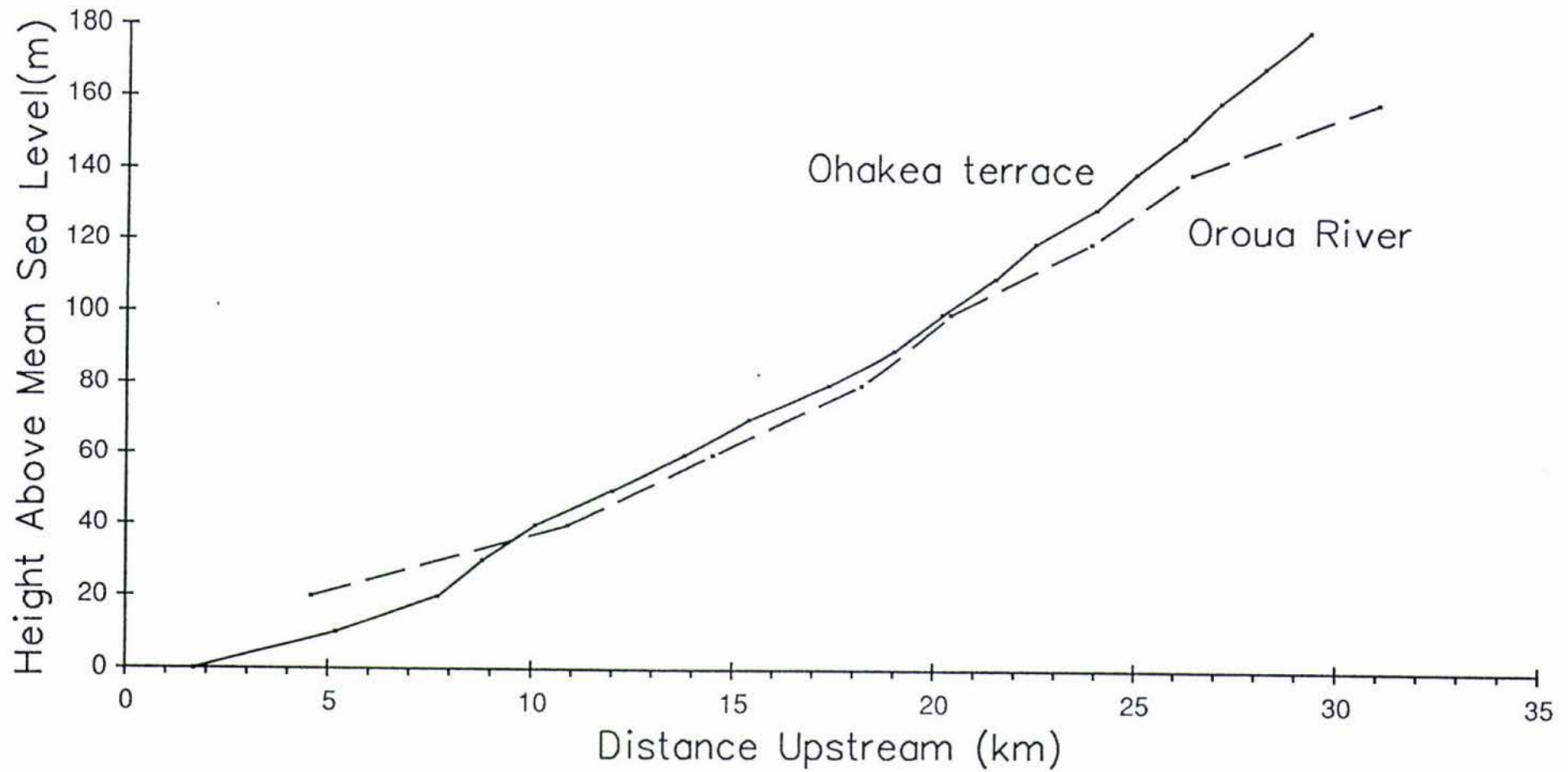


Figure 2.3 Present gradients of the Oroua River and the Ohakea terrace

similar. The third part of the profiles is marked by an increased gradient of the Ohakea terrace compared to the gradient of the Oroua River, this is a result of the lowered sea level when the Ohakea terrace was forming during the last phase of the Otiran Glaciation. Whereas the Oroua River has a very low gradient as it joins the Manawatu River and flows towards the present coastline. Holocene deposits occur from where the Ohakea terrace dips underneath the present land surface to the present coastline.

The second aggradational terrace identified is the Ratan terrace named the Milson Terrace by Fair (1968). This terrace is not very widespread in this study area (see figure 2.1). The Ratan terrace gravels are a result of aggradation of predominately greywacke gravels which accumulated during a cold period between 30,000 and 40,000 years B.P. (Milne 1973). Two sections, one on either side of the Manawatu River were described. One is called the Tua Paka section as it is located near the Massey University farm called Tua Paka (see profile 2, Appendix A), and the other is called the Freyberg section (see profile 3, Appendix A). Both contain approximately 10 cm of Aokautere Ash at a depth of 120 cm and 108 cm respectively. The Tua Paka section has 170 cm of loess cover and the Freyberg section has 205 cm of loess cover. The loess which overlies the Ratan gravels is termed the Ohakean loess as it accumulated on the Ratan terrace during the formation of the Ohakean terrace. The presence of the Aokautere Ash within the Ohakean loess is evidence that the Ohakean terrace was being formed during or subsequent to the deposition of the ash, ie. 22,500 years B.P., and that the Ratan terrace was already formed by this time.

The third and final aggradational terrace identifiable in this study area is the Porewan terrace which was termed the Forest Hill Terrace by Fair (1968). There is some confusion as to the extent and exact location of this terrace on the north-western side of the valley. On the south-eastern side of the valley there is only a small remnant still preserved and this is the location for Fair's (1968) type section for the Forest Hill Terrace (see figure 2.1). The distinguishable feature of this terrace is the presence of two loess units over predominately greywacke gravels. The Porewan gravels were thought to have been aggrading between 65,000 and 75,000 years B.P. (Milne 1973). The top loess unit is the Ohakean loess, in which the Aokautere Ash is preserved,

and the second loess unit is termed the Ratan loess because this loess is thought to have accumulated during the aggradation of the Ratan terrace gravels. Two sections were described in this study, one near the township of Ashhurst which is referred to as the Ashhurst section and one on the other side of the valley on Forest Hill Road. In the Ashhurst section there is 130 cm of Ohakean loess with 12 cm of Aokautere Ash interbedded within. Below the Ohakean loess is 120 cm of Ratan loess which directly overlies the Porewan gravels. There appears to be a paleosol (buried soil) between the depths of 130-150 cm in the profile (see profile 4, Appendix A). The Forest Hill section shows the increased accumulation of loess on the south-eastern side of the valley due to the dominant wind direction from the north-west. There is 650 cm of loess overlying the Porewan gravels in this profile of which 280 cm is Ohakean loess and 370 cm is Ratan loess (see profile 5, Appendix A).

The mapping of the terraces proved to be exceptionally difficult in the vicinity of Ashhurst township and to the north of Palmerston North city. The problem with the terrace sequence to the north of Palmerston North City is that the terrace scarps are very difficult to follow as there is not much difference in height between the lower and higher terraces and often the terrace scarp is very indistinct. To the west of Ashhurst there is a flight of terraces which are very limited in aerial extent but nonetheless appear to be distinct and separate terraces. At first it was thought that there must be a fault in this area which was upthrust to the west, this would account for the numerous terraces in the Ashhurst region. Petroleum reports which include seismic surveys throughout the area were examined at New Zealand Geological Survey, Lower Hutt. A number of reports identify a fault which runs along the present Pohangina River. However this fault is upthrown to the east and is too far to the east to be responsible for an offset of terraces to the west of Ashhurst. Knox et al. (1964) record a fault to the west of Ashhurst which is upthrown to the west (see figure 2.1) but it is too far to the west to explain the numerous terraces to the west of Ashhurst township. One of the terrace scarps may yet be a fault but it has not been identified on seismic surveys. Another possibility is that there is a terrace above the Porewan terrace which is aggradational and was formed some time between the later part of the Last Interglacial and the formation of the Porewan terrace during

a cooler period of time, perhaps oxygen isotope stages 5b or 5d. A possible explanation for the lower terraces is that during the Ohakean stage of the Otiran Glaciation there may well have been two or three separate advances resulting in two or three distinct aggradational terraces being formed.

The next terrace in the sequence is not an aggradational terrace but one of marine origin and is locally known as the Tokomaru Marine Bench. This surface forms a large part of the study area and has been described in some detail by Oliver (1948) and also by Rich (1959). The distinguishable feature of this surface is that it is mantled by three loess units, the Ohakean, Ratan, and Porewan loesses. Only one section was described on the Tokomaru Marine Bench (see profile 6, Appendix A). This section did not show up the paleosols of each of the three loess units but the occurrence of unconsolidated sand at the base of the profile clearly shows that it is of marine origin. This profile shows 300 cm of loess covering the marine strata at this locality but in other areas there may be up to 600 cm of loess cover.

2.3 DATING OF STRATIGRAPHY

During this research two radiocarbon dates, a uranium-thorium date, palynological, and paleontological information were located which concerned this study area. The two radiocarbon dates come from bore 0335 421 which is in the Kairanga Plains region. Two samples were taken from depths of 22 m and 93 m respectively. The sample from 22 m gave a conventional date of 25,900 \pm 410 years B.P. (NZ/7693). This date indicates that the tree trunk from which the date was obtained is of Otiran age possibly prior to the onset of the Ohakean. Figure 3.5 in chapter 3 shows bore 0335 421 and the location of the two radiocarbon dates in the profile. The gravels above the 25,900 year date are Ohakean gravels which here are 13 m thick; the gravels below this date are probably Ratan gravels. The second date is from 93 m depth and gave a radiocarbon date of >35,500 years B.P. (NZ/7694) and thus beyond the range of radiocarbon dating.

A uranium-thorium date has been obtained on a shell sample from the New Zealand Pharmaceuticals bore (bore number 0345 001) at a depth of 116 m. The date obtained was 67,000 +/- 10,000 years B.P.. There were problems obtaining a reliable date from this sample as the sample had a low uranium content, low uranium recovery rate, and the sample was relatively small. Problems arise when dating molluscs through uranium-thorium in that a reducing environment is often established around the shell as protein decomposes. This may result in precipitation of uranium from the groundwater yielding ages which are too young.

Two shell samples submitted to New Zealand Geological Survey by Dr. V.E. Neall from two different sites in the study area contain relevant information. The first sample comes from a location opposite the New Zealand Leather and Shoe Research Institute (LASRI) (NZMS 260 T24/315888) where the sample was collected from a depth of 45 m below the ground surface. This sample contained the macrofossil bivalve Austovenus stutchburyi, and a microfossil assemblage made up entirely of Ammonia becarrii. Both are indicative of muddy, sheltered, slightly brackish shallow harbour or lower estuarine environments. No precise age can be put on these fossils except to say that they are not older than the Kapitean stage of the Taranaki Series. The second sample comes from a bore on the true right bank of the Manawatu River at the north end of the Fitzherbert Bridge (NZMS 260 T24/327893) from a depth of 24 m. The macrofossils present included the bivalve Austovenus stutchburyi and the gastropod Zeacumantus lutulentus. The microfossils are dominated by Ammonia becarrii, Haynesia depressulus, and Elphidium spp. all of which are indicative of shallow sheltered, slightly brackish environments with a similar age range as for the sample from the LASRI site. About 25% of the fauna in this sample comprised open shelf benthics (eg. Uvigerina, Bolivinita, Oolina, Bolivnopsis) and numerous planktics. The open shelf fauna included Globorotalia crassaformis, G. inflata and Globigerina decoraperta giving a late Opoitian to mid Nukumaruan age. This sample contained a very rich assemblage of spores and pollen. Two extinct taxa occur: Nothofagidites cranwellae and Haloragacidites harrisii both having been reworked from Miocene or Pliocene sediments. The rest of the pollen is dominated by Podocarpus (29%), Dacrydium cupressinum (9%), Ascarina lucida (8%), Nothofagus fusca group (6%), Plagianthus (5%), Elytranthe (5%), Coprosma

(4%), and numerous tricolporate taxa (16%). When spores were included in the total count, *Cyathea* species form 61% of the count. This type of pollen rain can only come from a temperate to warm temperate, coastal broad-leaf/podocarp forest. Conditions were wet, humid, and probably slightly warmer than the present day. The assemblage is clearly Quaternary and interglacial probably younger than Castlecliffian. The sediments from which the analysis was done were probably estuarine since only two dinoflagellates were found and very close to the spore/pollen source, since preservation was so good. From this evidence it is suggested that the brackish fauna and flora are the younger sediments and that the shelf sediments were carried in from eroding late Opoitian - mid-Nukumaruan strata possibly from the headwaters of the Pohangina River.

2.4 PREVIOUS RIVER CHANNELS OF THE MANAWATU RIVER

The Manawatu River, which enters the study area at the western end of the Manawatu Gorge, flows south-westwards towards the coast in the Pohangina synclinal trough, called in this study the Lower Manawatu River Valley. On both sides of the present river are flights of terraces. The terraces directly adjacent to the present river are alluvial floodplain deposits of Holocene age. All the other major terraces are older aggradational surfaces corresponding to stadial periods of the Pleistocene. The most recent of these is known locally as the Ashhurst Terrace. The Ashhurst Terrace is correlated with the Ohakea terrace of the Rangitikei described by Milne (1973) and was aggrading between 10,000 and 25,000 years ago during the Ohakean substage of the Otiran Glaciation. Greywacke gravels that make up the Ohakea Terrace are approximately 10-15 metres thick based on water bore logs situated on this surface. During the period of aggradation the gravels occupied the entire width of the valley floor.

During the last 10,000 years the climate has steadily warmed forcing the Manawatu River to downcut into the older Ohakea Terrace gravels resulting in the formation of Holocene degradational terraces adjacent to the present river.

From lithologies recorded in logs of water-bores situated on the Holocene terraces it is possible to reconstruct the previous river channels of the Manawatu River. Some forty bores with adequate information (bore logs and bore heights) are situated on the Holocene terraces within the study area and these were investigated to see what lithologies occurred at various depths. Mean sea level was used as a reference for all the various heights/depths in the study area. Bore 0336 071 was used as an arbitrary reference bore from which all the heights/depths for figures 2.5(a-d) were calculated and is located near the Fitzherbert Bridge. The present gradient of the Holocene terraces was used as a gradient factor and assumed to have been similar during the last 10,000 years.

At a height of say +10 metres above mean sea level at bore 0336071 the lithology was noted and using the gradient of the present river the corresponding lithology at bore X was determined (see figure 2.4). This was done for all the bores with adequate data. Four groupings of heights/depths were chosen at 10 metre intervals: -10 m, mean sea level, +10 m, and +20 m. From the bore information it was possible to construct maps of lithologies for each level. If gravels occurred in the bore logs it was assumed that the river was at that position when the gravel was deposited. Sands indicate areas in close proximity to the river; silts and clays indicate areas at increasing distances from the river.

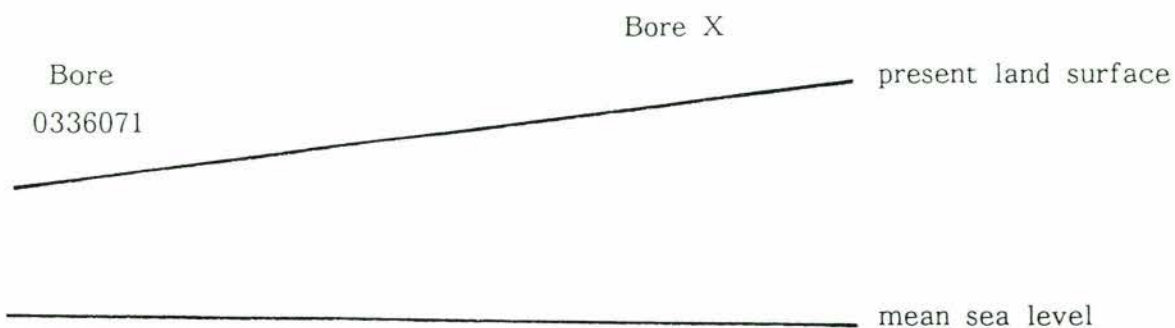


Figure 2.4 - Use of river gradient to calculate lithologies in water bores.

Figure 2.5(a) Lithologies located at -10 m below mean sea level.

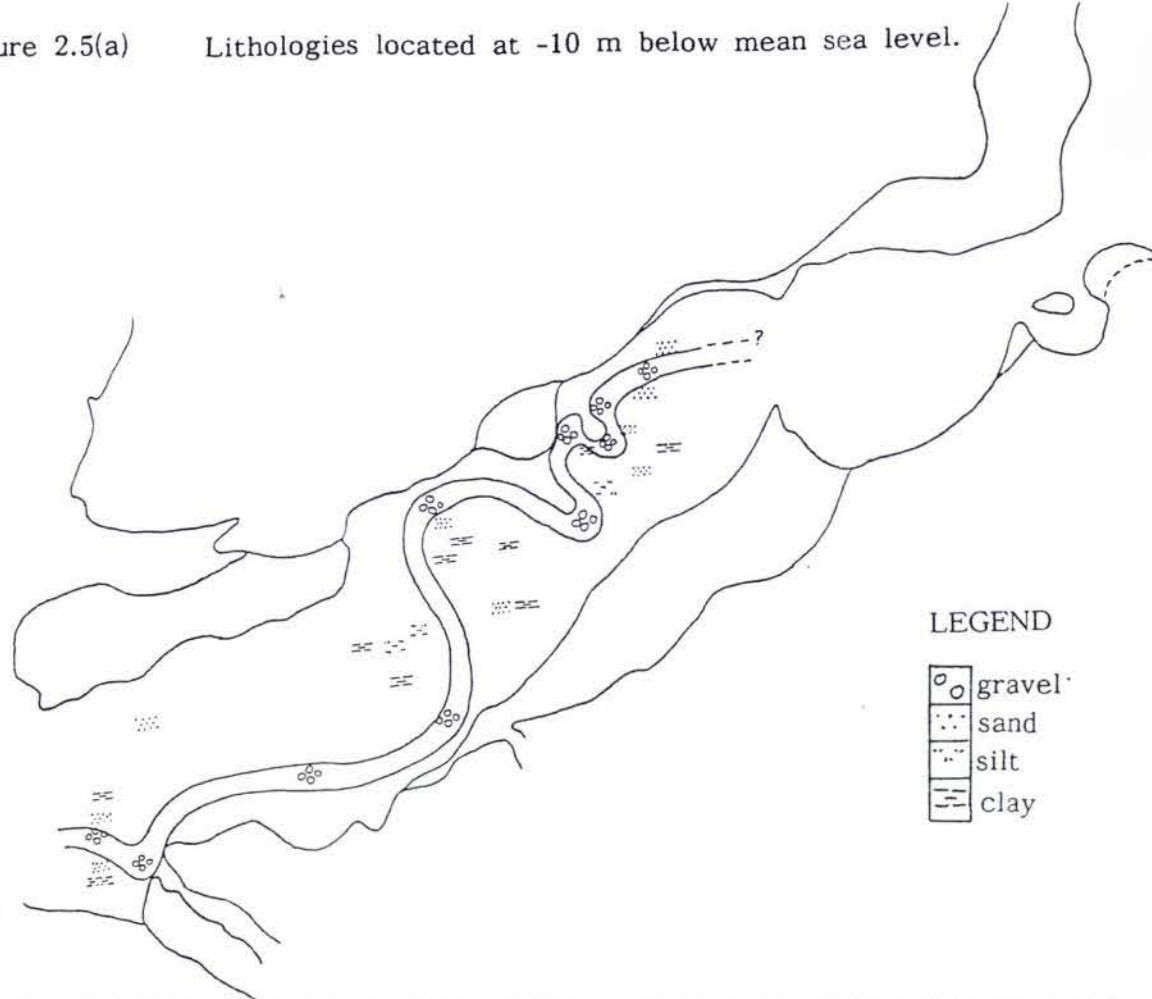


Figure 2.5(b) Lithologies located at mean sea level.

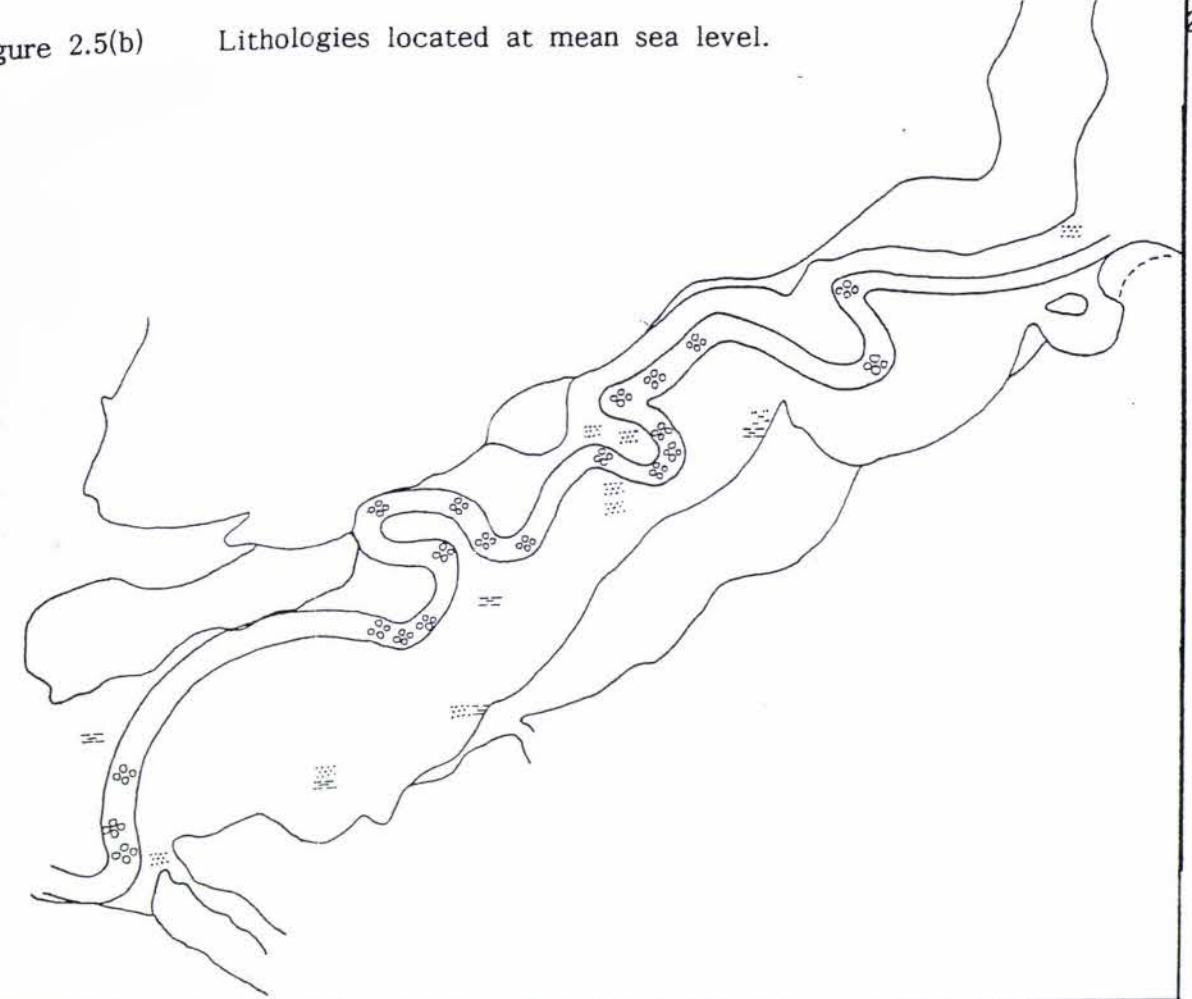


Figure 2.5(c) Lithologies located at +10 m above mean sea level.

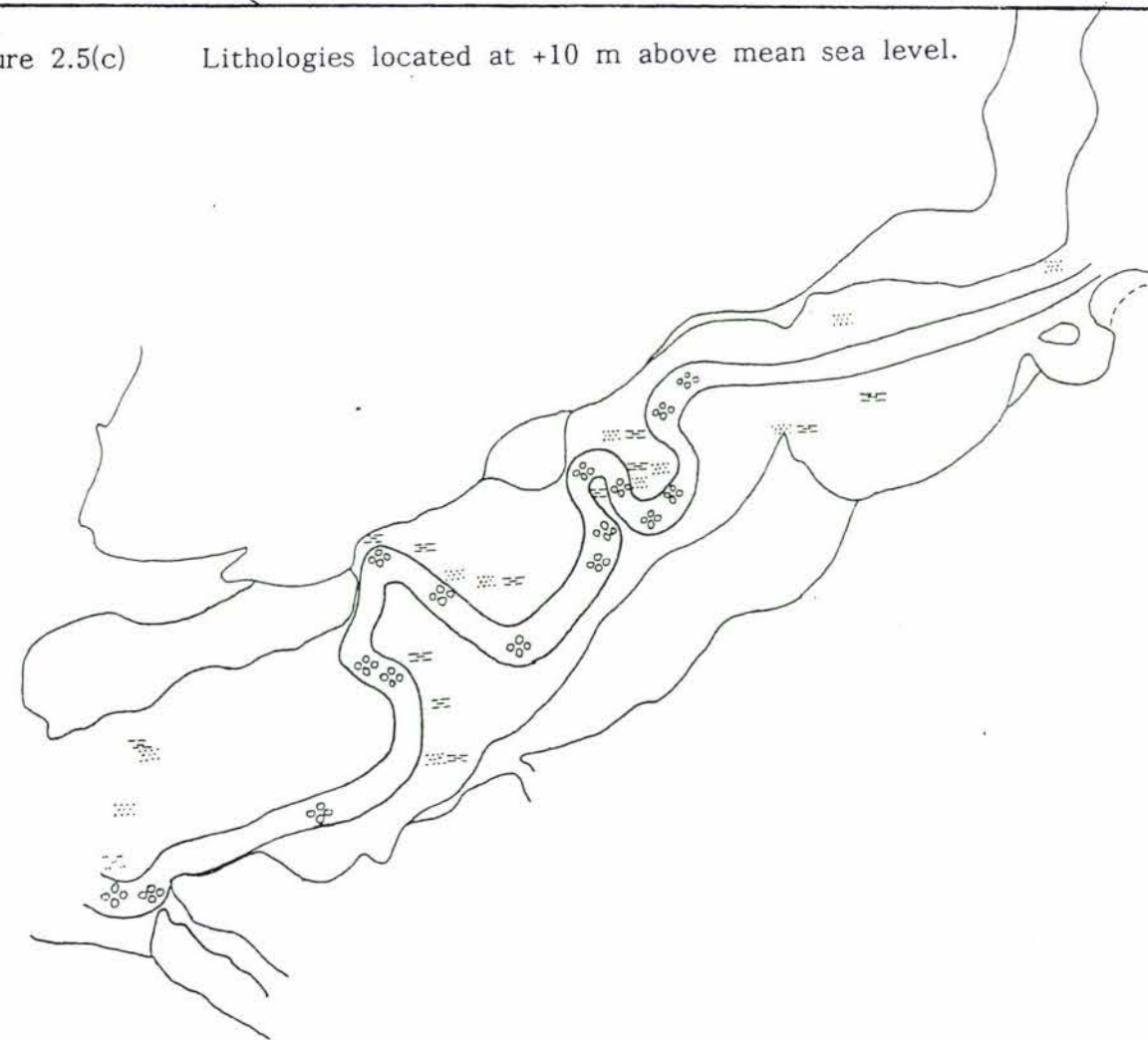


Figure 2.5(d) Lithologies located at +20 m above mean sea level.

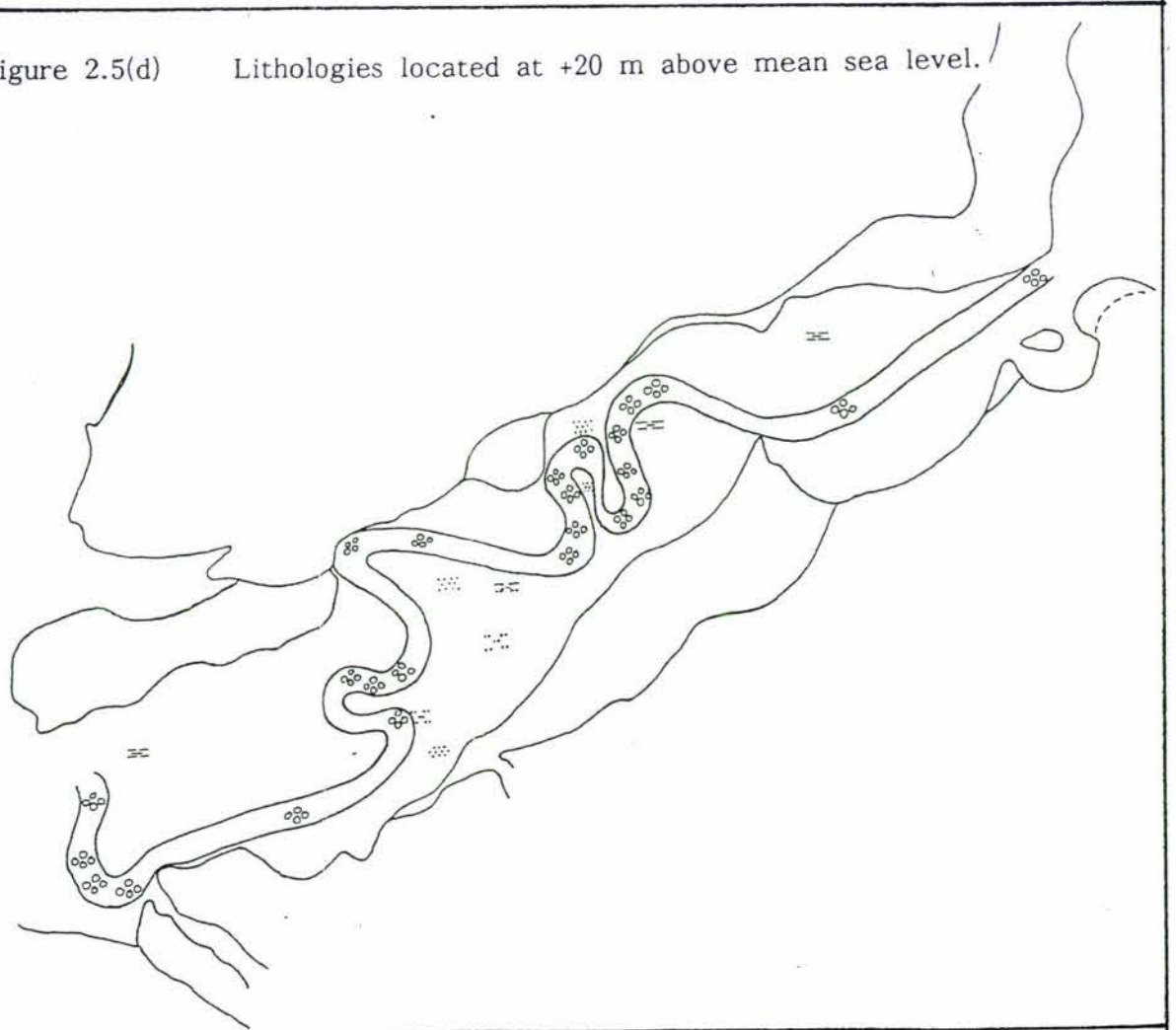


Figure 2.5 Maps showing previous river channels of the Manawatu River.

For the purpose of interpreting the previous river channels and how they relate to the present terrace landforms it is convenient to divide the valley into two parts, the eastern part and the western part.

The eastern part of the valley lies between Manawatu Gorge and Aokautere and the western part lies between Ashhurst and the western part of Palmerston North City. The river originally flowed along the north-west side of the valley between Ashhurst and Roberts Line removing the older Ohakea aggradational terrace (see figure 2.5(a)). The river continued to flow in the north-west of the valley for some time and continued to remove nearly all evidence of the Ohakea terrace except for a small remnant at Whakarongo (see figures 2.5(b) & 2.5(c)), until the river suddenly altered its course quite recently to the south of the valley to begin eroding the Ohakea terrace between Aokautere and the Manawatu Gorge (see figure 2.5(d)).

South-west of Roberts Line and Aokautere, the river seems to have always been restricted to the south-east of its channel removing all evidence of the Ohakea terrace on the south-east side of the river from Aokautere to the Tiritea Stream. Only the Ohakea terrace in the channel of the tributary Tiritea Stream remains preserved. However because the river tracked southwards in this segment of the valley, it preserved an extensive tract of Ohakea Terrace in the centre of Palmerston North city (see figure 2.5(d)).

The history of the Manawatu River explains why so much of the Ohakea Terrace is not present on the northern side of the valley and why the extensive surface on the south side of the valley is being currently eroded by the present Manawatu River.

CHAPTER THREE - THE AQUIFER SYSTEM

3.0 INTRODUCTION

Groundwater is a very important natural resource and should be properly managed to ensure continued availability for the future. It is therefore important to investigate the extent of such a resource and its capacity to supply suitable water for domestic, industrial, agricultural, and horticultural uses.

Within this study area there are 249 groundwater bores with available information regarding bore depth and numerous others which have no information because they are too old. To assess the type, extent, and potential of an aquifer system the following information would ideally be available for every bore:

1. Depth of bore from the land surface.
2. Bore log.
3. Static water level (SWL).
4. Height of bore above a reference level (normally mean sea level).
5. Pump test results.
6. Grid reference.

3.0.1 BORE REFERENCES EXPLANATION

Each bore in this study area has a bore number designation devised by the Manawatu Catchment Board, which is now incorporated into the Manawatu-

Wanganui Regional Council. NZMS 260 1:50,000 maps are divided up into rectangular blocks or grids measuring 8.25 km x 11 km, covering an area of 90.75 km², the grid lines for the blocks do not coincide with the grid lines of the topographic maps. Within this study area there are eleven grids represented: these are, starting from the top left hand corner of figure 1.1, chapter 1, moving right, 0324, 0325, 0326, 0327, the next row down are 0334, 0335, 0336, 0337, and finally the last row down is 0344, 0345, 0346 (see figure 1.1). Within each grid every bore has a second set of numbers denoting the individual bore, each number ends in the numeral 1. There is no particular numbering order within each grid. For example bore number 0336 041 represents bore number 041 within grid 0336. This system is useful for quick identification of individual bores and is used in this study. However for accurate location of all the bores it is necessary to also use the NZMS 260 1:50,000 grid coordinates. These were used in the preparation of the isoconcentration maps in section 4.2, and the piezometric maps in section 3.2.3.

3.1 AQUIFER DATA

3.1.1 BORE-LOGS

When a water bore is being drilled by a contractor, the rock types which are encountered during the drilling are brought to the surface and their approximate thickness recorded by the well-driller. Once the bore has been completed the final bore-log must be sent to the Regional Council. Of the 249 bores in this area with depth information, 177 have bore-logs which were obtained from the Manawatu-Wanganui Regional Council. There are many different types of bore-log forms (see figures 3.1 & 3.2) but all supply information regarding the various lithologies and thicknesses encountered during the drilling. Because there is no standard description method for describing lithologies the accuracy of the bore-logs will vary from one well-driller to another, for example what one driller may call a mudstone another may call clay. The bore-logs normally describe a lithology along with a colour and occasionally relative grain size such as very coarse, coarse, medium, fine, and very fine are included. Some of the gravels are described with the dominant size diametres recorded.

Richardsons Drilling Co., Ltd.

1. ZONE OF BORING K148 N148989277		Client: <u>Richardsons Drilling Co., Ltd.</u>		JOB NUMBER	
Location: <u>Richardsons Drilling Co., Ltd.</u>		Drilling Method: <u>Cable Tool</u>		BORING NUMBER	
Sampling Method: <u>Open Pit</u>		DATE: <u>10/10/19</u>		SHEET OF	
WATER LEVEL: <u>10.0m</u>		TIME: <u>10.00</u>		DATE: <u>10/10/19</u>	
CASING DEPTH: <u>10.0m</u>		SURFACE CONDITIONS: <u>Bore No. 148989277</u>		DATE: <u>10/10/19</u>	
DATUM: <u>Mean Sea Level</u>		ELEVATION: <u>10.0m</u>		TIME OF DAY: <u>10.00</u>	
INCHES DOWN RECORDED		FEET DOWN RECORDED		SOIL CLASS	
0 - 0.3		0.3 - 3.1		3.1 - 7.2	
7.2 - 12.1		12.1 - 13.6		13.6 - 15.2	
15.2 - 44		44 - 52		52 - 74	
74 - 85		85 - 86		86 - 94.5	
94.5 - 106		106 - 107.5		107.5 - 109.5	
109.5 - 118		118 - 122		122 - 125.5	
125.5 - 128		128 - 133		133 - 135	
135 - 137		137 - 138		138 - 139	
139 - 140		140 - 141		141 - 142	
142 - 143		143 - 144		144 - 145	
145 - 146		146 - 147		147 - 148	
148 - 149		149 - 150		150 - 151	
151 - 152		152 - 153		153 - 154	
154 - 155		155 - 156		156 - 157	
157 - 158		158 - 159		159 - 160	
160 - 161		161 - 162		162 - 163	
163 - 164		164 - 165		165 - 166	
166 - 167		167 - 168		168 - 169	
169 - 170		170 - 171		171 - 172	
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226 - 227		227 - 228		228 - 229	
229 - 230		230 - 231		231 - 232	
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547 - 548		548 - 549		549 - 550	
550 - 551		551 - 552		552 - 553	
553 - 554		554 - 555		555 - 556	
556 - 557		557 - 558		558 - 559	
559 - 560		560 - 561		561 - 562	
562 - 563		563 - 564		564 - 565	
565 - 566		566 - 567		567 - 568	
568 - 569		569 - 570		570 - 571	
571 - 572		572 - 573		573 - 574	
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577 - 578		578 - 579		579 - 580	
580 - 581		581 - 582		582 - 583	
583 - 584		584 - 585		585 - 586	
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589 - 590		590 - 591		591 - 592	
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610 - 611		611 - 612		612 - 613	
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619 - 620		620 - 621		621 - 622	
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640 - 641		641 - 642		642 - 643	
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646 - 647		647 - 648		648 - 649	
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652 - 653		653 - 654		654 - 655	
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664 - 665		665 - 666		666 - 667	
667 - 668		668 - 669		669 - 670	
670 - 671		671 - 672		672 - 673	
673 - 674		674 - 675		675 - 676	
676 - 677		677 - 678		678 - 679	
679 - 680		680 - 681		681 - 682	
682 - 683		683 - 684		684 - 685	
685 - 686		686 - 687		687 - 688	
688 - 689		689 - 690		690 - 691	
691 - 692		692 - 693		693 - 694	
694 - 695		695 - 696		696 - 697	
697 - 698		698 - 699		699 - 700	
700 - 701		701 - 702		702 - 703	
703 - 704		704 - 705		705 - 706	
706 - 707		707 - 708		708 - 709	
709 - 710		710 - 711		711 - 712	
712 - 713		713 - 714		714 - 715	
715 - 716		716 - 717		717 - 718	
718 - 719		719 - 720		720 - 721	
721 - 722		722 - 723		723 - 724	
724 - 725		725 - 7			

The occurrence of shells in a bore-log is vitally important as the first shells indicate the sediments are of marine origin. A problem arises in that shells occur in Castlecliffian sediments further upstream in the Pohangina River Valley which are currently being eroded and can be carried downstream and redeposited along with other fluvial material. This would falsely lead one to believe that the sediments were *in situ* marine but are in fact redeposited fluvial sediments. In this study however it is assumed that once the shells are eroded further downstream, the river flow would cause the fragile shells to be smashed and broken into fairly small fragments. For a well-driller to note the occurrence of shells in a bore the shells would have to be either in tact or of large enough size to be noticed and he would not note down shells if small fragments were present. Therefore in this study if shells are noted in a bore-log lithology it is assumed to represent marine shells *in situ* and not reworked marine sediments.

Once all the bore-logs were obtained they were then all drawn up in pictorial form using conventional geological symbols. This was necessary if correlation between bores was to be attempted. Correlation proved to be extremely difficult even between bores which are only tens of metres apart. The difficulty of correlation stems from the fact that the nature of the Manawatu River and its meandering history (see chapter 2, section 2.3) resulted in a very complex sequence of lithologies being deposited with very limited spatial extent. The correlations achieved were mainly concentrated on the water bearing gravel and sand strata.

3.1.2 PIEZOMETRIC DATA

The piezometric water heights refer to the height to which the groundwater from a particular depth in a bore will rise to in its natural state. If the water rises to reach the ground surface and is naturally flowing the bore is said to be a flowing artesian bore and will produce a positive pressure or a positive static water level. Measurements of positive static water levels is done by means of a portable pressure meter which measures the pressure in either kilo-pascals (KPa) or milli-bar (mb). These pressure measurements can be converted into heights by multiplying the pressure (in mb) by 10.2 giving a

static water level in milli-metres. If the water in the bore does not reach the surface the measurement of the piezometric water height is made by lowering a line with two electrodes down the bore casing until the electrodes make contact with the water allowing the current to flow. This is observed on a meter at the surface. The static head is the length of line required to reach the water from the surface and is said to be negative.

There are 144 bores in this study area with recorded static water levels. Of these 43 have static water levels below the land surface and the rest are naturally flowing. Most of the static water levels recorded come from the bore-logs where the driller has noted the approximate water level at the time of the drilling. Water levels in wells vary over time due to numerous reasons:

1. Seasonal oscillations caused by increased recharge in the winter and decreased recharge in the summer months.
2. Influence of pumping of bores which are in close proximity. Pumping a bore creates a cone of depression around the bore which may cause the water level in neighbouring bores to be lowered.
3. Some bores close by the coast may have tidal influences which can cause minor oscillations in the water level in the bore.
4. Continuous pumping of a bore over a long period of time may cause the natural water level in the aquifer to decrease.

These variations in water levels must be taken into account when dealing with piezometric interpretations. The Manawatu-Wanganui Regional Council has an ongoing programme which monitors the water levels in 14 bores continuously throughout this study area, which the author has assisted with. The bore at Milson Airport, bore 0336 001, has been continuously monitored since 1970 and during this time a decrease in mean annual static water level is noticed (see figure 3.3). Therefore since many of the static water levels come from bore-logs which are fairly old their water levels are very likely to have changed and thus there may be considerable error in using these to produce the

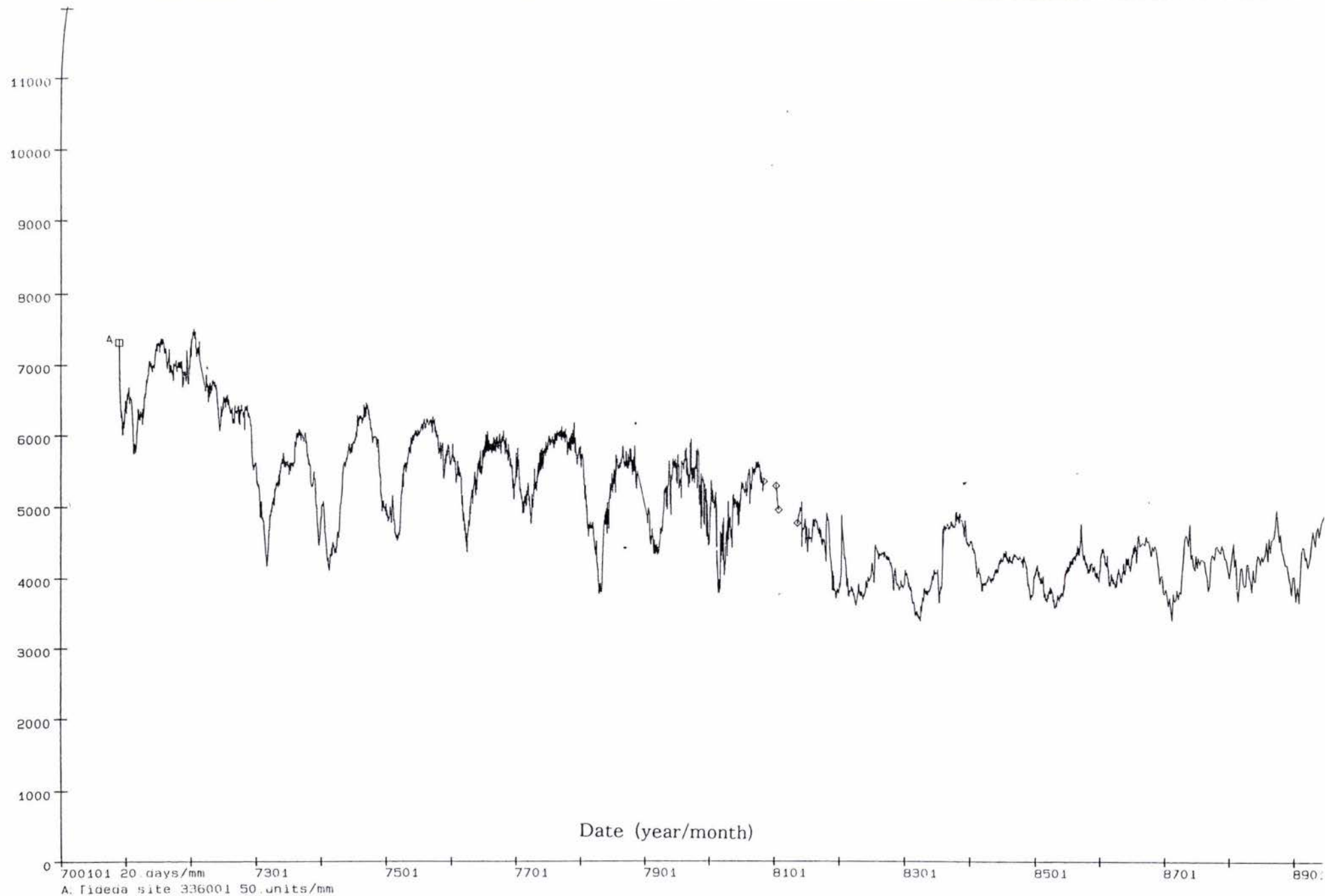


Figure 3.3 Variation in static water level over time for bore number

piezometric maps in section 3.2.2.2. From figure 3.3 the average water level is assumed to have dropped approximately 1 m over a 10 year period. Static water levels are meaningless unless they are referred to a set reference level, in this case all heights are referred to mean sea level (see section 3.1.3).

3.1.3 WELL LEVEL DATA

A necessary part of any hydrogeological investigation is the measurement of the height above mean sea level of the top of each bore. Some of the bore-logs provided this data but in most cases leveling of the bores is required. This is done by means of a theodolite starting at a known height above mean sea level, normally a Department of Lands and Survey benchmark, and measuring the difference in height (rise or fall) to each bore. An ongoing bore height leveling survey is being carried out by the Manawatu-Wanganui Regional Council in which the author assisted and the number of bores which have been measured in this study area is presently 177.

The Department of Lands and Survey uses two reference datum points for mean sea level in the Manawatu, mean sea level Wellington and mean sea level Moturiki. The difference between mean sea level Moturiki, which is an island situated near Mount Maunganui, and mean sea level Wellington was 0.12 m in 1953 so is not very significant in this type of study as errors in water level measurements are estimated to be in the order of ± 0.5 m. The measurement of bore levels is very accurate as they are measured to 0.1 mm. In some cases the height of a bore was estimated from NZMS 260 1:50,000 topographic maps. Large errors, probably ± 5 m, are associated with this type of estimation but these are greatly reduced by using the known heights of surrounding bores in estimating the height of the unknown bore.

Well level data is a necessity to establish the relative depth of each bore, to calculate static water levels, and to produce useful cross-sections of the aquifer system.

3.1.4 PUMP TEST DATA

When drilling of a bore is finished it is usual that a pump test is carried out to establish whether or not the well will supply enough water for the intended use and to see whether or not the required pumping rate will affect surrounding bores. During a pumping test the well is pumped at a constant rate in excess of the required rate for a period of time until the water level in the bore approaches a stable level, normally not more than 10 mm change in water level in 30 minutes is considered to be the equilibrium. The bore is then allowed to recover with the water level being monitored during the withdrawal and the recovery periods. There are a number of different methods which are used to analyse pump test data but all use the following assumptions: i) the aquifer is of seemingly infinite aerial extent; ii) the aquifer is homogeneous, isotropic and of uniform thickness over the area influenced by the pumping test; iii) the pumped well penetrates the entire aquifer and thus receives water from the entire thickness of the aquifer by horizontal flow; and iv) the aquifer is confined (Kruseman & De Ridder 1970 in Tracey 1986). In most natural situations assumptions i), ii), and iv) are not met due to the nature of the geology within an area. Assumptions i) and iv) definitely do not apply in this study area because the river has built up a sequence of complex lithologies of very limited spatial extent which form both the aquifer and confining lithologies.

Ideally if a full pump test is being done on a bore then it is necessary to have a second bore, known as an observation bore, situated nearby. Static water level would be monitored in the observation bore to see the effect the pumping has on the surrounding bores due to the cone of depression created around the bore being pumped. If an observation bore is monitored then the following aquifer parameters can be calculated from the results:- transmissivity, hydraulic conductivity, storativity, and specific storage. If no observation bore is monitored then only the transmissivity can be calculated.

All the data on pump tests was obtained from the Manawatu-Wanganui Regional Council. Only five bores within this study area have had full pump tests with observation wells being monitored and a further eight have had pump tests without an observation well being monitored. Many of the bore

logs contain information regarding natural flow rates but these are only very rough estimates because no flow meter was used. In total 111 bores have some information regarding the discharge of the bore (see table 3.1). Little work was done in this study regarding pump test analyses as reliable data is very sparse and the rest of the available data is not very reliable. There is an overall trend of increasing discharge with increasing depth, the average discharge for the bores in the depth range 0 - 60 m is 571 m³/day, the average discharge for bores in the depth range 60 - 120 m is 1122 m³/day and for the bores deeper than 120 m the average discharge is 1441 m³/day. Transmissivities, which is a measure of the amount of water that can be transmitted horizontally by the full stratal thickness of the aquifer under a hydraulic gradient of one, throughout the area range between 150 - 2000 m²/day with an average of 994 m²/day. The storativity, which is the volume of water produced from storage per unit decline in head perpendicular to the surface (Freeze & Cherry 1979), of the aquifers throughout this area range from 1.1×10^{-4} to 3.2×10^{-4} with an average value of 1.86×10^{-4} .

3.1.5 RIVER GAUGING DATA

Recharging of aquifers can originate from several different sources. A very important source of recharge water is through the loss of river water as the water moves downstream. To detect any water losses or gains in a river the river must be gauged. This entails measuring the flow rate or river velocity at varying depths at set distances across a point in the river, this procedure is then repeated at various points downstream or upstream in the river. The various flow rates measured across the river at the various depths can be used to calculate an overall flow rate at that point in the river using a gauging formula which is dependent on the make and model of the flow rate measuring device. Once several flow rates have been calculated for points up and down the river a graph of discharge versus position along the river can be plotted which will show any gains or losses in the river system. It is normal to see an overall gain in the river system as tributary streams flow into the major river. A series of river gaugings were carried out by the Manawatu-Wanganui Regional Council during the month of March 1989 from one end of

Table 3.1 Discharge rates for bores in the 0-60m, 60-120m, and >120m depth ranges.

0-60m				60-120m				>120m			
Grid	Bore	Disch.	Depth	Grid	Bore	Disch.	Depth	Grid	Bore	Disch.	Depth
		(m ³ /day)	(m)			(m ³ /day)	(m)			(m ³ /day)	(m)
325	051	384	12	326	361	430	63	334	031	530	124
344	021	192	12	336	531	650	66	335	051	1945	126
335	021	130	13	327	071	1300	69	326	181	260	135
326	031	120	14	335	171	325	69	326	221	1440	135
335	401	153	15	335	381	650	69	345	011	1872	135
336	611	346	16	336	031	1166	70	344	051	875	137
335	061	120	17	336	161	855	70	335	331	273	141
335	281	144	19	325	001	144	73	336	251	1944	152
336	281	40	24	335	341	650	74	326	191	650	154
335	151	710	25	335	391	1500	74	335	041	2500	155
337	021	1945	27	335	091	518	77	325	071	985	170
335	251	100	28	326	051	150	79	335	351	2270	171
336	351	32	28	336	071	3240	80	325	091	2280	172
326	021	120	29	336	311	520	80	335	191	3000	176
335	111	194	29	335	001	360	82	326	091	290	208
344	011	192	29	335	271	45	82	335	291	1945	237
336	221	227	30	337	031	2130	83				
324	031	1010	31	326	331	3200	86				
336	591	103	31	345	071	150	87				
335	301	163	33	325	081	260	89				
344	081	72	35	334	051	110	90				
336	051	336	36	326	041	32	91				
336	291	26	37	335	071	1945	91				
336	241	130	40	335	011	192	92				
337	001	1555	40	335	211	130	92				
327	011	713	41	334	021	1944	95				
336	391	1230	42	335	321	1440	95				
336	141	1620	43	327	001	130	96				
336	601	163	45	336	491	1620	96				
336	481	1166	47	334	041	3240	99				
327	021	130	48	336	301	2700	100				
335	031	580	48	326	171	1296	102				
336	471	650	48	335	261	170	103				
336	511	1620	49	335	241	432	104				
325	031	72	50	327	081	130	106				
335	141	2700	50	326	101	130	108				
336	431	2600	50	335	371	385	108				
336	551	160	52	335	421	144	108				
345	051	227	52	336	231	194	111				
335	231	97	56	335	361	3900	112				
325	041	1556	57	326	011	650	113				
336	021	1620	58	336	361	2200	113				
336	061	78	59	344	071	97	113				
336	561	40	61	335	221	8865	114				
337	051	130	61	326	001	1300	117				
				327	041	78	120				
				335	101	970	120				
				336	581	1200	120				

AVERAGE

DISCHARGE: 571 m³/day

AVERAGE

DISCHARGE: 1122 m³/day

AVERAGE

DISCHARGE: 1441 m³/day

the Manawatu Gorge downstream to about the Whakarongo area by means of a jet boat in which the author assisted. A detailed discussion on the results of this gauging is presented in section 3.2.4.1.

3.2 THE AQUIFERS

3.2.1 INTRODUCTION

The idea that an aquifer system is made up of many discrete and separate aquifers only very rarely exists in natural systems. The geological history of the area will control the extent of both the water bearing and the impermeable confining strata. The nature of the Manawatu River and its history has resulted in a sequence of clay, silt, sand, and gravel deposits which are exceedingly complex in detail. The coarsest deposits, the sand and gravel, provide the best water-bearing aquifer materials whereas the finer deposits, the silts and clay, usually form the confining non-permeable layers. Despite the great lateral variability of river valley sediments, most of the valley deposits have a simple vertical succession from coarse sands and gravels near the bottom of the channel to silts and clays at the top. The relative thicknesses of the coarse and fine layers is dependent on the type of sediments carried by the river and the geologic history of the river (Erdelyi & Galfi 1988).

Because there is such a complex sequence of sediments in the river valley of the Manawatu River the identification of separate isolated aquifers is impossible. Instead the aquifer system is divided into depth ranges which are considered to be the closest resemblance to separate aquifers. In reality the nature of the sediments in the whole of the system is such that most of the water bearing strata and non-water bearing strata are in contact with one another both vertically and laterally. This has resulted in a aquifer system which is called a 'leaky' system, meaning that the water bearing strata are interconnected allowing groundwater to flow both horizontally and vertically without much restriction.

3.2.2 THE THREE AQUIFERS

The separation of this aquifer system into three separate aquifers is tentative as the whole system appears to be interconnected in some way or another. The separation is based on the depth of the bores and three depth ranges are recognized, 0 - 60 m, 60 - 120 m, and greater than 120 m depth. These depth ranges are with reference to the depth of the bore from the ground surface. It can be seen from figure 3.4 that there appears to be a layer of low permeability material, either clay or silt, at a depth of about 40 m from the surface. There are many exceptions to this situation but this layer may well act as a confining layer throughout a large area of the lower river valley.

It can be seen from the cross-sections (see figures 3.4 & 3.5) that correlation of the bore-logs, even as simplified as they are presented here, is very difficult due to the nature of the Manawatu River. Figures 3.4 & 3.5 both show the complexity of the aquifer system but there does seem to be some pattern in the distribution of the water bearing strata and it is on the basis of this that the depth divisions were chosen. Approximately 75% of the bores within this study area extract water from gravel aquifers, 15% from sand aquifers, and 10% from sand/gravel aquifers.

3.2.3 PIEZOMETRIC MAPS

The static water levels along with the height of the bore above mean sea level were used to construct piezometric maps. The static water level, with respect to mean sea level, in an aquifer system normally decreases from the area of recharge to the area of discharge. Piezometric maps are very useful in determining the direction of flow within an aquifer system and will show the hydraulic gradient of the system.

At first the water level data from all bores regardless of depth was used to construct a piezometric map for the whole study area (see figure 3.6). The NZMS 260 grid references were used as the X and Y coordinates and the

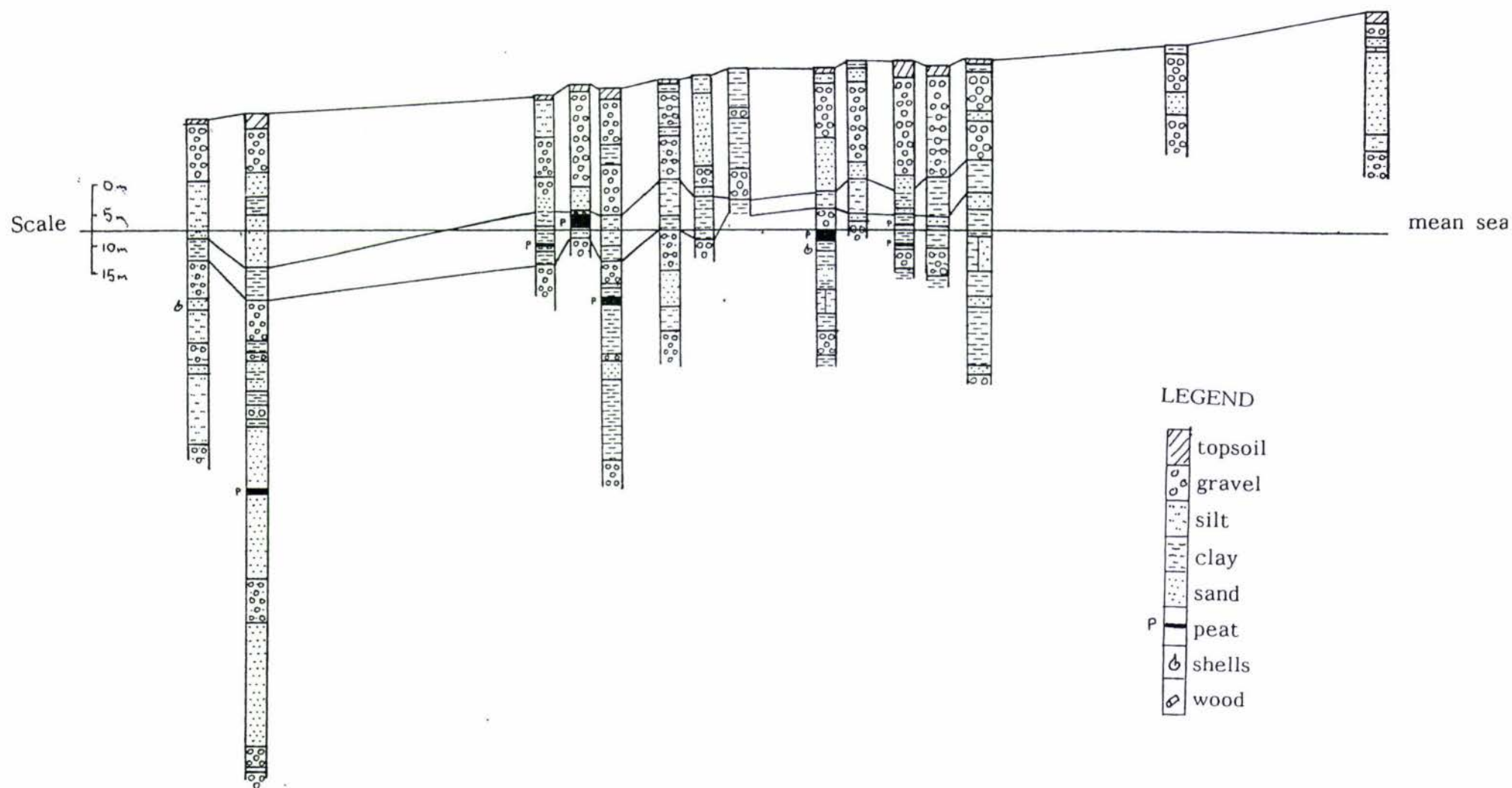


Figure 3.4

Cross-section using bore-logs from Ashhurst to Palmerston North City along the Manawatu River.

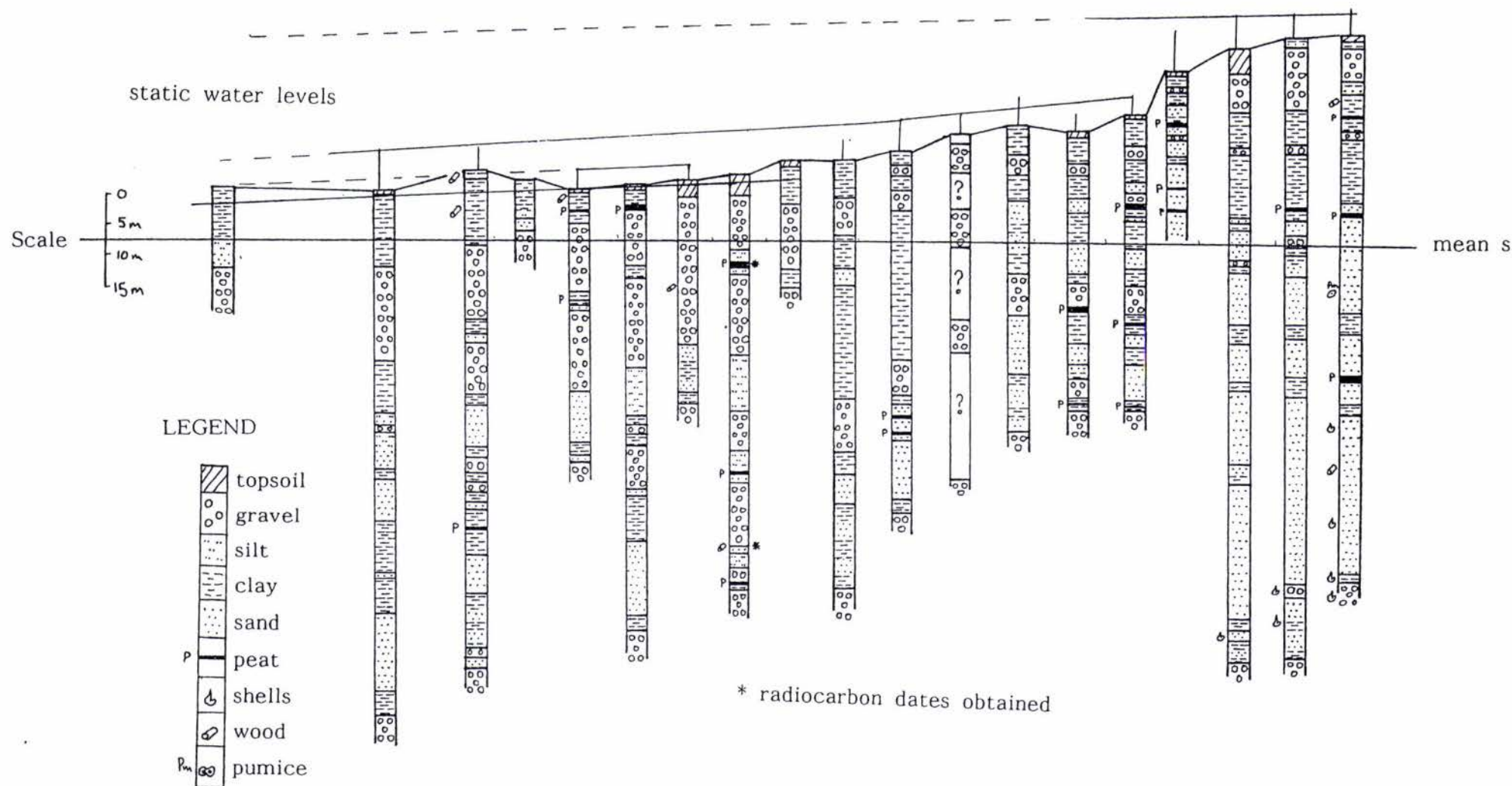


Figure 3.5

Cross-section using bore-logs from Bunnythorpe township to the confluence of the Manawatu and Oroua Rivers.

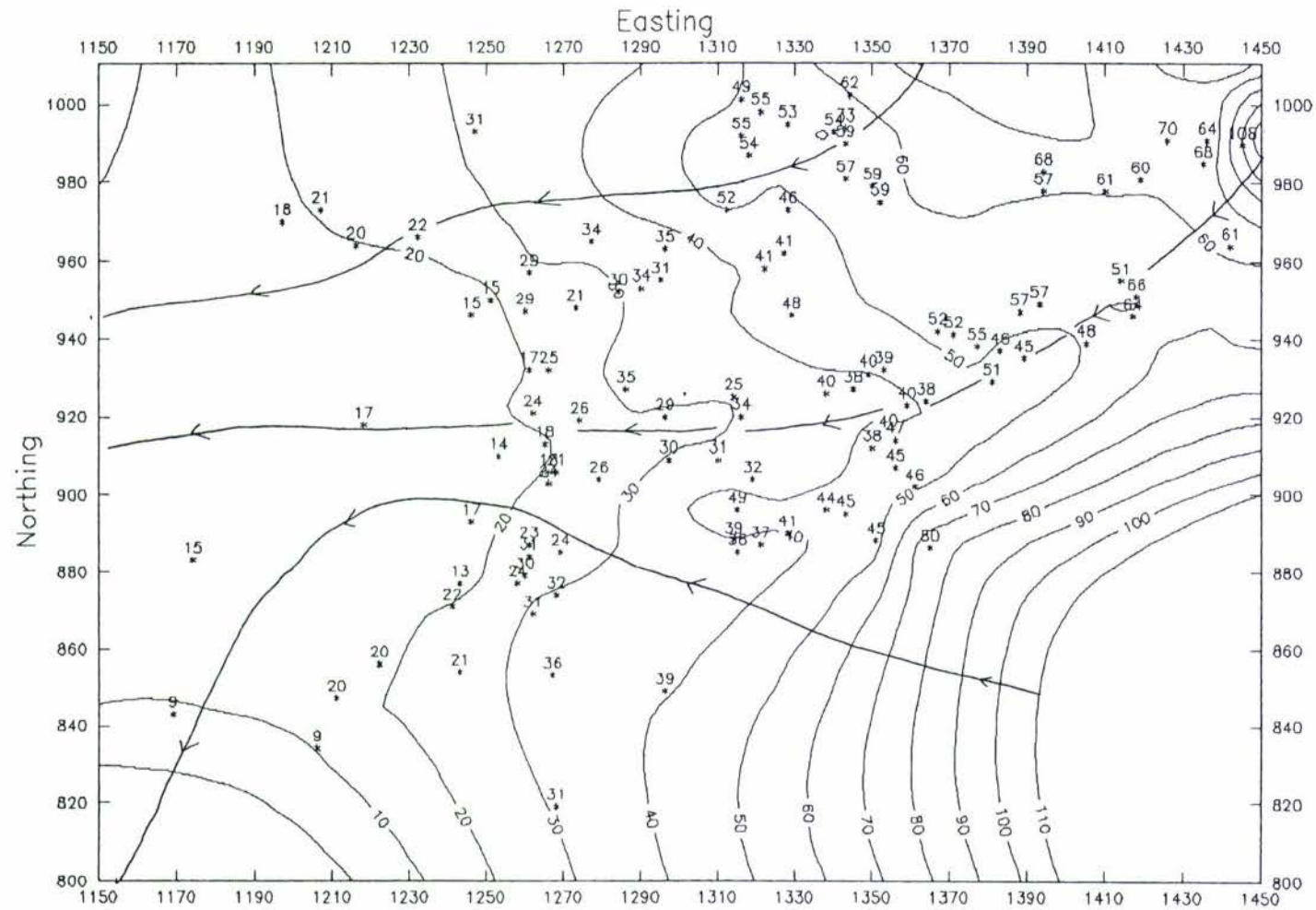


Figure 3.6 Piezometric contour map using all static water levels available for all depths.

static water level as the Z coordinate. These were manipulated by a computer package called SURFER which constructs both two dimensional topographic maps and three dimensional surface plots given X, Y, and Z coordinates (see chapter four, section 4.2 for the discussion on the computer package). Figure 3.6 shows a trend of decreasing static water level from east to west in the study area. Static water levels decrease from the ranges to the river valley bottom. The contour lines all have a marked kink upstream in the Manawatu River valley. The underlying structure of the Pohangina Anticline may be responsible for the noticeable kink in the 60 m contour line between Bunnythorpe and Ashhurst. Water movement in the aquifer system will be perpendicular to the piezometric contour lines, which is shown in figure 3.6.

Once the divisions of the aquifers into depth ranges was completed new piezometric maps were constructed for each depth range. The three piezometric contour maps are shown in figures 3.7, 3.8, and 3.9. The piezometric contour map for the 0 - 60 m bores is similar to figure 3.6 with a prominent bulge in the area between Bunnythorpe and Ashhurst and contours deviating up the Manawatu River valley. The flow lines are again similar to the figure representing all the data. Figure 3.8 shows the piezometric map for the depth range 60 - 120 m, this map has contours which run more parallel north-south than do the contours in any of the other piezometric maps. There is still a noticeable kink in the contour lines up the Manawatu River valley. There is also an indication of water entering the system from both the Pohangina and Oroua River catchments in the vicinity of Ashhurst and Bunnythorpe. The flow lines on figure 3.8 converge less than on the other maps and the water appears to flow in a more direct east to west route towards the coast. The piezometric map for bores which are deeper than 120 m is shown in figure 3.9. This map has the least data points and therefore is less reliable than the rest. However there is still a marked kink in the contour lines up the Manawatu River valley and new water may be entering the system from the Pohangina and Oroua Rivers as can be seen by the contour lines in the vicinity of Bunnythorpe and by the flow lines in figure 3.9.

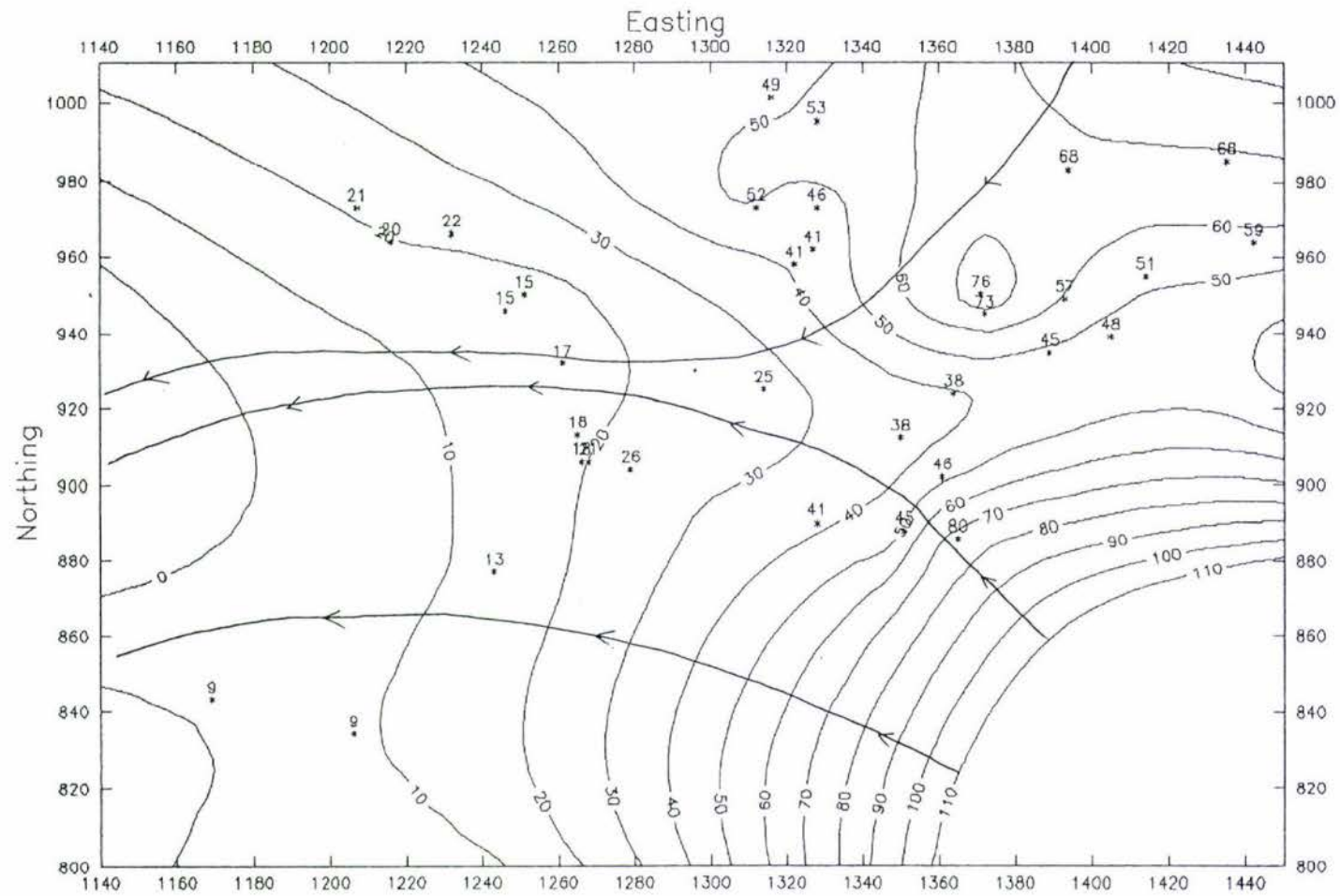


Figure 3.7 Piezometric contour map for bores between 0-60 m depth.

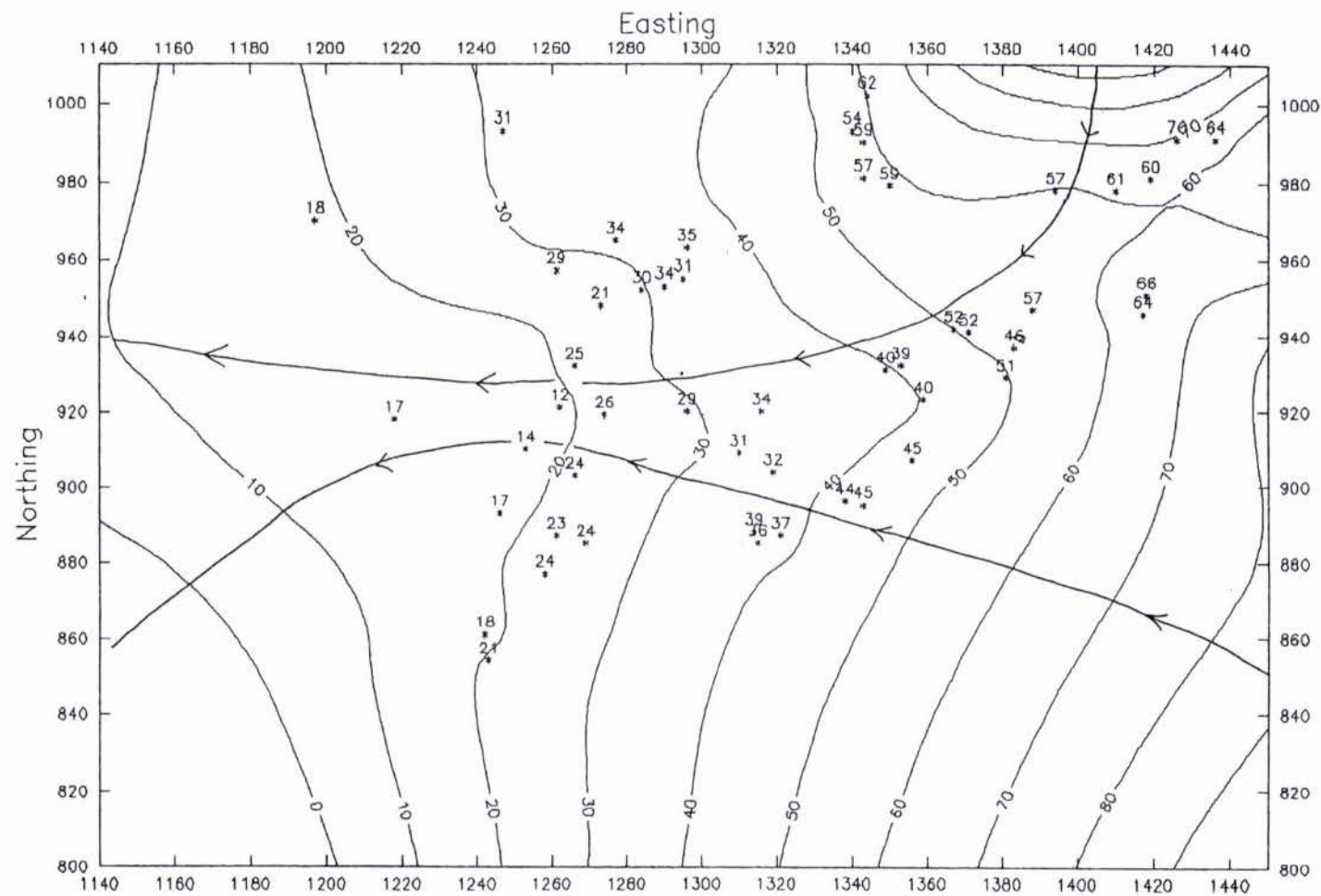


Figure 3.8 Piezometric contour map for bores between 60-120 m depth.

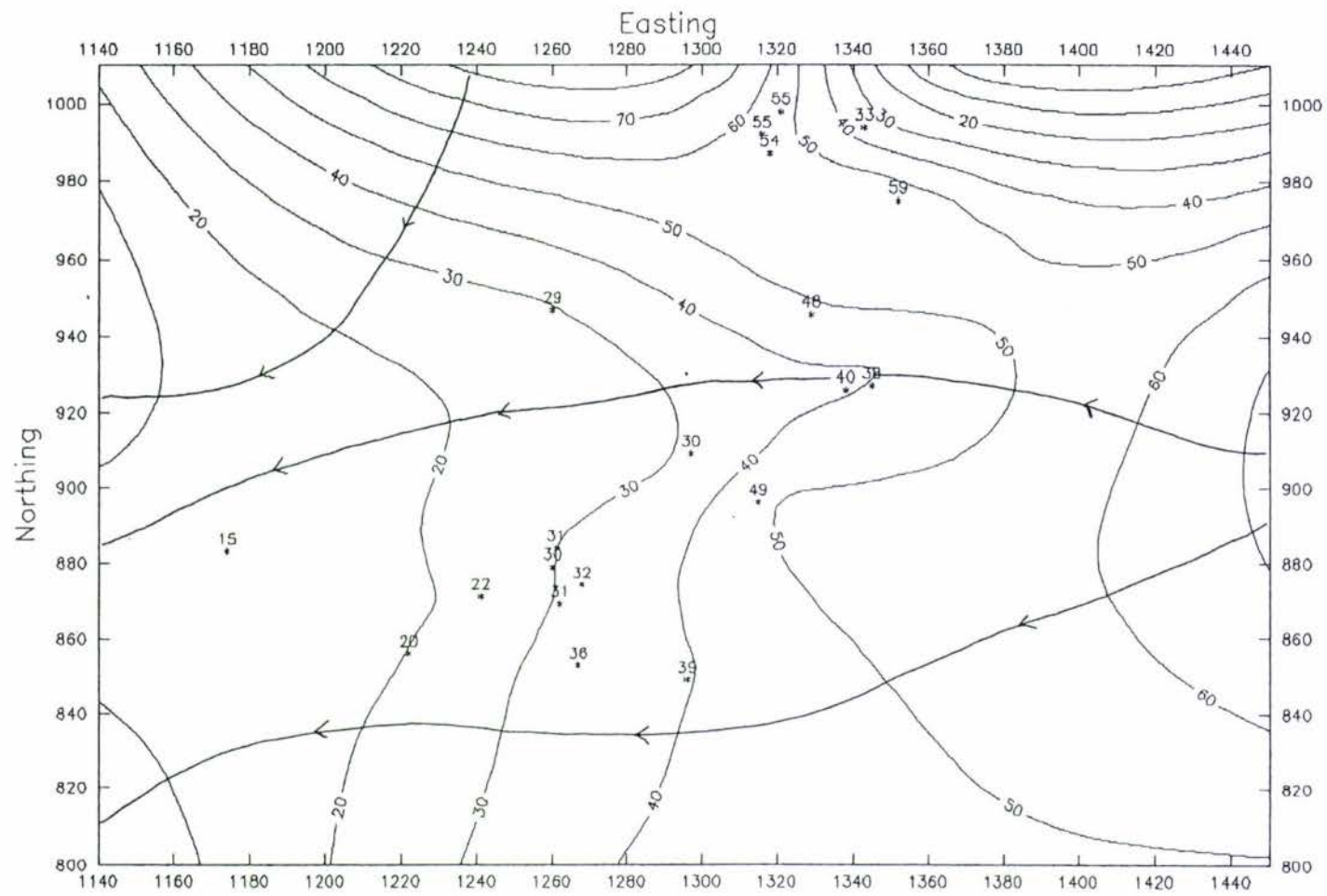


Figure 3.9 Piezometric contour map for bores >120 m depth.

The cross-section in figure 3.5 show the relationship between the position of the bore in the study area and the static water levels, *ie.* there is a marked decrease in static water level with decreased elevation and a decrease in static water level from east to west. These cross-sections also show the increase in static water level with respect to depth.

3.3 RECHARGE ZONES

3.3.1 INTRODUCTION

The areas where atmospheric and surface water enters the groundwater system is termed the recharge zone. The identification of the precise locations of recharge is very difficult but some educated estimations may be made based on the topography of the land, the static water levels in bores, and by gauging of the rivers which flow through the area under consideration.

3.3.2 POSSIBLE RECHARGE ZONES

Within this study area there are considered to be two types of recharge, firstly recharge from atmospheric precipitation which falls directly onto the ground surface and infiltrates into the groundwater system and secondly recharge from the rivers which flow through this catchment area.

The most likely areas which supply the first type of recharge are the Tararua Range to the south of the Manawatu Gorge, the Ruahine Range to the north of the Manawatu Gorge, and both the eastern and western flanks of the Pohangina Anticline. Evidence of these possible sources comes mainly from the topography of the area, and the flow lines on the piezometric maps. Groundwater which enters this system from the Oroua River catchment area may possibly have its original recharge much further north. Water, either as atmospheric precipitation or as older deep circulating water, may enter the groundwater system via the numerous faults which run through the axial ranges but there is no firm evidence for this.

The second type of recharge is river recharge. This type of recharge involves water being lost to the groundwater regime from rivers flowing over gravel beds which are in some way connected to the groundwater system. To detect the loss of water in a river a river gauging program must be carried out (see section 3.1.5). River recharge is very important in the recharge of the shallower aquifers. The Manawatu-Wanganui Regional Council have an on going river gauging programme which will hopefully make recharge area identification possible. Discussion of an example of river recharge follows.

3.3.3 WHITE HORSE RAPIDS, A RECHARGE EXAMPLE

From river gaugings along the Manawatu Gorge it was found that a considerable amount of water was being lost in the vicinity of the White Horse Rapids. Discharge upstream of the rapids was 29,000 l/s whereas downstream of the rapids the discharge was 22,500 l/s, this represents a 22% loss of 6,500 l/s (see figure 3.10).

The geology of the Manawatu Gorge is very complex and has been studied in some detail by Marden (1984). Two lithotypes are represented, the Wharite Lithotype occurring in the west and the Tamaki Lithotype to the east. They are separated by the Manawatu Gorge Fault which runs parallel to the axial ranges and crosses the Manawatu Gorge about 1.8 km from the bridge which crosses the Manawatu River at the eastern end of the Manawatu Gorge. The White Horse Rapids occur in the Wharite Lithotype which can be considered a "melange" rock body consisting of a variety of clastic, pelagic, and volcanic blocks. From the rapids downstream to Ashhurst the lithologies consist of foliated sandstones and argillites, cherts, and volcanics. A fault is located to the west of the rapids and is upthrown to the east, with foliated argillite on the eastern side of the fault.

The Manawatu River may have eroded the less resistant rocks to the west of the rapids to produce a river bed full of gravels, whereas to the east of the rapids, which is where the river is at present actively eroding, there are few or no gravels in the river bed. This implies a narrow finger of gravels which

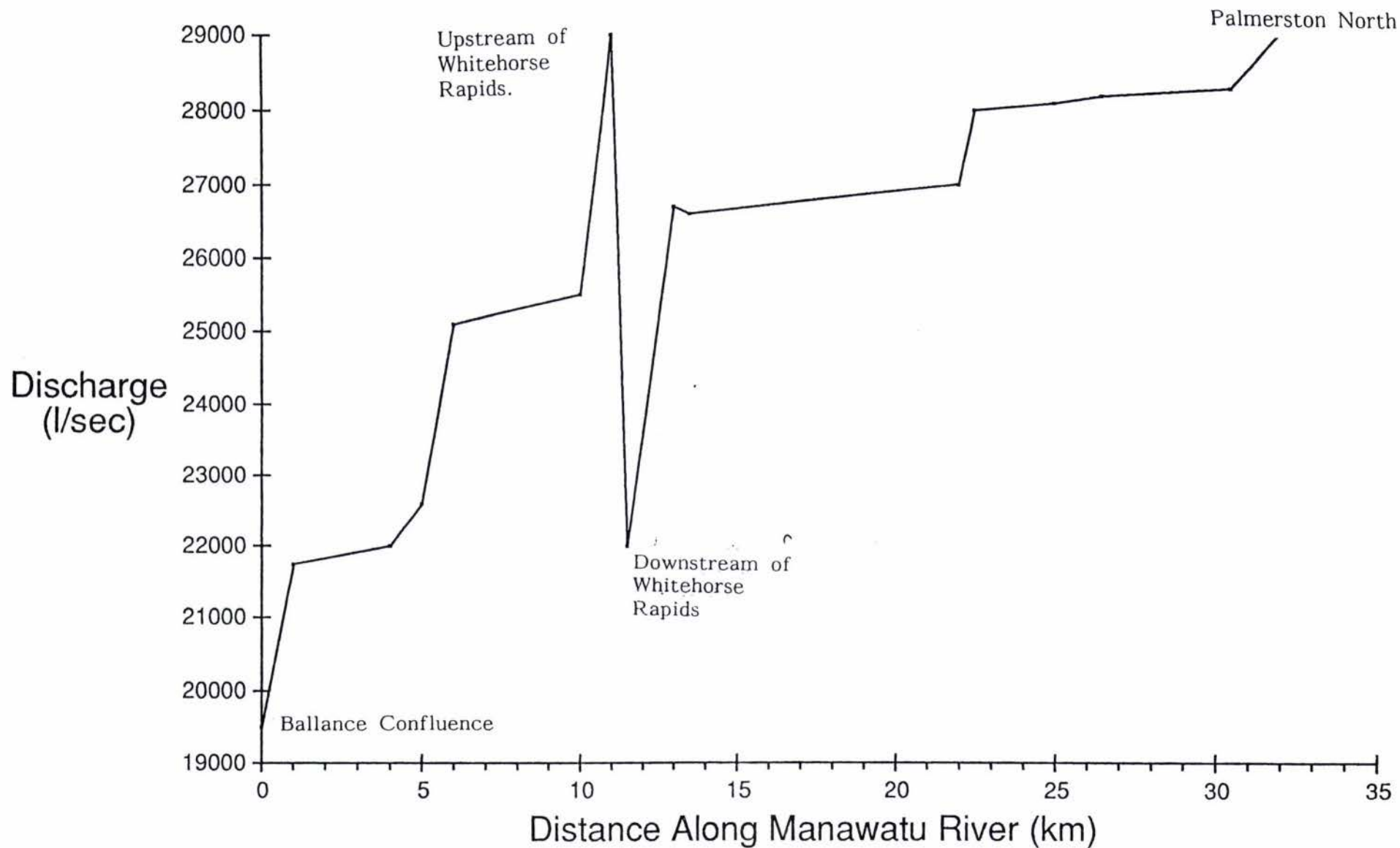


Figure 3.10 Discharge of the Manawatu River between Balance confluence and Palmerston North City.

extend from the White Horse Rapids to the western end of the Manawatu Gorge where they are likely to splay outwards and where further river losses may occur. Water flowing over the White Horse Rapids may well seep into these gravels and thus reduce the flow of the river. Similar situations exist in the Hutt Valley (Stevens 1974), the Rakaia River (Wilson 1973), and the Ngaruroro River at the Heretaunga Plains (Thorpe *et al.* 1982).

3.4 GROUNDWATER USES

The use of groundwater as a source of water has increased dramatically within the Manawatu district over the last 15 years. In 1977 groundwater accounted for approximately 40% of the total water used as compared to nearly 90% in 1989. For the total groundwater rights allocated in this study area there are fifteen different uses for the groundwater extracted; dairy shed uses, stockwater, other agricultural not including irrigation, herbicide spraying, chemical industry, freezing works, milk and dairy industry, fruit and vegetable processing, other food manufacturing (grain, cereals etc.), shingle plants, spray irrigation, trickle irrigation, institutional water supply, public water supply, and cooling and heat exchange water. In addition water is also used for stock and domestic uses which do not require water rights. Figure 3.11 shows the proportion of each of the above uses with the exception that stockwater, other agricultural, herbicide spraying, fruit and vegetable processing, other food manufacture, and shingle plants are grouped under "others" as their individual quantities are insignificant.

The daily water extraction rate for the entire area is 110,572 m³/day for the 177 bores which require water rights. The daily extraction rate for stock and domestic uses which do not require water rights is estimated at 7,302 m³/day giving a total daily extraction from the groundwater system of 117,874 m³/day (approximately 43 x 10⁶ m³/year). The daily extraction rates for the individual uses is given in table 3.2. These extraction quantities are to be taken as maximum values as it is unlikely that the water rights are unlikely to be fully exercised in an average season. Of the 177 bores with water rights 120 of these are for spray irrigation which is also by far the major use of groundwater.

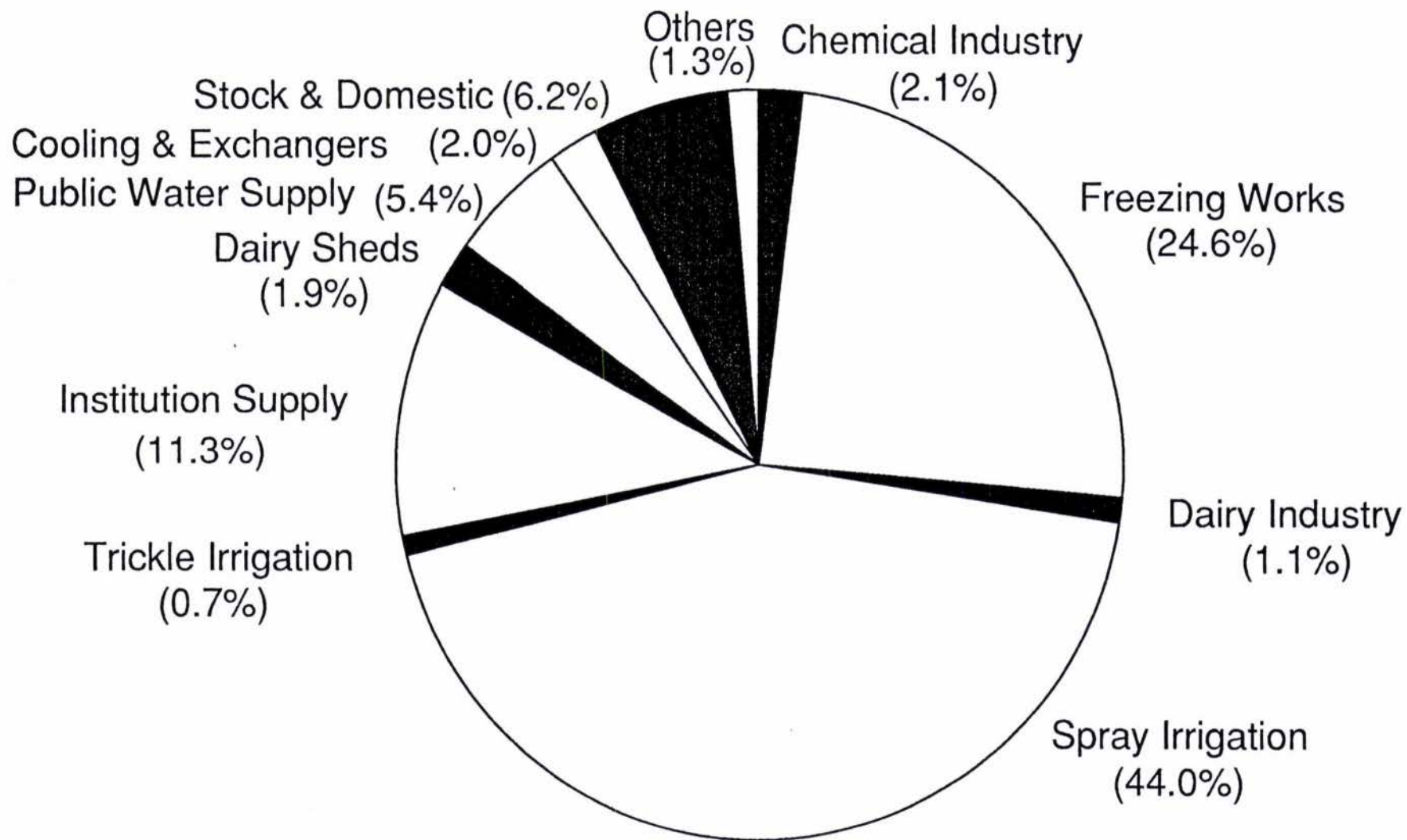


Figure 3.11 Groundwater uses within study area.

Table 3.2 Water uses, daily extraction rates, and number of water rights for each water use for all groundwater rights in this study area.

Water Use:	Daily Water Extraction (m ³ /day)	No. of Water Rights	% of Total Groundwater
Stockwater	31.4	4	0.03
Dairy Shed Uses	2235.8	10	1.90
Other Agricultural	48.5	2	0.04
Herbicide Spraying	10	1	0.01
Chemical Industry	2400	1	2.04
Freezing Works	28802	6	24.43
Milk and Dairy Industry	1316	2	1.12
Fruit and Vegetable Process	432	1	0.37
Food - Others	200	1	0.17
Shingle Plants	800	2	0.68
Spray Irrigation	51558.6	120	43.74
Trickle Irrigation	831.1	11	0.71
Institutional Water Supply	13215.5	6	11.21
Public Water Supply	6377	8	5.41
Cooling and Heat Exchange	2314	2	1.96
Total (Water Rights):	110571.9	177	
Stock and Domestic	7302.4	-	6.20
TOTAL:	117874.3 m ³ /day		

In contrast, the total water used from surface water, streams, rivers and lakes, is only 9,601 m³/day for surface water right users and 2,349 m³/day for stock and domestic users which do not require water rights giving a total of 11,950 m³/day (approximately 4.5×10^6 m³/year). There are only 28 water rights issued for surface water extraction in this area and the water is only used for four different uses; spray irrigation (61.6%), trickle irrigation (14.9%), stock and domestic (19.7%), and public water supply (3.8%).

CHAPTER FOUR - HYDROCHEMISTRY

4.1 INTRODUCTION

Whether or not water is useful for industrial, agricultural, horticultural, or domestic use is determined by the chemical and biological characteristics of the water. The study of groundwater chemistry gives important indications of the geological history of the enclosing rocks, the velocity and direction of water movement, and the evidence of pollution and pollution sources.

During the period February-May 1989 the Manawatu-Wanganui Regional Council conducted a water quality survey of selected water-bores throughout the Manawatu, in which the author assisted. Within the area of this study 82 bores were sampled and analyses of 18 chemical parameters were conducted. To obtain the best representative sample from each bore the entire water volume of the well casing was pumped or allowed to flow before a sample was collected; this ensured that the sample best reflected the water of the aquifer. The samples were analysed in the Regional Council's chemical testing laboratory in Marton within 24 hours of collection, and kept chilled at all times. The following chemical parameters were tested: pH, conductivity, calcium (Ca), magnesium (Mg), total hardness, total iron (Fe), dissolved iron, manganese (Mn), sodium (Na), potassium (K), carbonate alkalinity, total alkalinity, chloride (Cl⁻), sulphate (SO₄²⁻), fluoride (F⁻), total dissolved solids, and for bores shallower than fifty metres, nitrate (NO₃⁻) and nitrite (NO₂⁻) were analysed. These chemicals and chemical compounds can be classified according to their normal occurrence in groundwater. Four major categories have been defined as follows:

1. Major constituents - where concentrations range between 1-1000 ppm.
2. Secondary constituents - where concentrations range between 0.01-10 ppm.
3. Minor constituents - where concentrations range between 0.0001-0.1 ppm.
4. Trace constituents - where concentrations are <0.001 ppm.

(Davis & DeWeist 1966)

Of the chemical parameters analysed Ca, Mg, Cl, Na, SO_4^{2-} , and HCO_3^- are major constituents, Fe, K, NO_3^- , F^- , and CO_3^{2-} are secondary constituents and Mn was the only minor constituent tested. A brief discussion on the general occurrence of the various compounds in groundwater and their relation to water use follows.

4.1.1 DISCUSSION OF CHEMICAL PARAMETERS

pH

The pH of water determines the solubilities of many elements, the major exceptions being Ca, NO_3^- , Na, and Cl. The range of pH in natural groundwaters is limited, normally being between pH 5.0 - 8.0. This range is due to the presence of dissolved carbon dioxide (CO_2) gas and bicarbonate (HCO_3^-) ions which form a buffered system with carbonic acid (Schwille & Weisflog 1968, in Matthes 1982). Waters with high pH (>9.0) are usually associated with high sodium-carbonate-bicarbonate waters. Waters with low pH (<4.5) are usually associated with acid mine wastes as a result of oxidation of sulphides, or in thermal waters that contain hydrogen sulphide (H_2S) or hydrochloric acid (HCl) (Matthes 1982). Measurement of pH should ideally be taken *in situ* as pH will change with temperature, the presence of microorganisms in the collecting vessel, and the presence of air. The collecting vessels should therefore contain a biological inhibitor and be filled as full as possible during collection to minimize inaccuracies.

TOTAL DISSOLVED SOLIDS (TDS)

All solid material in solution whether ionized or not makes up the TDS. Groundwaters generally range from less than 10 ppm TDS for rain and snow to >300,000 ppm TDS for some brines (Davis & DeWeist 1966). Water for domestic and industrial uses should be less than 1000 ppm TDS. The United States Environmental Protection Agency (USEPA) and the World Health Organisation (WHO) have put a recommended TDS concentration limit of 500

ppm in drinking water; this value is to provide acceptable aesthetic and taste characteristics for the water. The USEPA has put a recommended limit of 3000 ppm and 700 ppm TDS for livestock and crop irrigation water, respectively (Freeze & Cherry 1979). The potential use, however, should be based on the concentrations of individual ions present rather than on the total dissolved solids.

DISSOLVED AND TOTAL IRON

The iron in most natural groundwater originates from the weathering of mafic minerals such as pyroxene, amphibole, biotite, and magnetite. During weathering the Fe is transformed into slightly soluble stable ferric (Fe^{3+}) oxide and oxyhydroxide, which are generally redeposited after weathering. The amount of iron in sea water (0.0034 mg/kg) (Matthess 1982) reflects the element's low mobility. Iron plays an important biochemical role in the life cycles of plants and animals. Microorganisms influence the occurrence of Fe in groundwaters by either oxidizing Fe to the ferric ion under aerobic conditions or reducing Fe to the divalent ferrous (Fe^{2+}) ion under anaerobic conditions. The presence of Fe^{2+} can be a good indicator of pollution of organic substances. In groundwater, Fe^{2+} is the most common form of dissolved iron and FeOH^+ can occur in very low CO_2 waters. Fe^{3+} can be dissolved in acid solutions as Fe^{3+} , FeOH^{2+} , and $\text{Fe}(\text{OH})_2^+$. Small changes in pH can greatly affect the solubility of iron. High dissolved iron contents can be associated with the oxidation of reduced iron minerals such as FeS in the boundary zone between reducing and oxidizing environments. In groundwaters which are oxygenated, dissolved iron is detectable only in minor amounts or may not be present at all. In 'reduced' groundwaters dissolved iron is normally measured between 1 - 10 ppm Fe^{2+} (Matthess 1982). The WHO has put a recommended taste and aesthetic limit of 0.3 ppm Fe (Freeze & Cherry 1979).

CALCIUM

Calcium is one of the most common ions to occur in groundwater and is derived from the weathering of anorthite, calcite, dolomite, aragonite, anhydrite and gypsum. Calcium is easily soluble in water provided there is an abundant supply of hydrogen ions (H^+) present, one of the most important sources of H^+ being the dissociation of carbonic acid (H_2CO_3). The solubility of Ca also increases in the presence of both K^+ and Na^+ salts. But the most important factor controlling the solubility of Ca is the presence of CO_2 . As CO_2 is added, solution continues, whereas if it is removed from the system deposition of $CaCO_3$ is likely to occur (Davis & DeWeist 1966). Concentrations of Ca in normal potable groundwater generally range between 10-100 ppm.

MAGNESIUM

A common source of Mg is the dissolution of dolomite, other sources being the weathering of olivine, biotite, hornblende and augite. In addition most calcite contains some Mg so a solution of limestone commonly yields some Mg as well as Ca. The geochemistry of Mg is very similar to that of Ca so the solubility of Mg is also strongly controlled by the presence of CO_2 . Magnesium compounds tend to have higher solubilities than the corresponding calcium compounds. Magnesium is generally found in less abundance in groundwaters than calcium despite its higher solubility, the greater abundance of Ca in the Earth's crust probably accounting for this difference. In contrast with fresh water, sea-water contains about five times as much Mg as Ca. This Ca deficiency in sea-water is due to preferential Ca uptake over Mg by marine plants and animals that use it for their hard parts. In groundwater common concentrations of Mg range from 1 - 40 ppm; waters from rocks rich in Mg may have up to 100 ppm Mg. Very low concentrations of Mg and Ca are found in some waters which have undergone natural softening by cation exchange (Davis & DeWeist 1966).

TOTAL HARDNESS

The most commonly noticed effect of Ca in water is its tendency to react with soap to form a precipitate called soap curd. Ions of Mg, Fe, Mn, copper (Cu), barium (Ba), and zinc (Zn) also cause a similar difficulty, and, with Ca, must be precipitated before soap can either cleanse or lather. The soap neutralizing power of these ions is called hardness. All the ions except Mg and Ca generally occur in only trace amounts therefore hardness is usually considered as the sum of the effects of only the Ca and Mg. Hardness is normally expressed in terms of weight of CaCO_3 which would produce the hardness actually measured in the water (Davis & DeWeist 1966). There are various hardness classification systems used throughout the world but in this study total hardness is the sum of the calcium and magnesium concentrations. Some authors have shown a significant correlation between the hardness of groundwater and arteriosclerosis, and other cardiovascular diseases (Perry 1971).

SODIUM

Sodium, unlike magnesium and calcium, is not found as an essential constituent of many of the rock forming minerals. The primary source of most Na in groundwater is from the release of soluble products during the weathering of plagioclase feldspars (Davis & DeWeist 1966). Clay minerals may be a large supplier of Na under the right conditions. Sodium salts are very soluble and will not precipitate until several hundred thousand parts per million is exceeded. Ion exchange is the only common mechanism in which large amounts of Na can be removed. The action of ion exchange has been quoted by many authors as the mechanism by which Na ions are removed from sea-water which has infiltrated into fresh water aquifers (Davis & DeWeist 1966). The reaction of calcium bicarbonate to sodium bicarbonate in many aquifers is also undoubtedly due to ion exchange, being reversible depending on the relative concentrations of each ion. All groundwater contains measurable traces of Na, from <0.2 ppm Na in rainwater to $>100,000$ ppm Na in some brines in contact with salt beds (Davis & DeWeist 1966). Sodium is a biometal and occurs in various chemicals used by man, so it can

enter into the groundwater system with man-made pollution (Matthess 1982). Sodium is normally present as Na^+ ions, however in concentrated solutions sodium forms ion pairs and complex ions such as NaCO_3^- and NaSO_4^- (Hem 1970 in Matthess 1982).

POTASSIUM

The main source of K in groundwater comes from the weathering of orthoclase, microcline, biotite, leucite and nepheline. Potassium abundance in the Earth's crust is similar to that of Na but in groundwaters K is commonly less than one tenth the concentration of Na (Davis & DeWeist 1966). This relative immobility of K is due to a number of reasons; firstly, during weathering of many of the K minerals the K enters and/or is incorporated into the structures of certain clay and clay-like minerals, and secondly, the resistance to weathering of many of the K minerals is higher than Na minerals. Potassium salts are highly soluble, similar to Na salts. All natural groundwater contains some measurable trace of K; some rainwater contains as little as 0.1 ppm K, and some brines contain >100,000 ppm K. Most potable water contains <10 ppm K and commonly ranges between 1 - 5 ppm K (Davis & DeWeist 1966). Potassium is used as an agricultural fertilizer and this can lead to significantly higher K concentrations in groundwaters below cultivated areas; human pollution may also increase K concentrations in groundwaters (Matthess 1982).

BICARBONATE AND CARBONATE

In water quality analyses the term '*alkalinity*' refers to the amount of a standard concentration of sulphuric acid (H_2SO_4) required to titrate a water sample to an endpoint of pH 4.5, and not the common chemical usage in which only solutions with pH >7.0 are termed alkaline. It is the carbonate and bicarbonate ions which almost exclusively produce the alkalinity of groundwaters. Hydroxide, iron and silicate may have some influence on alkalinity at pH >9.0 and phosphate (PO_4^{3-}) will affect the alkalinity throughout normal pH ranges. However the natural concentrations of PO_4^{3-}

are almost insignificant in comparison to the concentrations of both carbonate and bicarbonate ions and because only very few groundwaters have a pH >9.0, it is usually only the carbonate and bicarbonate which affect the alkalinity (Davis & DeWeist 1966). Bicarbonate will dissociate into carbonate ions but below pH 9 the carbonate ions react with H^+ to become bicarbonate: $H^+ + CO_3^{2-} \rightarrow HCO_3^-$. Below pH 4.5 the bicarbonate ions are converted to carbonic acid: $HCO_3^- + H^+ \rightarrow H_2CO_3$. The part of the alkalinity above pH 8.2 is therefore a measure of carbonate ions present. Most carbonate and bicarbonate present in groundwater is derived from the CO_2 in the atmosphere, CO_2 in the soil, and the solution of carbonate rock. Because most natural groundwaters range from pH 5 - 8 there is often very little or no carbonate present. Bicarbonate concentrations are generally greater than 10 ppm but less than 800 ppm with most waters being in the range 50 - 400 ppm bicarbonate.

SULPHATE

All atmospheric precipitation contains sulphate(SO_4^{2-}), which although commonly in concentrations of less than 2 ppm (Davis & DeWeist 1966), is one of the major dissolved constituents in rain or snow. The SO_4^{2-} in the atmosphere is derived from dust particles containing SO_4^{2-} minerals, and from the oxidation of SO_2 and H_2S gases. Volcanic emissions and decomposition of organic matter under extremely anaerobic conditions produce the H_2S gas in the atmosphere. The burning of coal, oil, and the smelting of ores, along with volcanic emissions, discharge large amounts of SO_2 into the atmosphere (Davis & DeWeist 1966). Sulphur products can also be introduced into the sulphur cycle by man's activities, particularly SO_4^{2-} in agricultural fertilizers (Matthess 1982). Most SO_4^{2-} compounds are readily soluble in water and one of the most effective ways to remove SO_4^{2-} from groundwater appears to be the reduction of SO_4^{2-} by bacteria which use sulphate and sulphides in their life cycles. A by-product of the reduction of SO_4^{2-} is H_2S gas, some of which remains in groundwater and the rest escapes into the atmosphere. Iron sulphide may be precipitated if very anaerobic conditions occur and sufficient Fe is present, thus removing Fe as well as SO_4^{2-} . Sulphate concentrations in groundwaters can vary from less than 0.2 ppm to greater than 100,000 ppm in

brines, especially magnesium sulphate brines (Davis & DeWeist 1966). The USEPA and WHO have put a recommended concentration limit of 250 ppm sulphate in drinking water (Freeze & Cherry 1979).

CHLORIDE

Chloride is only a minor constituent in the Earth's crust but is a major dissolved constituent in most natural groundwater. Nearly all Cl in groundwater can be attributed to four main sources - firstly, Cl from ancient sea-water entrapped in sediments; secondly, by the solution of halites and related minerals; thirdly, concentration by evaporation of rain, and fourthly, by solution of dry fallout from the atmosphere especially in arid areas (Davis & DeWeist 1966). Of these it is the Cl from atmospheric rain which is quantitatively the most important, especially in a maritime country like New Zealand. Chloride contents in rainfall near most coastlines range between 3 - 6 ppm. Additional Cl may be added into groundwaters by way of fertilizers which contain Cl compounds. All Cl salts are highly soluble and are relatively free from the effects of exchange, adsorption, and biological activity, and therefore rarely precipitate from groundwaters. Groundwaters normally contain between 0.1 - 150,000 ppm Cl (Davis & DeWeist 1966). The USEPA and WHO have put a recommended concentration limit of 250 ppm Cl for drinking water, this is mainly for aesthetic and taste reasons (Freeze & Cherry 1979).

CARBON DIOXIDE

Carbon dioxide (CO_2) is very important in groundwater systems and forms part of the $\text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{CO}_3 \rightleftharpoons \text{HCO}_3^- + \text{H}^+ \rightleftharpoons \text{CO}_3^{2-} + \text{H}^+$ system. CO_2 is important in controlling the formation of various carbonate species which originate from free carbon dioxide and carbonate rocks. Free carbon dioxide in groundwater can have various origins and comprises dissolved carbon dioxide and undissociated H_2CO_3 . Carbon dioxide may enter the groundwater system by means of i) rainfall as atmospheric CO_2 becomes dissolved in the rainwater, and ii) during the carbonization process which turns peat into

lignite and coal when liberation of large amounts of carbon dioxide occurs (Krejci & Graf 1934, in Matthess 1982). Free carbon dioxide is produced by the oxidation of organic substances, by man-made organic pollution, and by the effect of organic and inorganic acids on carbonates. If two chemically different "hard" groundwaters mix and there are pH and pressure-temperature changes then the precipitation of calcium carbonate may release large amounts of carbon dioxide into the groundwater (Matthess 1982). Normal free CO_2 concentration in groundwaters ranges between 10 - 20 ppm, but higher values are not uncommon due to localized conditions.

MANGANESE

Manganese is not a common element in the common rock forming minerals but can occur by the substitution of other divalent cations of similar size. This sometimes occurs in ferromagnesium minerals such as biotite and hornblende (Matthess 1982). It is the Mn^{2+} which is the dominant ion form in the pH range of most groundwaters and where there is abundant HCO_3^- present the complex MnHCO_3^+ occurs. This complex may account for half the Mn present at HCO_3^- concentrations of approximately 1000 ppm (Matthess 1982). The MnSO_4 can be important in waters with high SO_4^{2-} contents. The concentrations of Mn are usually half that of iron in most groundwaters although their geochemistry is very similar. Concentrations are normally less than 0.2 ppm under reducing conditions and Mn concentrations greater than 1.0 ppm are rare. The USEPA and WHO have put a recommended concentration limit of 0.05 ppm Mn in drinking water (Freeze & Cherry 1979).

FLUORINE

Fluorine can substitute for hydroxyl groups in amphiboles and micas and once weathering of these minerals occurs they can supply fluorine for groundwaters. Fluorine is a biologically important constituent in teeth and bones and is often present in industrial flue gases. In the form of F^- ions, which are normal in water, fluorine can form strong complexes with aluminium, beryllium and ferric iron. The solubility product of fluorite (CaF_2) is presumed to be the

controlling factor in the fluorine content of waters in the presence of Ca, with significantly higher F values associated with Ca deficiencies (Matthess 1982). In most groundwaters F concentrations are less than 1.0 ppm with a range of 0.01 - 10 ppm (Davis & DeWeist 1966). Very few waters have greater than 10 ppm F and these are normally associated with hot thermal waters (Matthess 1982). The USEPA and WHO have put a recommended concentration range between 1.4 - 2.4 ppm F depending on the air temperature, and a limit of 2 ppm F for livestock and 1 ppm F for crop water irrigation use (Freeze & Cherry 1979).

NITRATE AND NITRITE

Nitrate in groundwater originates from two main sources - organic sources and chemicals associated with industry and agricultural practices. During decomposition of organic matter by bacterial action the complex proteins change through amino acids to ammonia, nitrites, and finally nitrates (Matthess 1982). Some of these compounds may find their way into the groundwater system via deep percolation. It is the introduction of nitrogen compounds, especially nitrate, in the form of agricultural fertilizers that is of major concern to environmentalists. Nitrate can be harmful to infants when concentrations exceed 10 ppm N. The WHO and the USEPA have made 11.3 ppm and 10 ppm N respectively, the maximum permissible value in drinking water. Concentrations of nitrate in groundwater range from 0 - 10 ppm, but in areas influenced by excessive application of N-fertilizers up to 600 ppm may occur (Davis & DeWeist 1966).

CONDUCTIVITY

Conductivity, measured in units of micro-siemens per centimetre ($\mu\text{S}/\text{cm}$) or milli-siemens per metre (mS/m), were previously known as micro-mhos per centimetre, is a sum of the electrical conductancies of the cations plus anions in solution (Matthess 1982) and is directly proportional to the total dissolved solids. An estimate of the TDS in ppm can be made by multiplying the conductivity (in units of $\mu\text{S}/\text{cm}$) by 0.65. In rainfall the conductivity ranges

between 5 - 30 $\mu\text{S}/\text{cm}$; in groundwater it ranges between 30 - 2000 $\mu\text{S}/\text{cm}$, and in sea-water is normally about 50,000 $\mu\text{S}/\text{cm}$ (Matthess 1982).

4.1.2 METHODS OF CHEMICAL ANALYSES

As was mentioned earlier the chemical parameters were measured in the Manawatu-Wanganui Regional Council's chemical testing laboratory at Marton. The following parameters were however analysed by the Palmerston North City Council Laboratory - iron, manganese, sodium, potassium and fluorine. The remaining parameters were tested in accordance with the American Public Health Association (APHA) "Standard Methods for the Examination of Water and Wastewater".

Calcium was measured by EDTA titration, chloride by argentometric titration, nitrate-N by cadmium reduction, diazotisation, and colorimetry. Nitrite-N was measured by diazotisation and colorimetry; conductivity by a conductivity metre; pH by a pH metre; sulphate by turbidimetry, total alkalinity and total hardness, both expressed as CaCO_3 , by titration to an end-point of pH 4.5. Magnesium was calculated as the difference between the total hardness and the calcium. Total dissolved solids were measured by the evaporation method which is discussed in more detail in section 4.4.

The chemical parameters measured by the Palmerston North City Council chemical testing laboratory were all measured by atomic absorption spectrophotometry.

4.2 ISOCONCENTRATION MAPS

4.2.1 METHODS

The chemical data from the water quality survey undertaken by the Manawatu-Wanganui Regional Council were used to produce isoconcentration maps of all the chemical parameters. The data were entered into a spreadsheet package named MULTIPLAN, along with the NZMS 260 grid coordinates for each bore. The grid coordinates along with one chemical parameter for each bore were then manipulated by a software package called SURFER to produce the isoconcentration contour maps used in this study. SURFER uses the easting grid coordinate as the X axis, the northing grid coordinate for the Y axis, and uses the chemical parameter as the Z (or height) value. Once all the data have been entered as X, Y, Z values SURFER grids the data, this creates a regularly spaced grid from irregularly spaced data. Contour maps and three dimensional surface plots require data in a regularly spaced form before they can be generated by SURFER. The purpose of gridding is to use the known Z data points to calculate a Z value at the intersection of imaginary grid lines. Three interpolation methods are available in this package, inverse distance, kriging, or minimum curvature are used to interpolate a Z value at the intersections of a specified rectangular grid made up of any desired rows and columns. For the purposes of this study a grid size of 25 x 25 lines was used for all the maps. At first the interpolation method used was the inverse distance method but this method produced contour maps which did not realistically represent the chemical trends within the study area. This was because inverse distance estimates points using a weighting factor which reduces the influence of one data point on another as distance increases and therefore this method is not the best for showing trends over large distances. Kriging was not used as it assumes an underlying linear variogram which rarely exists in the real world. The interpolation method used for all the contour maps was minimum curvature (for explanation on how minimum curvature works see Briggs 1974). Once the data has been gridded it can be used by SURFER to construct both contour and three dimensional plots. The contour maps produced here show lines of equal concentration and are called isoconcentration maps. For each chemical

parameter four maps were produced, one using all the data and three for the different depth ranges, 0-60 m, 60-120 m, and >120 m depths. This was done to see if there was any observable differences in the chemistry of the different aquifers. Not all the depth division maps are included in this chapter as many of them did not show any major differences.

4.2.2 HYDROCHEMICAL DISTRICTS

For this study and the following discussion on the isoconcentration maps, it is useful to delineate various regions or districts which have similar chemical characteristics. Five districts are classified and named on the basis of either a prominent geographical feature or the major township within the area.

1) **West Oroua River:** this area includes all the land to the west of the Oroua River (see figure 4.1).

2) **Manawatu River:** this area includes land on both sides of the Manawatu River from the Manawatu Gorge to the confluence of the Manawatu and Oroua Rivers (see figure 4.1).

3) **Bunnythorpe:** this area forms a triangular shape centred on the township of Bunnythorpe (see figure 4.1).

4) **Kairanga :** this area is bounded to the west by the Oroua River and extends from the Bunnythorpe region to the north and the Manawatu River region to the south (see figure 4.1).

5) **Ashhurst:** this area lies to the north-east of the study area and is bounded by the Manawatu River region to the south and the Bunnythorpe region to the west (see figure 4.1).

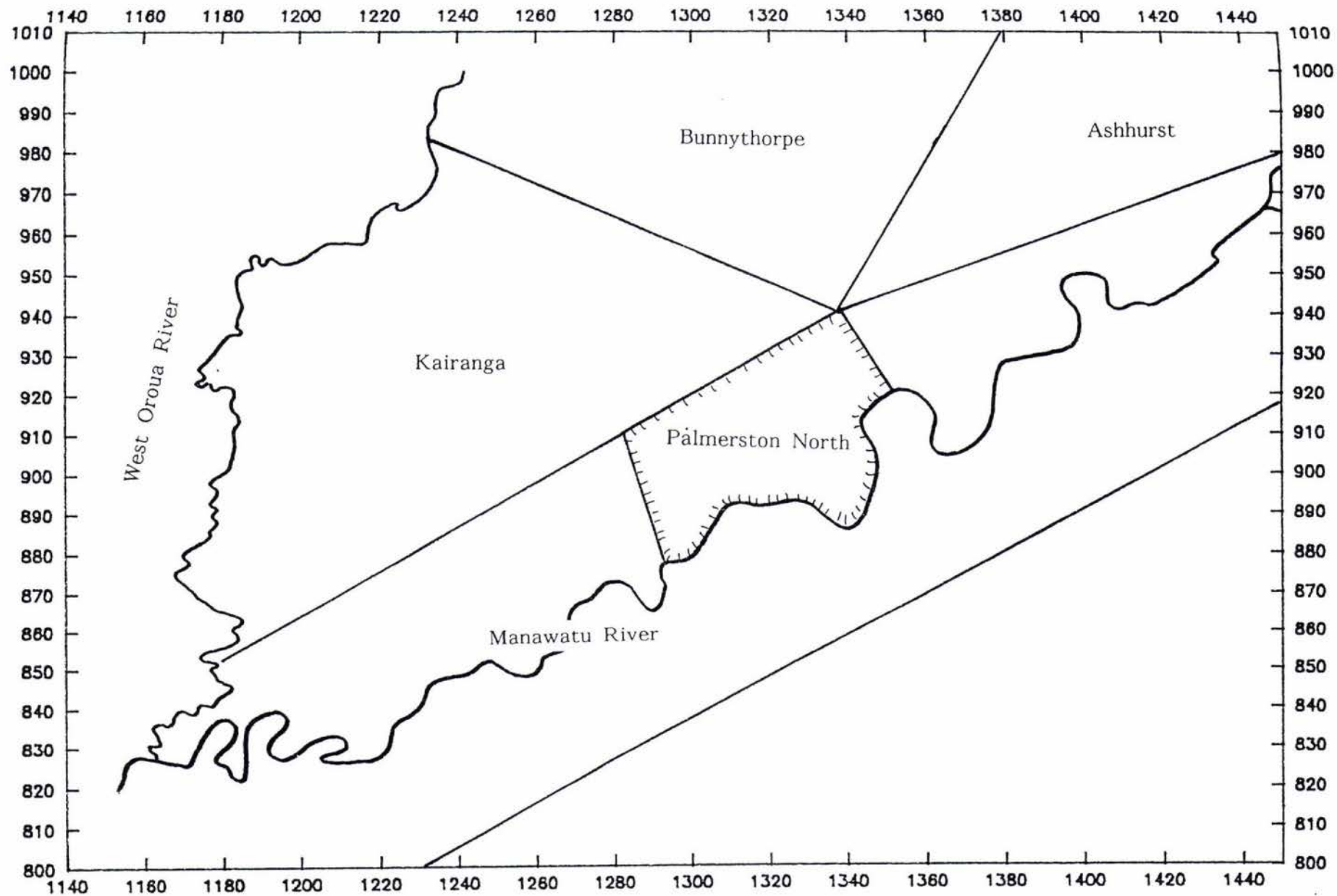


Figure 4.1 Hydrochemical regions within study area.

4.2.3 DISCUSSION

TOTAL ALKALINITY (Figure 4.2)

As discussed earlier it is primarily the bicarbonate and carbonate which produce the alkalinity of groundwater, and only in waters with high pH does carbonate exist and contribute to alkalinity. In this study only two bores contained carbonate, bores 0336 301 and 0337 001. Bore 0336 301 is located in Palmerston North and has a carbonate concentration of 14 ppm and a bicarbonate concentration of 94 ppm. This bore recorded the highest pH in the study area (pH 9.0), while bore 0337 001 had a carbonate concentration of 5 ppm and recorded the second highest pH in the study (pH 8.3). At these high pH values bicarbonate dissociates into carbonate, which explains why these two bores are the only bores in the study to contain any carbonate. Therefore in all the other bores it is bicarbonate which is responsible for the total alkalinity in the water. The overall trend of total alkalinity throughout the study area is one of increasing total alkalinity from east to west (see figure 4.2) with the highest concentrations occurring in the West Oroua River region, generally between 300 - 500 ppm alkalinity. Bores in the Manawatu River region tend to have the lowest concentrations, generally between 100 - 200 ppm alkalinity. Most of the bores within the study area have total alkalinity concentrations between 100 - 200 ppm, the lowest being 82 ppm (bore 0327 001) and the highest being 504 ppm (bore 0334 051). Depth division maps showed shallow bores tend to have higher total alkalinity concentrations than the deeper bores.

CALCIUM (Figure 4.3)

The isoconcentration map for calcium shows an increase in calcium concentration from east to west (see figure 4.3). The highest calcium concentrations occur in the West Oroua River region where two bores recorded calcium concentrations of 200 ppm, bores 0334 051 and 0334 071. Concentrations in the Manawatu River region are the lowest, normally below 100 ppm, with the lowest concentration being 39 ppm in bore 0327 071.

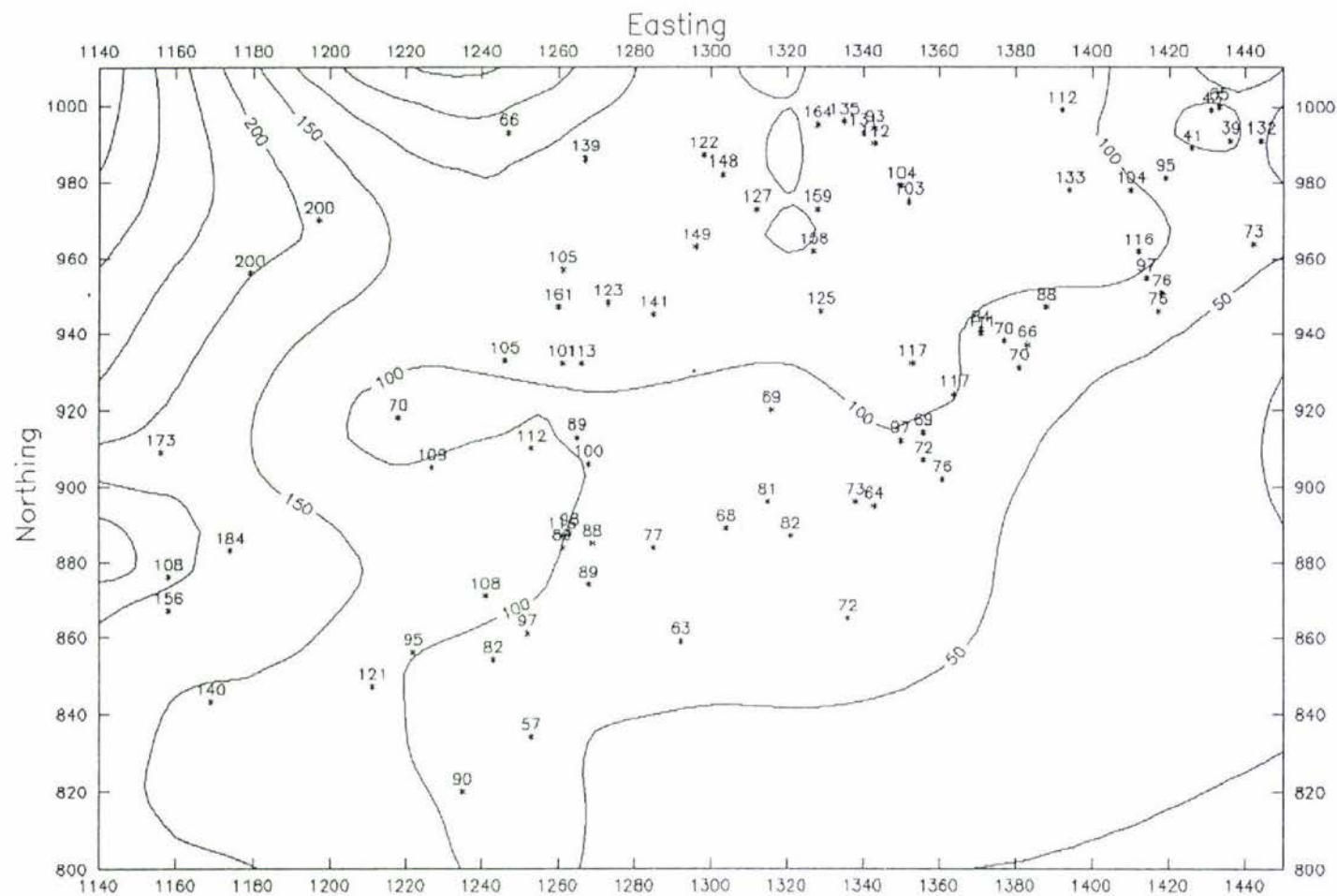


Figure 4.3 Isoconcentration contour map for Calcium (ppm).

Some influx of better quality groundwater from the Oroua River Valley may be occurring as the bore 0325 081 has a relatively low (66 ppm) concentration compared with the surrounding bores which have concentrations in the region of 100-150 ppm. In any particular region it appears that the deeper bores contain less calcium than the shallower bores.

CHLORIDE (Figures 4.4, 4.5, 4.6, 4.7)

The isoconcentration map for chloride shows an increase in chloride concentration from east to west with the exception that there is an area of high concentrations in the Bunnythorpe-Kairanga region (see figure 4.4). One bore, bore 0326 021, has an exceptionally high concentration of 217 ppm Cl, and this bore also has very high concentrations of sodium and manganese. The other bores in the Bunnythorpe-Kairanga regions have concentrations in the range of 50 - 80 ppm Cl. Other high concentrations are found in the West Oroua River region, the highest being 103 ppm in bore 0334 051. The lowest chloride concentrations are found in the Manawatu River region and in the Ashhurst region where concentrations are normally below 30 ppm Cl, the lowest being 7 ppm in bores 0337 001 and 0337 031. Again bore 0325 081 has a relatively low chloride concentration which may indicate influx of better quality groundwaters from the Oroua River Valley. The map of the chloride concentration in the bores 60 - 120 m depth clearly shows the area near Kairanga with relatively high concentrations. An interesting observation is that for most areas the shallow bores have higher chloride concentrations than the deeper bores but towards the coast the deeper bores seem to have the higher concentrations. This may be due to either some salt water encroachment at depth or "fossil" salts in the recently deposited marine sediments of upper Quaternary age which form the aquifers. The reason why the rest of the bores have higher concentrations at shallower depth is probably due to either chloride concentrations increasing in the rainfall towards the coast and sea spray being carried inland by the wind or by way of fertilizer application. Because chloride is a non-reactive anion it may move directly into shallow aquifers.

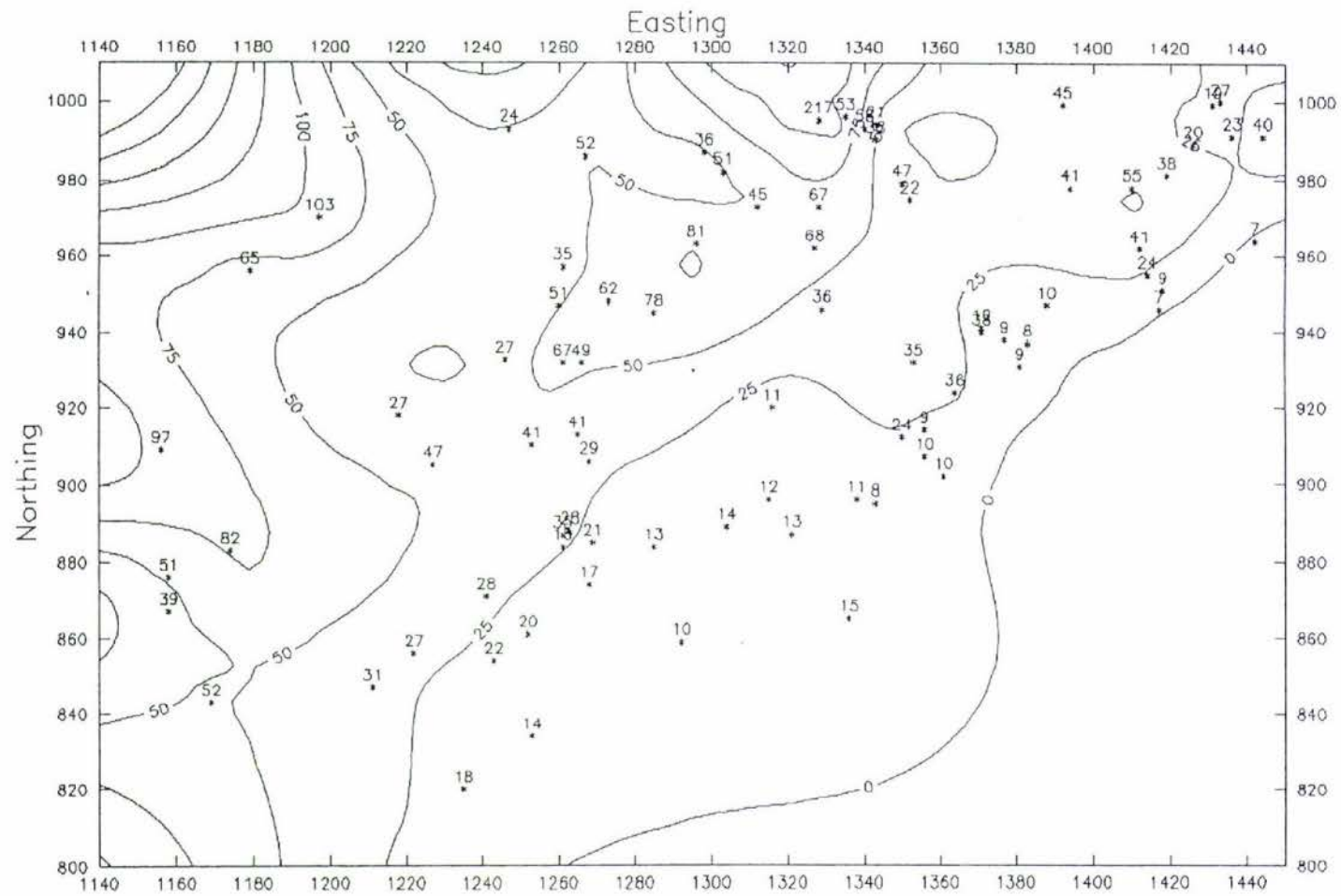


Figure 4.4 Isoconcentration contour map for Chloride (ppm): All Depths.

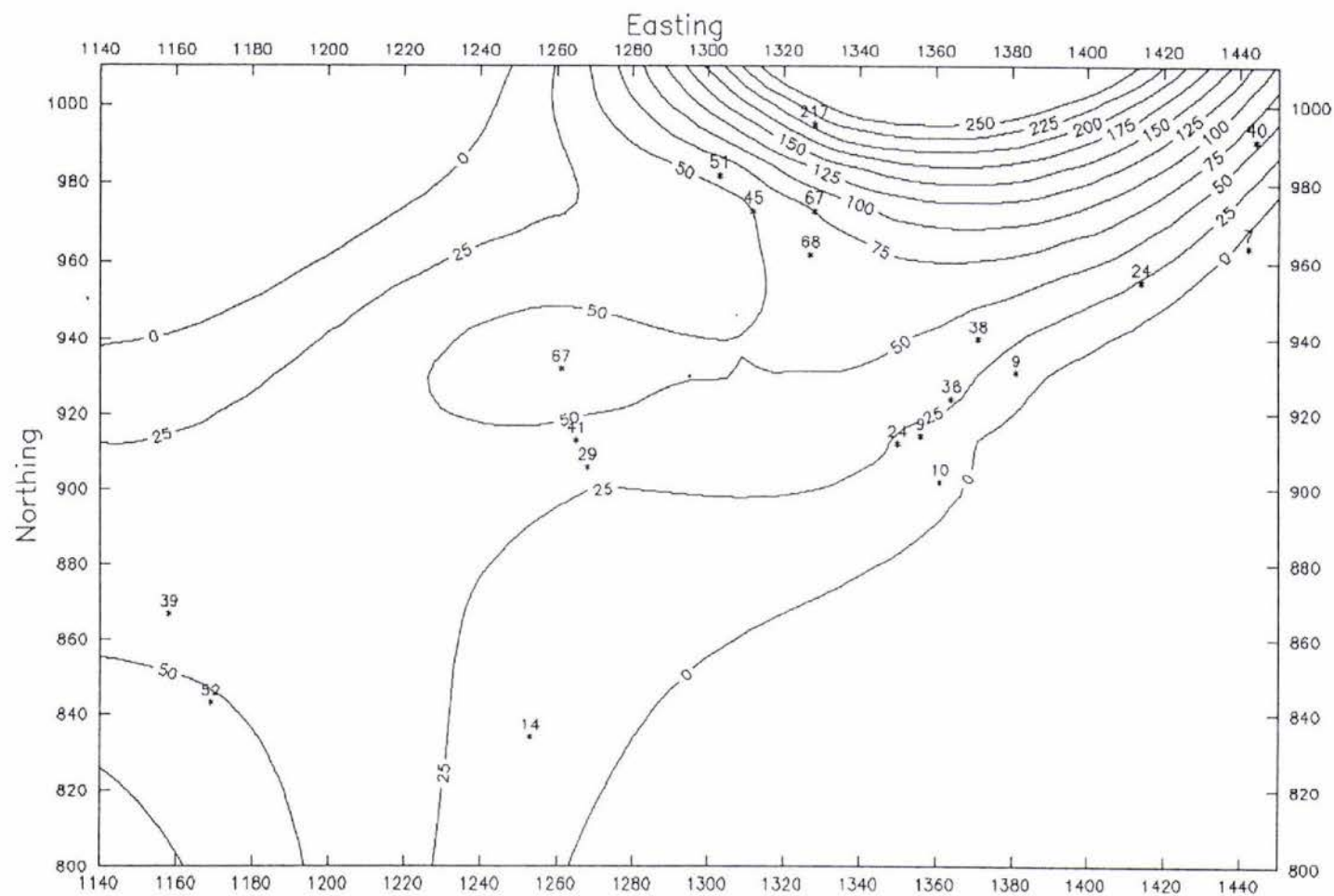


Figure 4.5 Isoconcentration contour map for Chloride (ppm): 0-60 m Depth.

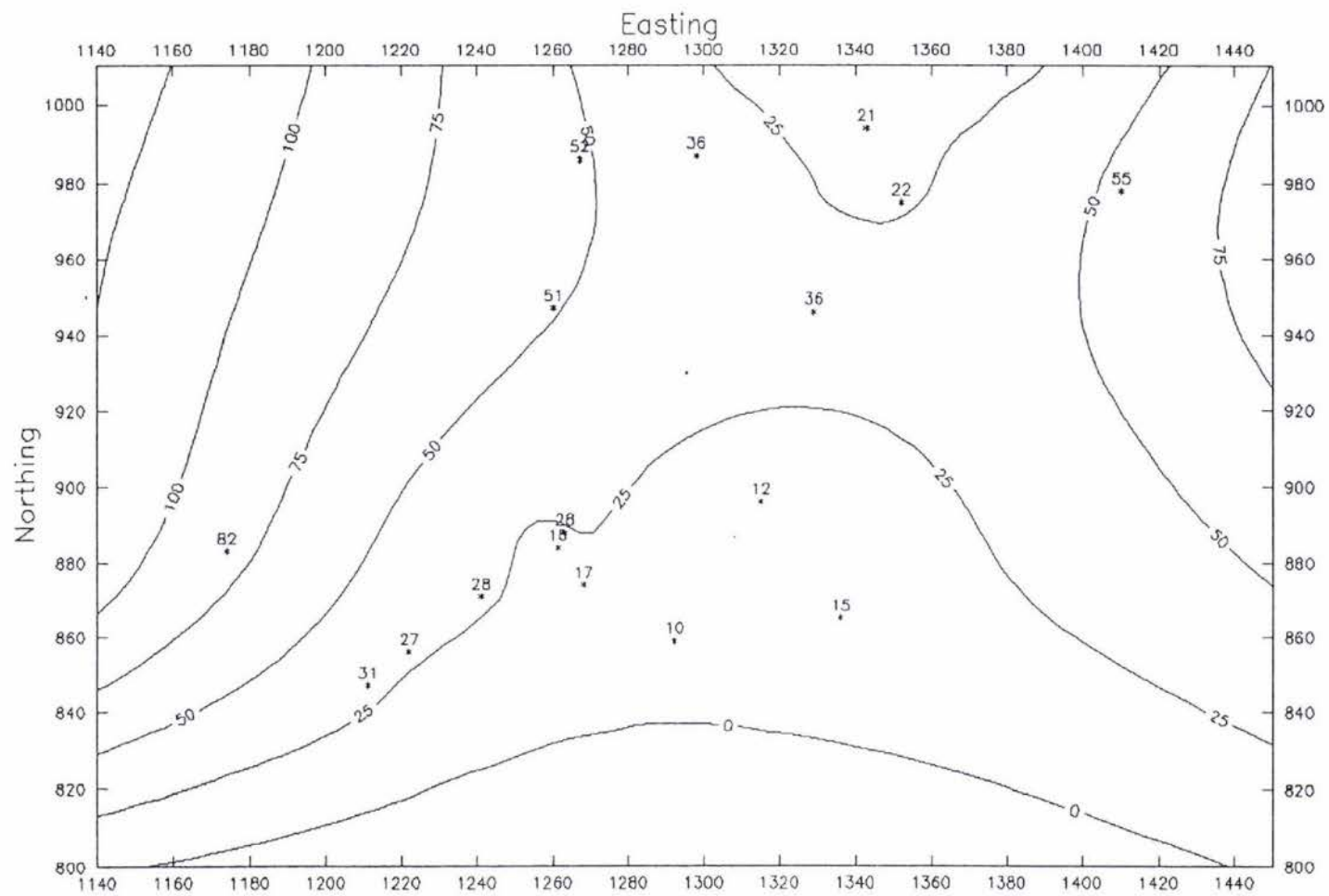


Figure 4.7 Isoconcentration contour map for Chloride (ppm): >120 m Depth.

FREE CARBON DIOXIDE (Figure 4.8)

The isoconcentration map for free carbon dioxide has very little trend (see figure 4.8) with nearly all the concentrations being less than 20 ppm. In two shallow bores (0-60 m depth) the carbon dioxide concentrations exceeded 115 ppm, the highest concentration being 160 ppm CO₂ in bore 0334 031. Other areas where high concentrations were encountered are the Kairanga (29 & 60 ppm) and Ashhurst (33 ppm) regions but these are only isolated bores and there seems to be no overall trend from east to west. In the Manawatu River region the concentrations are low, generally below 10 ppm, with most of these bores having 1 or 2 ppm carbon dioxide.

CONDUCTIVITY (Figure 4.9)

The overall trend of conductivity is one of increasing conductivity from east to west within the study area (see figure 4.9). Conductivity is directly related to total dissolved solids and therefore the isoconcentration maps for the two are very similar (see also figure 4.20). Conductivities in the Manawatu River region are the lowest, and show an increase downstream. Bores around Ashhurst have low conductivities as well. Bore 0336 301 has the lowest in the entire area of 21.5 mS/m. The West Oroua River region has the highest conductivities, some greater than 100 mS/m, with bore 0326 021 having the highest in the entire area of 106.5 mS/m. Bores in the Kairanga-Bunnythorpe region have medium conductivities, generally between 40 - 60 mS/m. Bore 0325 081 has a relatively low conductivity compared to neighbouring bores; this again may be due to the influx of better quality water from the Oroua Catchment. Bores in the 0-60 m depth range have slightly higher conductivities than deeper bores, with not much difference between the medium and deep bores.

FLUORINE (Figure 4.10)

The isoconcentration map for fluorine does not show any trend of increasing fluorine concentration from east to west but instead shows that there are

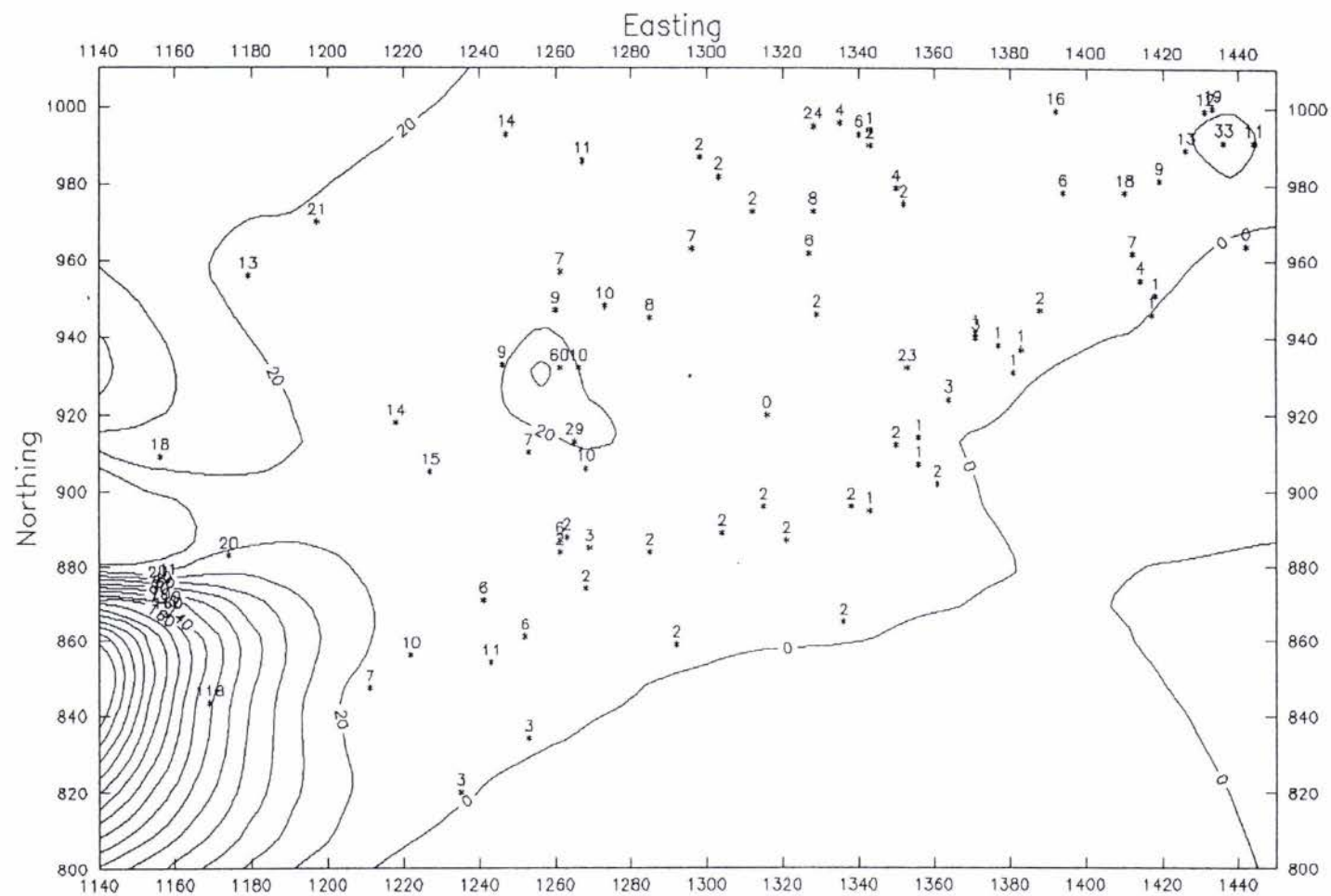


Figure 4.8 Isoconcentration contour map for Free Carbon Dioxide (ppm).

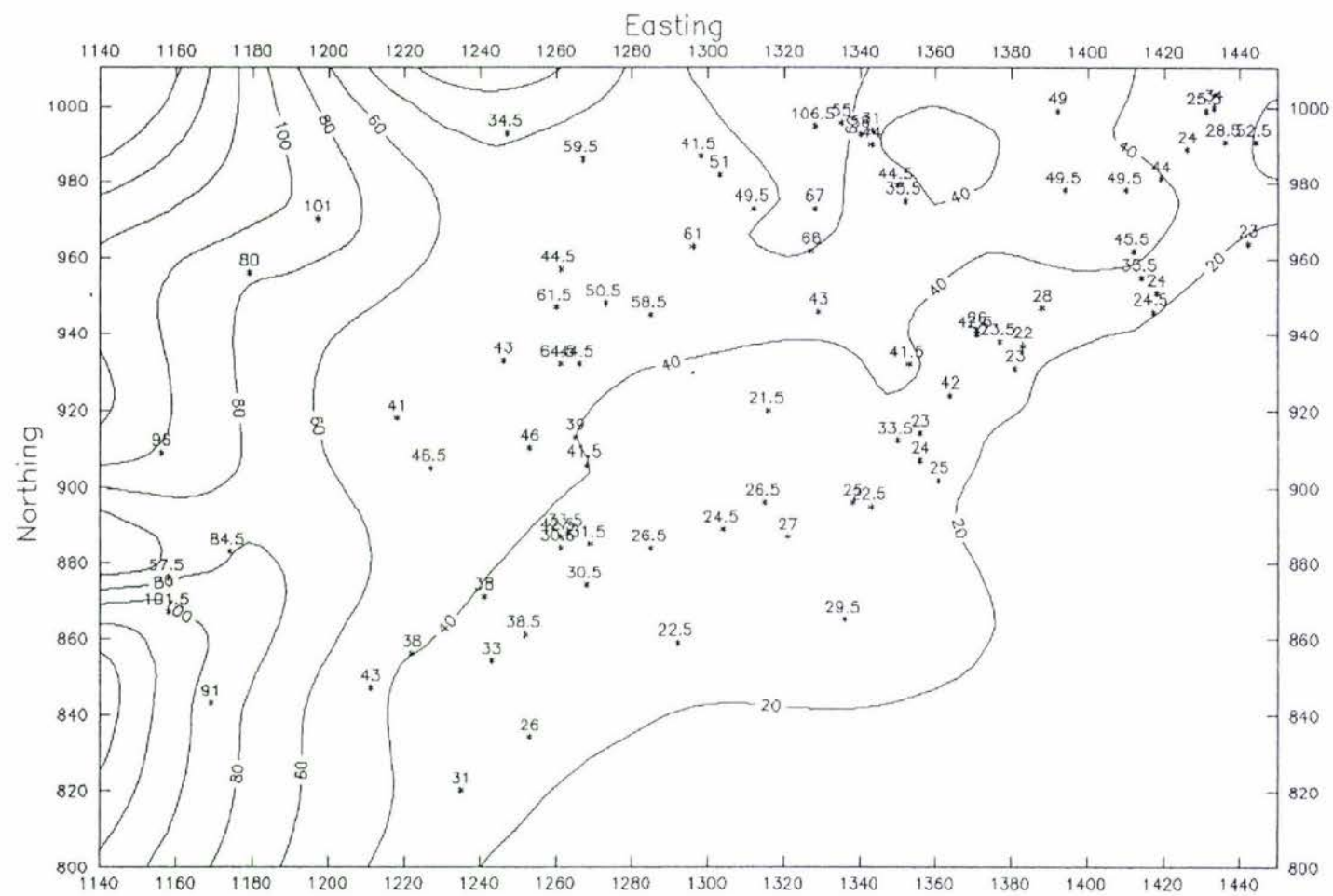


Figure 4.9 Isoconcentration contour map for Conductivity (mS/m).

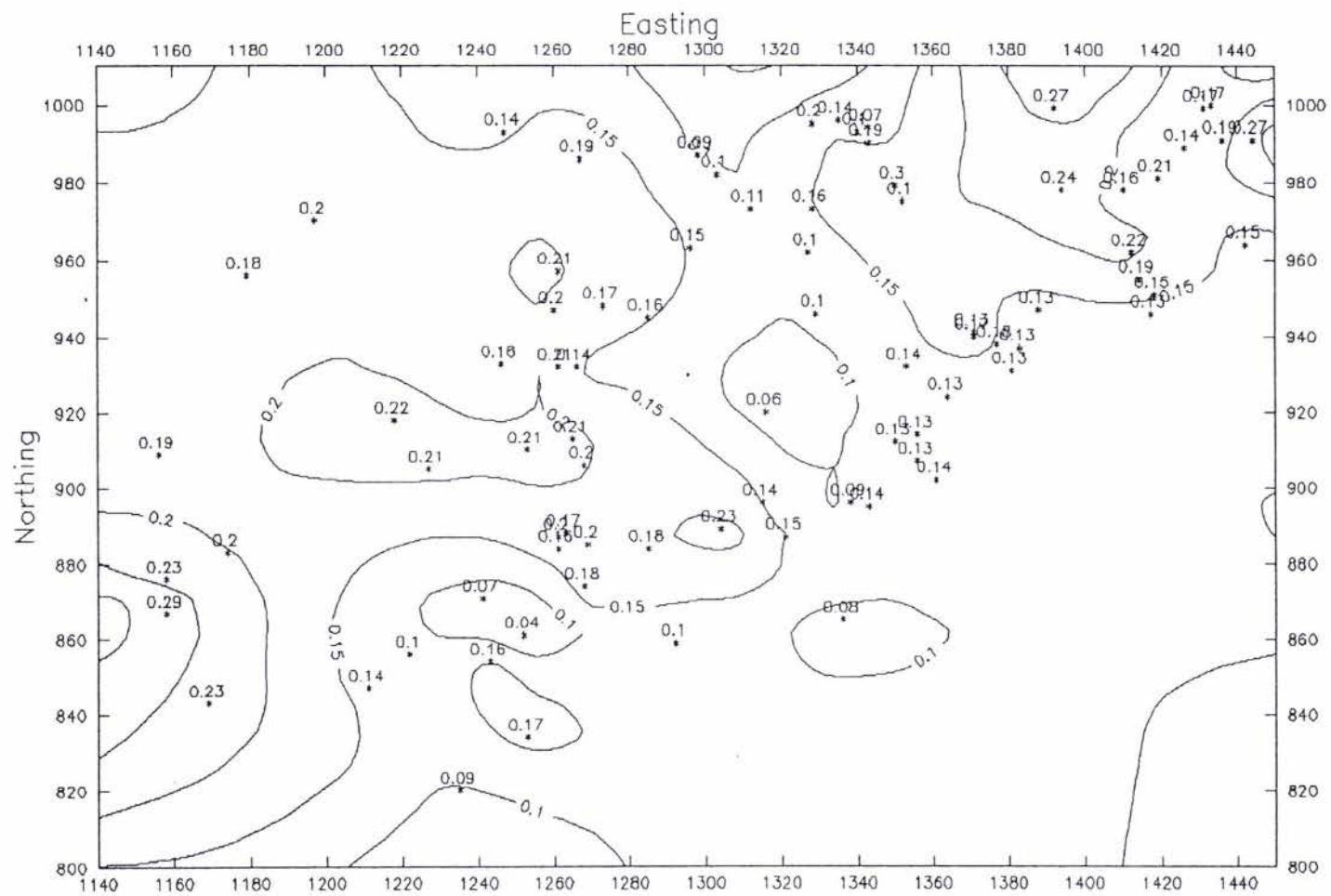


Figure 4.10 Isoconcentration contour map for Fluorine (ppm).

areas with high and areas with low concentrations (see figure 4.10). Most of the bores in the Manawatu River region have low fluorine concentrations, generally between 0.13 - 0.20 ppm. There is an area of very low concentration to the south of Linton where bore 0345 071 has a F concentration of 0.04 ppm. Areas with higher fluorine concentrations include Kairanga, the confluence of the Manawatu and Oroua rivers, and the area between Bunnythorpe and Ashhurst where concentrations are normally greater than 0.2 ppm F, the highest being bore 0326 171 with 0.30 ppm F. In general the deeper bores contain less fluorine than do the shallower bores.

IRON (Figure 4.11)

All but five of the bores in this area contain less than 6.0 ppm Fe and approximately half of the bores contain less than 1.0 ppm Fe. The Ashhurst region generally has high iron contents and this is an important problem for the citizens of the township of Ashhurst and the farmers nearby. The West Oroua River region has the highest concentrations, 18.5 and 22 ppm Fe in bores 0344 031 and 0334 081 respectively. The Manawatu River region has the lowest concentrations, with bores 0336 041, 0336 151, 0336 481, 0336 491, and 0337 031 recording < 0.1 ppm Fe. The shallow bores (0 - 60 m) have the highest concentrations and the concentrations tend to decrease with depth.

POTASSIUM (Figure 4.12)

The isoconcentration map for potassium shows a trend of increasing K concentrations from east to west of the study area (see figure 4.12). The bores in the Manawatu River region have the lowest concentrations, generally less than 3.0 ppm, the lowest being bores 0337 001 and 0337 041 with 1.2 ppm K. The concentrations increase downstream where the concentrations exceed 5.0 ppm K. The Ashhurst and Kairanga regions have medium values, normally between 4.0 - 5.0 ppm K, and the West Oroua River region has the highest concentrations in the entire area with concentrations in the vicinity of 10 ppm K, the highest being 12 ppm K in bore 0344 031. For any particular area the concentration of K generally decreases with depth but there are many exceptions to this trend.

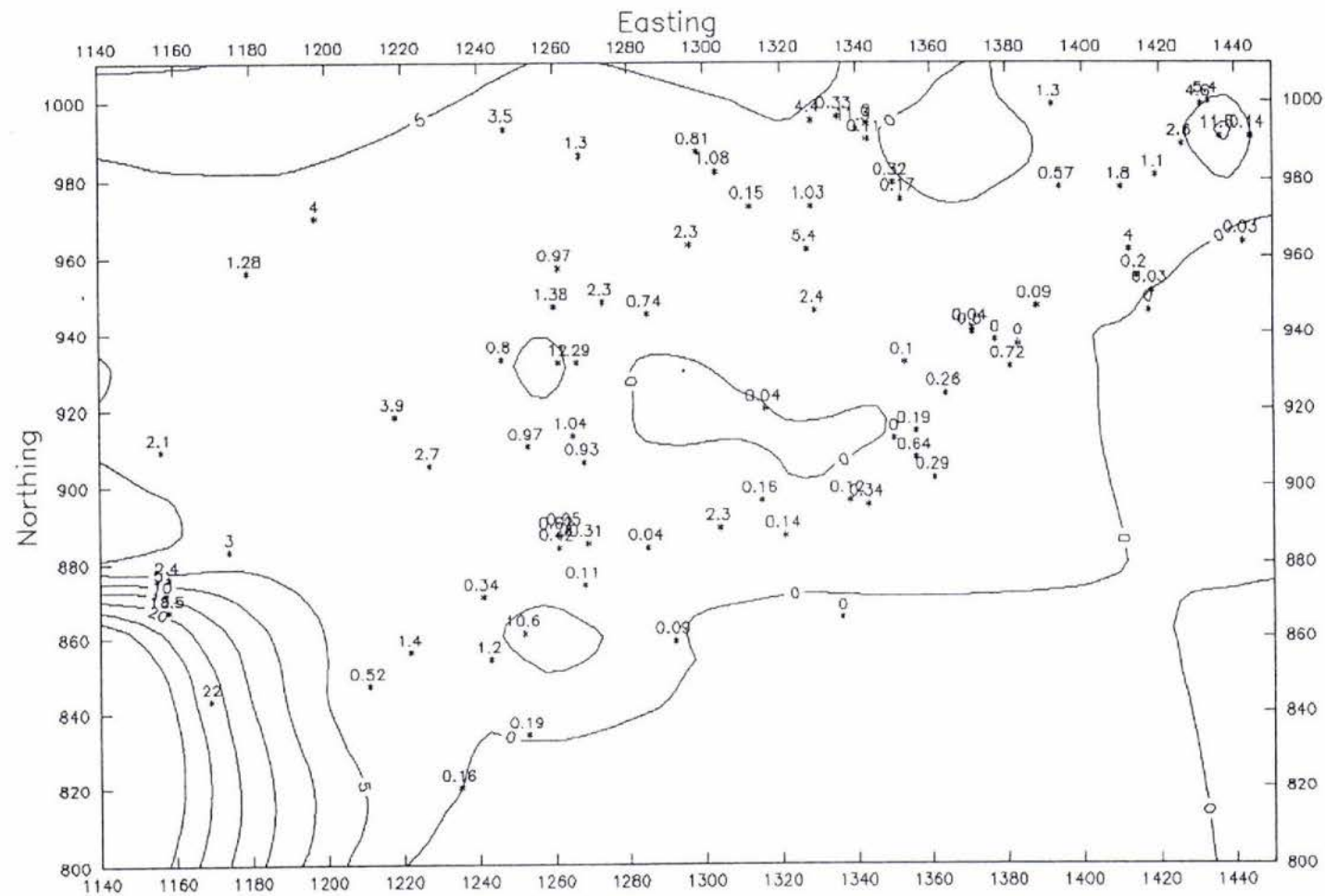


Figure 4.11 Isoconcentration contour map for Iron (ppm).

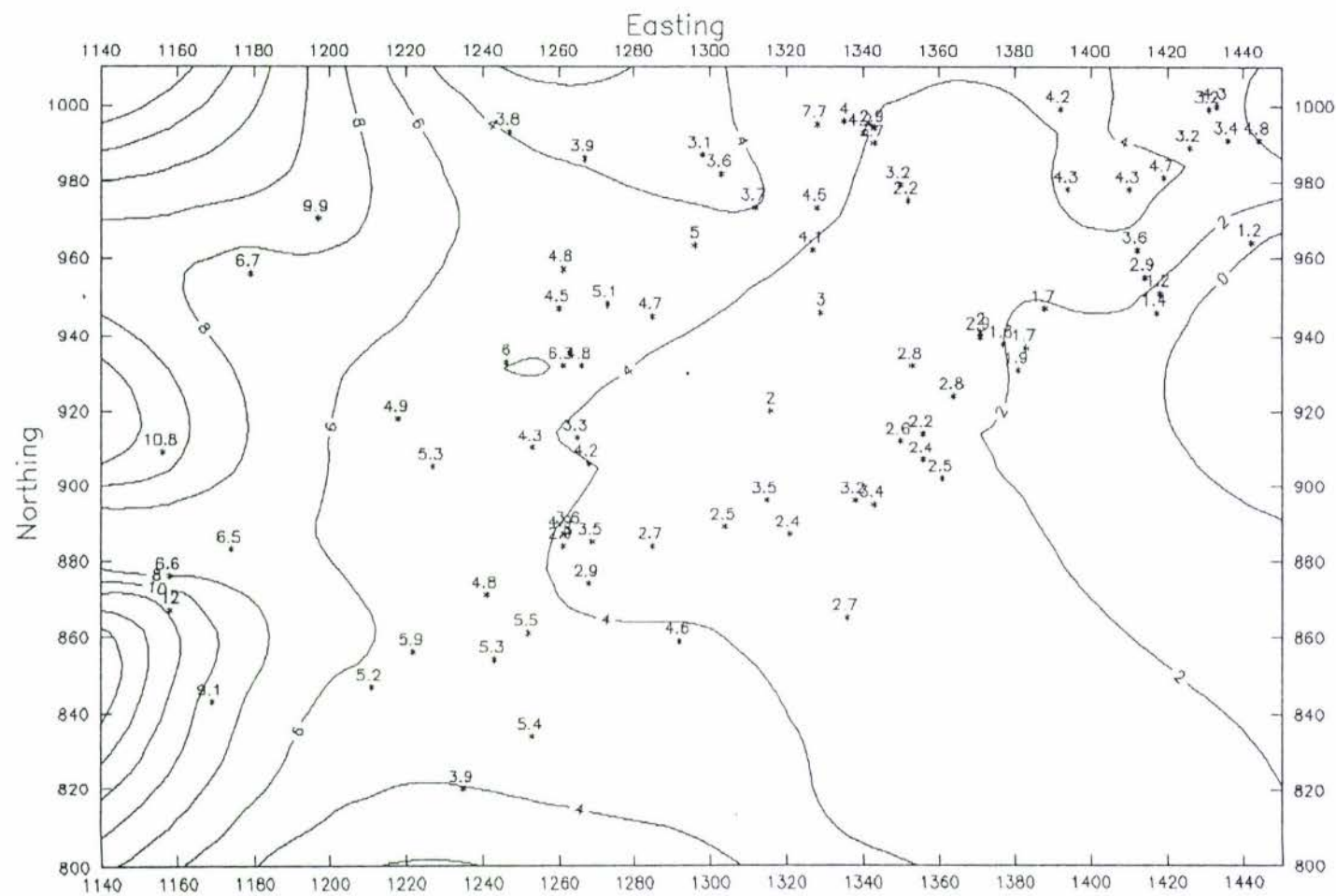


Figure 4.12 Isoconcentration contour map for Potassium.

MAGNESIUM (Figure 4.13)

Magnesium concentrations increase from east to west within the study area (see figure 4.13). The lowest concentrations being in the Manawatu River region where concentrations are generally between 20 - 40 ppm Mg, the lowest being 12 ppm K in bore 0344 041. The concentration tends to increase downstream. The Ashhurst and Kairanga regions have medium concentrations normally between 50 - 70 ppm Mg. The Bunnythorpe and West Oroua River regions have the highest concentrations, most of which are greater than 100 ppm Mg with the highest being bore 0334 051 which has 198 ppm Mg. The major trend with respect to depth is a decrease in Mg concentration with increasing depth, the two lowest concentrations 12 and 13 ppm Mg occurring in the depth range greater than 120 m.

MANGANESE (Figure 4.14)

All but seven of the bores in this study have manganese concentrations of less than 1 ppm and nearly half of all the bores contain less than 0.10 ppm Mn. The isoconcentration map shows an overall trend of increasing Mn from east to west but there are areas where anomalies occur (see figure 4.14). In the Manawatu River region the Mn concentrations are very low, generally below 0.09 ppm Mn, the lowest being 0.02 ppm Mn recorded in several bores along the Manawatu River. The concentration increases downstream. The higher concentrations occur in the Bunnythorpe area, with bore 0326 021 recording 2.3 ppm Mn, and the West Oroua River regions where two bores contain more than 2.0 ppm Mn. Other areas with medium to high Mn concentrations are the Kairanga and Ashhurst regions. Manganese concentrations in any particular area generally decrease with depth.

NITRATE

Nitrate was analysed for bores which obtained water from less than fifty metres depth. All the nitrate concentrations were well below 0.2 ppm, thus nitrate contamination does not appear to be a problem in this study area. As there were only about ten bores tested no isoconcentration maps were constructed.

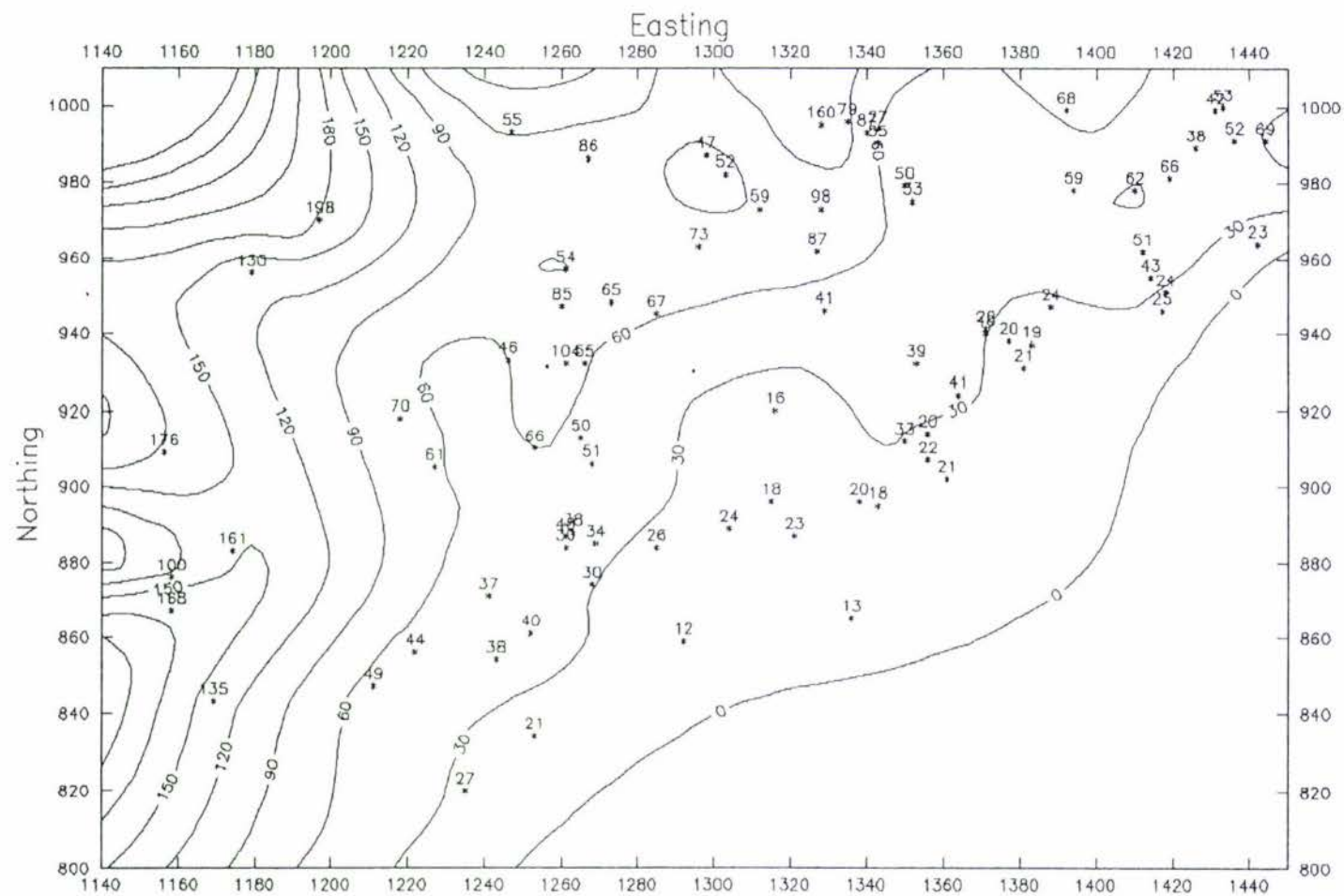


Figure 4.13 Isoconcentration contour map for Magnesium.

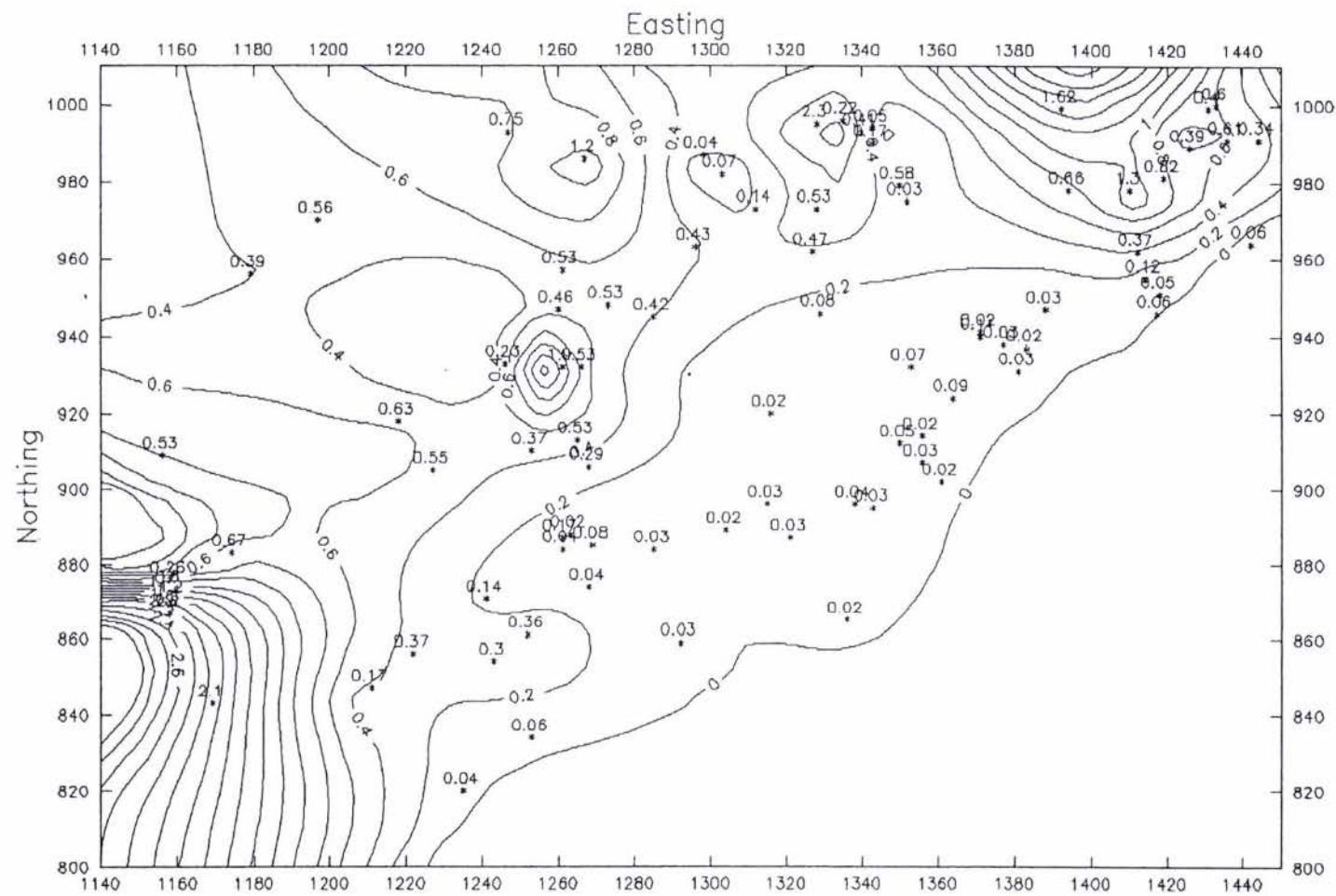


Figure 4.14 Isoconcentration contour map for Manganese.

SODIUM (Figures 4.15, 4.16, 4.17, 4.18)

The isoconcentration map for sodium shows a trend of increasing sodium concentration from east to west (see figure 4.15). The lowest concentrations occur in the Manawatu River region where the concentrations are normally between 10 - 20 ppm, bore 0337 041 recording the lowest Na concentration of 8 ppm. Na concentrations tend to increase downstream. Concentrations in the Kairanga, Bunnythorpe and Ashhurst regions are medium, generally between 20 - 40 ppm, with the exception of bore 0326 021 which has a Na concentration of 78 ppm. The west Oroua River region has the highest concentrations which are generally greater than 50 ppm, with bore 0344 031 recording a Na concentration of 84 ppm. Most of the higher sodium concentrations are located in the shallower bores (see figure 4.16) and the deeper bores tend to contain less sodium (see figures 4.17 & 4.18).

SULPHATE (Figure 4.19)

The isoconcentration map for sulphate shows a trend of increasing sulphate concentration from west to north-east (see figure 4.19). The bores to the west of the study area contain no sulphate at all and only in the vicinity of Bunnythorpe and Ashhurst is there any substantial sulphate content. The highest concentration of sulphate however is in bore 0334 051 which is anomalous as all the surrounding bores recorded zero sulphate. There is no general trend of sulphate concentration with respect to depth with some high values and many zero values at all the depth intervals.

TOTAL DISSOLVED SOLIDS (Figure 4.20)

The total dissolved solids (TDS) is the sum of all the dissolved chemical constituents of the water and therefore the isoconcentration map for TDS will appear similar to the major constituents' isoconcentration maps *ie.* Ca, Mg, alkalinity, Na, and Cl. All these maps show an increase in concentration of the chemical constituent from east to west in this study area and therefore the isoconcentration map for TDS also shows this trend. The same general

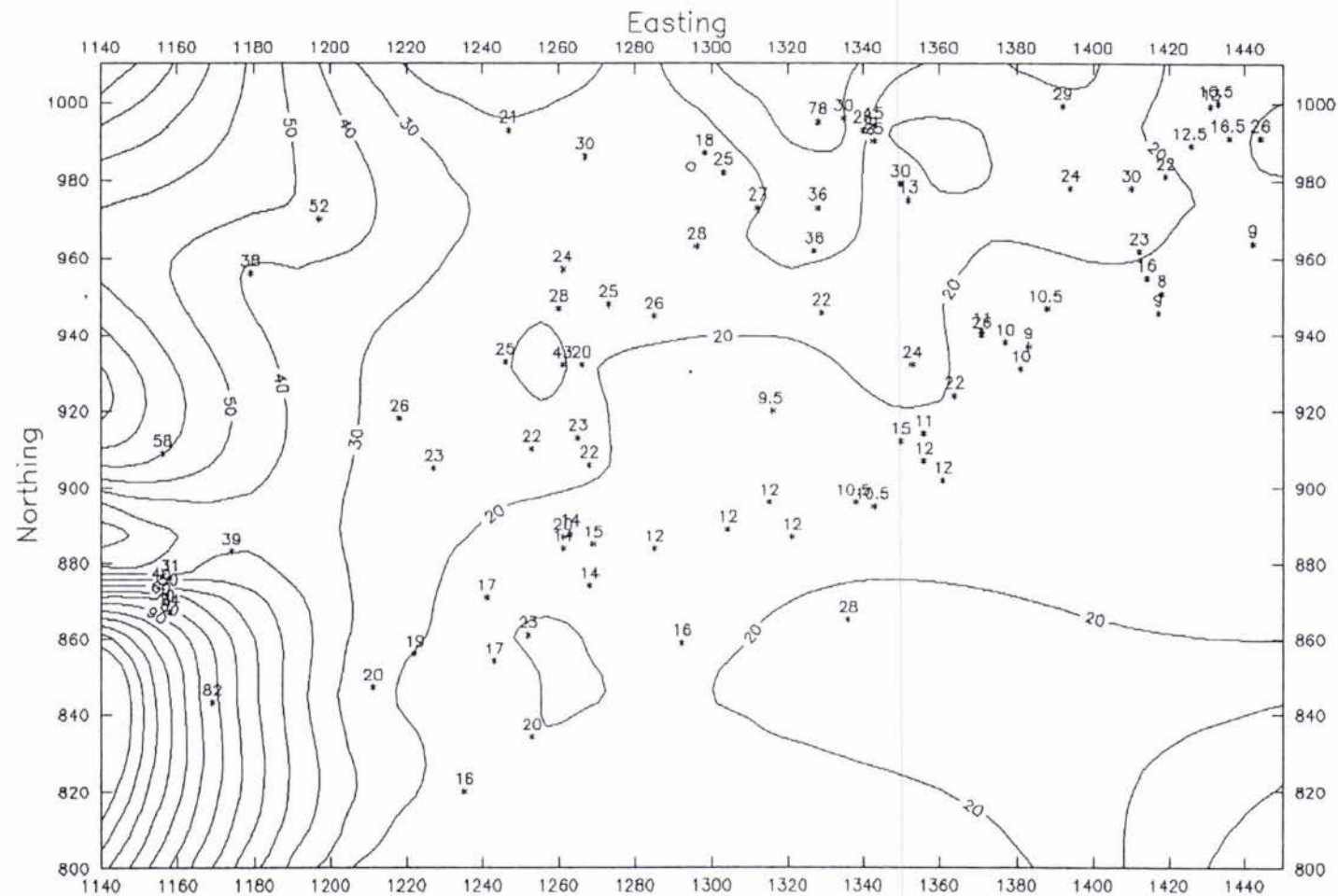


Figure 4.15 Isoconcentration contour map for Sodium (ppm): All Depths.

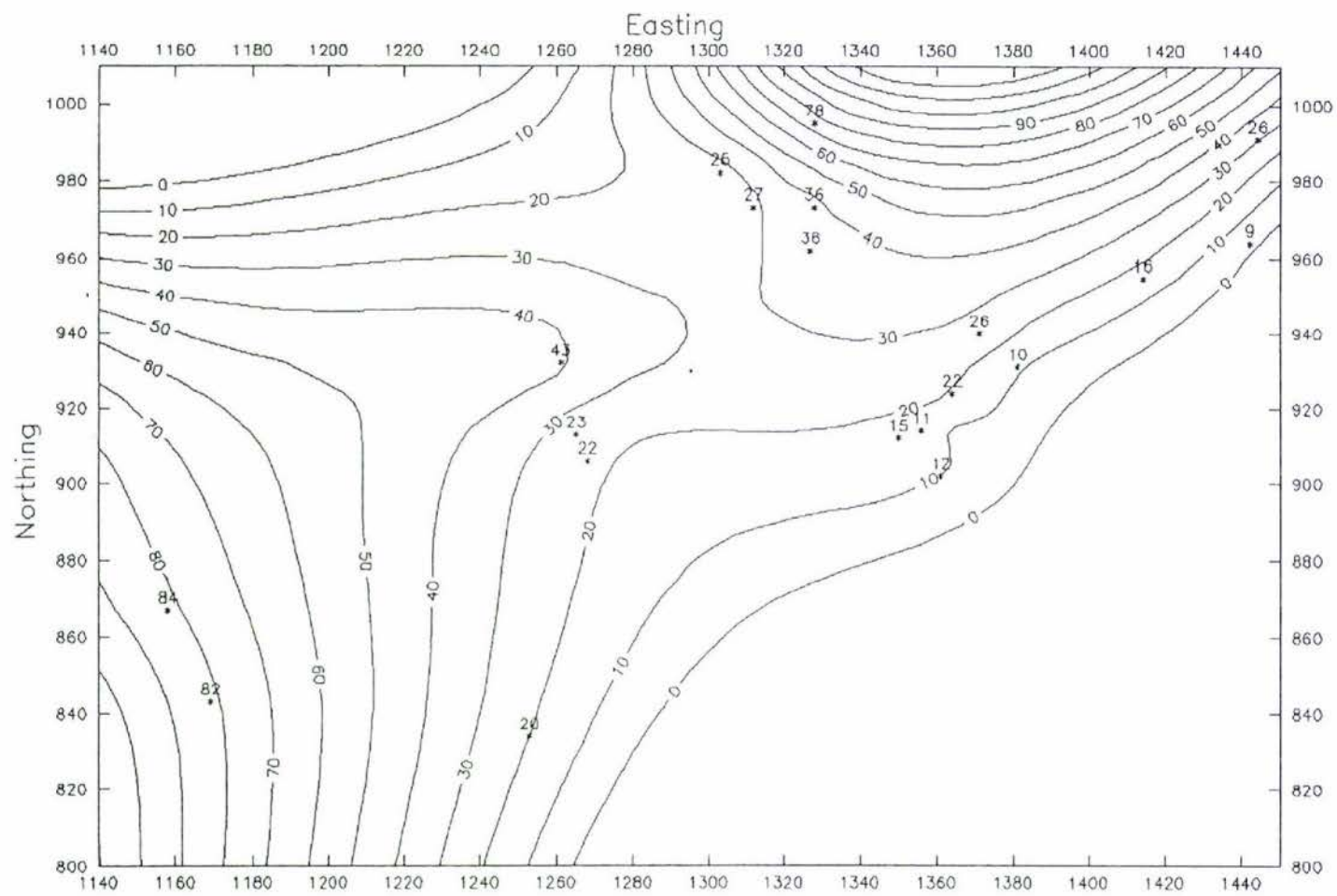


Figure 4.16 Isoconcentration contour map for Sodium (ppm): 0-60 m Depth.

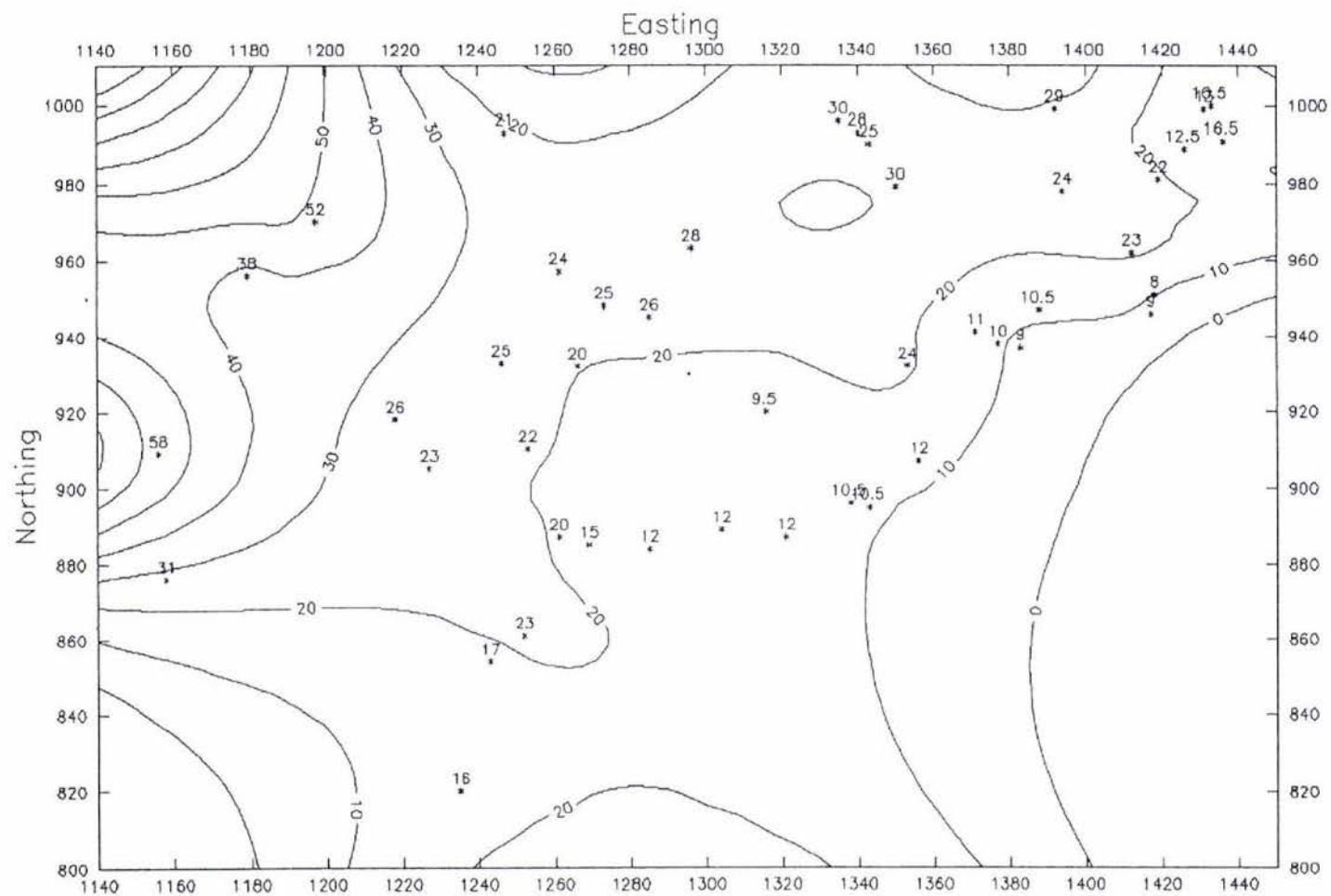


Figure 4.17 Isoconcentration contour map for Sodium (ppm): 60-120 m Depth.

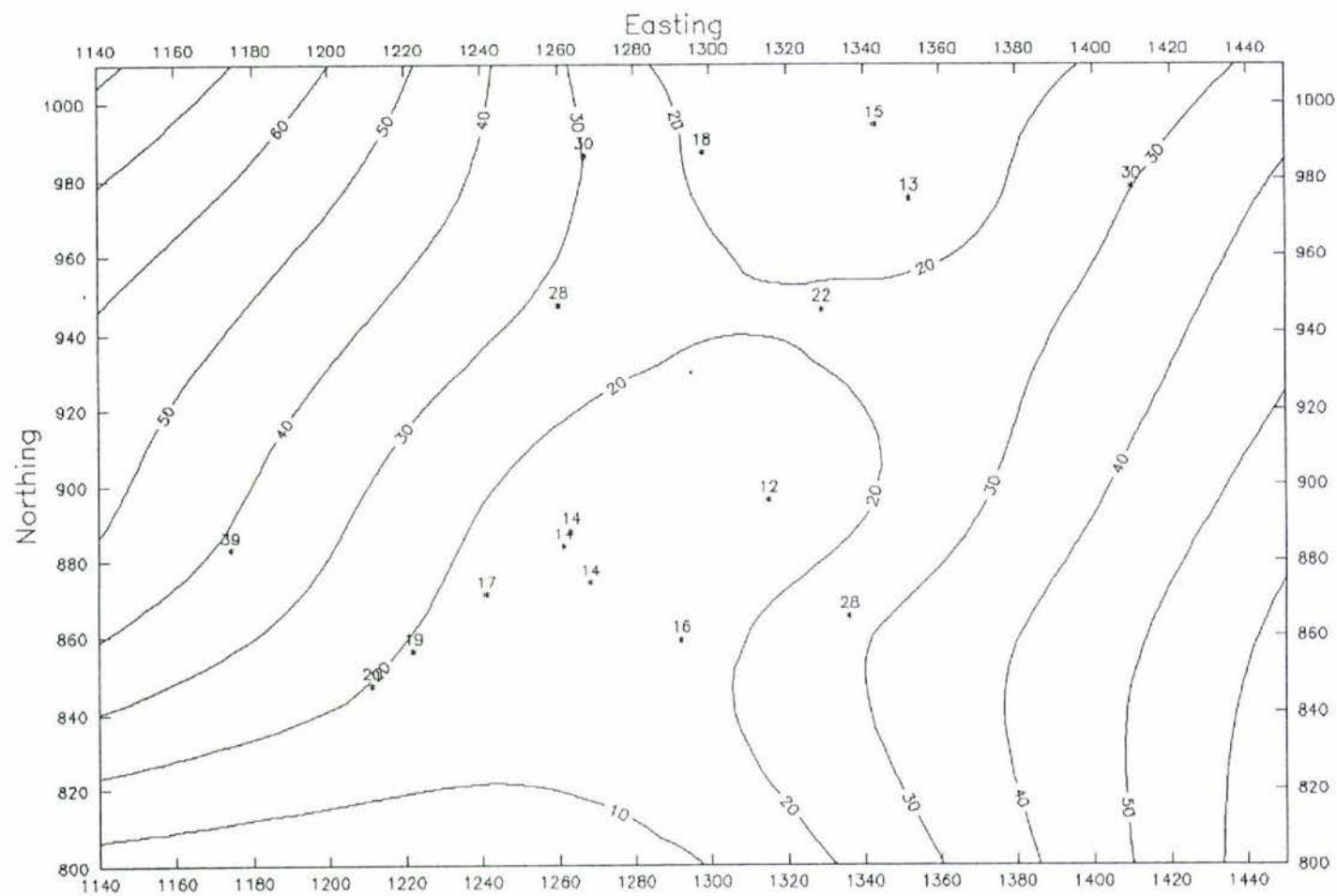


Figure 4.18 Isoconcentration contour map for Sodium (ppm): >120 m Depth.

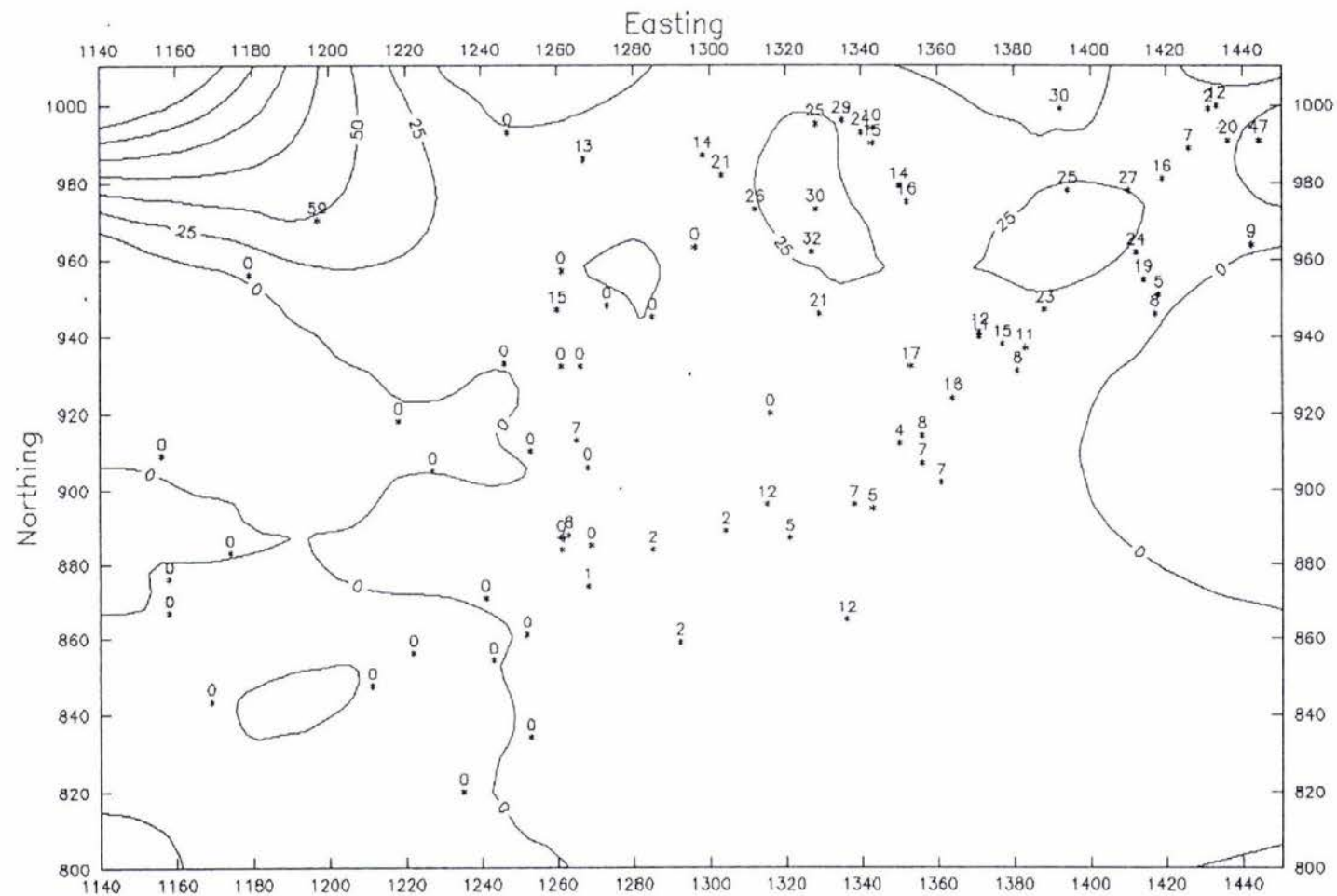


Figure 4.19 Isoconcentration contour map for Sulphate (ppm).

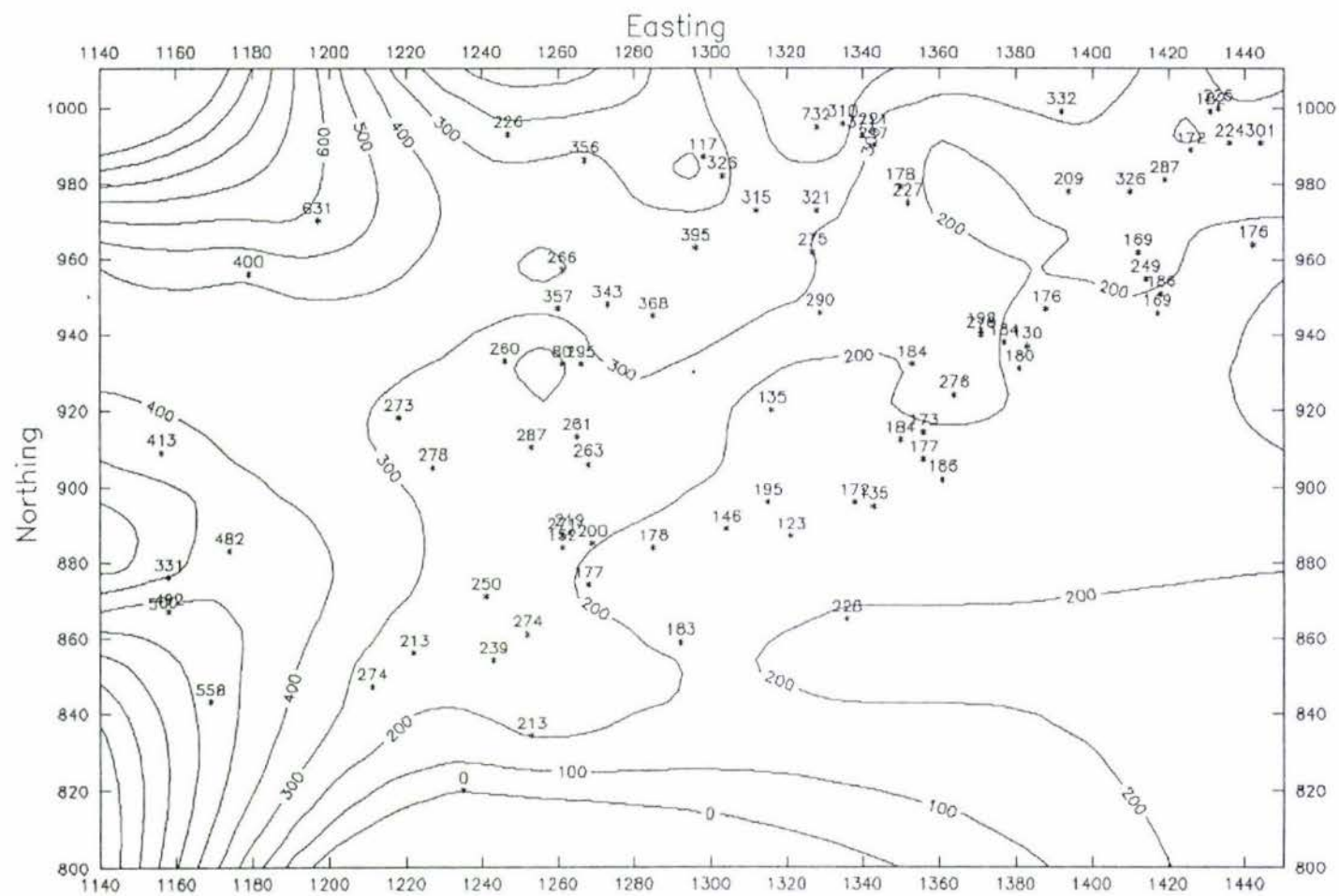


Figure 4.20 Isoconcentration contour map for Total Dissolved Solids.

trends exist for the different regions, *ie.* the lowest TDS values occur in the Manawatu River region where the TDS is generally between 100 - 200 ppm, and concentrations increase downstream. Medium values occur in the Kairanga-Bunnythorpe and Ashhurst regions, normally between 200-400 ppm, with an anomaly in bore 0326 021 which has a TDS concentration of 732 ppm. The area with the highest concentrations is the West Oroua River where TDS concentrations normally exceed 400 ppm. There is a general decrease in TDS concentrations with increasing depth.

4.2.4 INTERPRETATION

The isoconcentration maps for total alkalinity, calcium, chloride, electrical conductivity, potassium, magnesium, manganese, sodium, and total dissolved solids all show a general increase in concentration from east to west within the study area. These increases coincide with the direction of water movement within the aquifer system; *ie.* the water is flowing from east to west with an influx of water from the Oroua and Pohangina catchments. The increase in concentrations of the chemical parameters is due to the water reacting with and dissolving the various chemicals from the rocks along which the water flows.

Free carbon dioxide, fluorine, and iron show no overall trend of increasing concentrations in any particular direction but instead tend to have areas where their concentrations are high. This can be attributed to highly localized conditions which may exist in a particular area. For example where high iron concentrations are found the rock type in that area may have a uncharacteristically high iron content which is reflected by the high concentrations in the water of the area.

Sulphate is the only chemical parameter which increases in concentration from west to east. No reason for this has been postulated but the sulphate must in some way be removed from the system as the water flows from east to west.

4.3 CHEMICAL CHANGES WITH RESPECT TO DEPTH

The chemistry of groundwater normally changes with respect to depth. To best illustrate the major trends in this study area, a locality where bores of differing depth but relatively close proximity to each other was chosen. The bores should be close together to reduce the influence of spatial variation of the chemical parameters. Six bores were chosen, all within grid 0326: bores 0326 011, 0326 021, 0326 091, 0326 171, 0326 181, and 0326 331. All these bores are within a 1.5 km radius of each other and each represents a different depth, 113 m, 29 m, 118 m, 208 m, 102 m, 135 m, and 86 m respectively. For each chemical parameter the concentration in each bore was plotted against the depth of the bore and all six bores were plotted on the same graph (see figure 4.21(a-n)). Best fit curves were fitted to show the main trends. All the graphs show an overall decrease in concentration with depth. Ca, Mg, Na, Cl, Fe, CO₂, alkalinity, conductivity, and total dissolved solids show this trend exceptionally well whereas K, Mn, F, and sulphate have some exceptions but still show the same overall pattern of decreasing concentration with depth. Throughout the study area where bores are located close together similar trends occur with the deeper bores having lower concentrations than shallower bores. There are of course exceptions to this trend and these can be attributed to unusual local conditions, *ie.* isolated blocks of rocks rich in a particular cation or anion may be supplying abnormal amounts of the cation or anion to a limited area; also point source pollution may artificially increase some chemical parameters in a localized area.

The reasons why the deeper bores have lower concentrations may well be due to the fact that the aquifer systems in this area are 'leaky' allowing groundwaters from deeper aquifers to flow vertically upwards into shallower aquifers. During this journey the groundwaters from deeper levels flow through additional lithologies allowing further dissolution of cations and anions from these rocks and this may explain why the shallower groundwaters have higher concentrations of certain cations and anions than deeper waters. Shallow bore waters are susceptible to increased concentrations of some chemical parameters by way of rainfall, pollution, and fertilizer applications. Increased Na and Cl in shallow bores may well be due to the higher concentration of these chemicals in rainfall in coastal areas. This may be

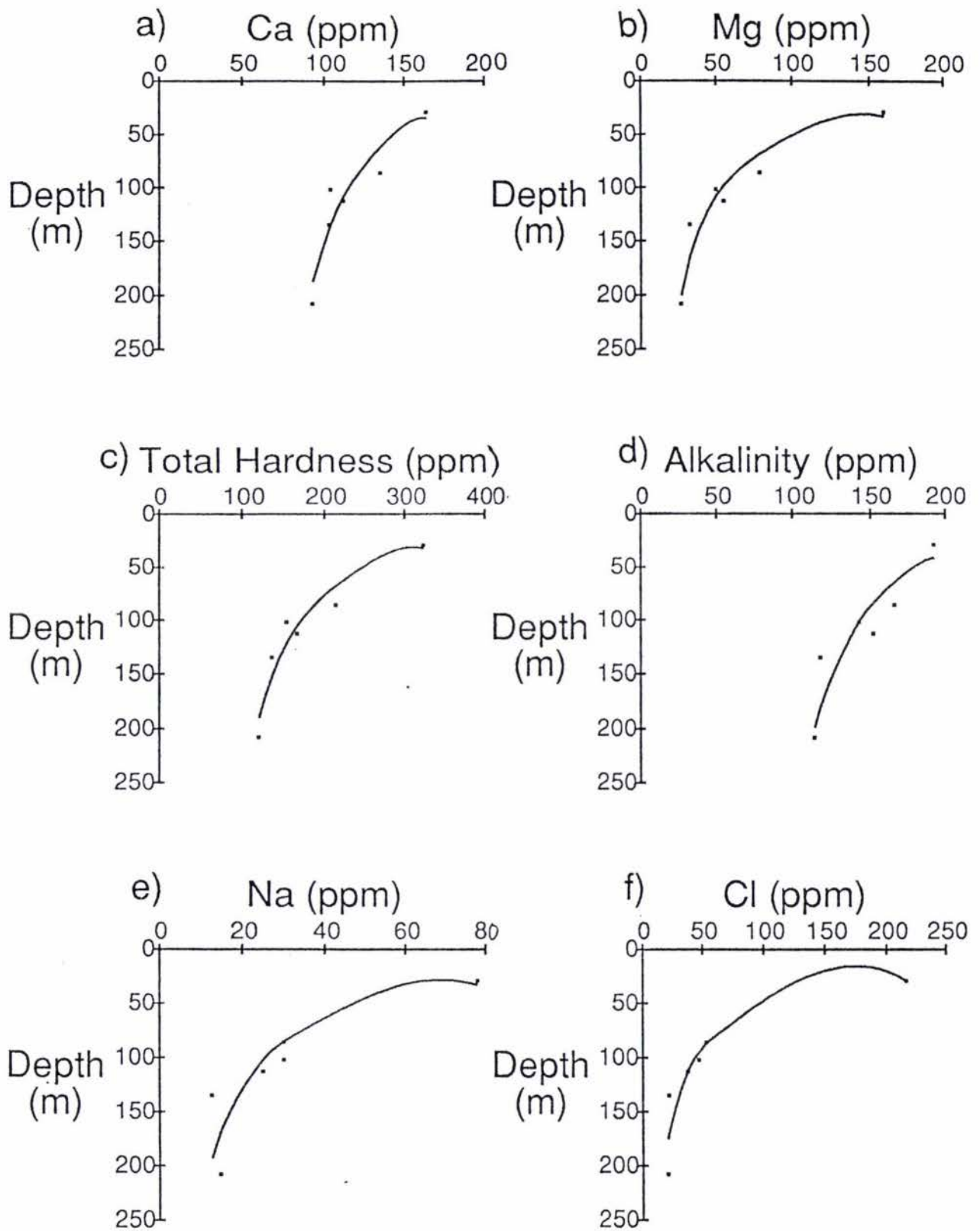


Figure 4.21 Graphs of chemical parameters versus dept

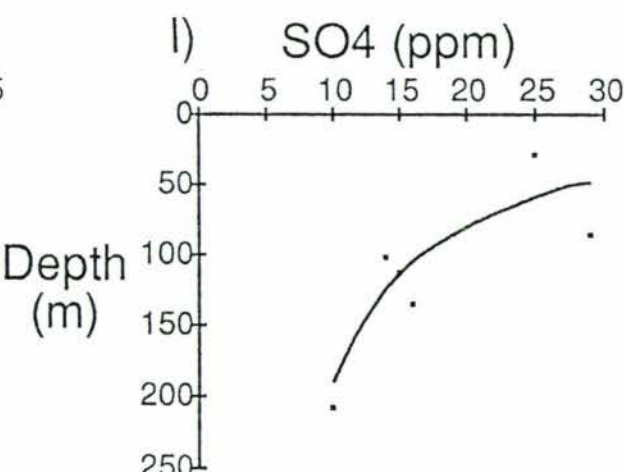
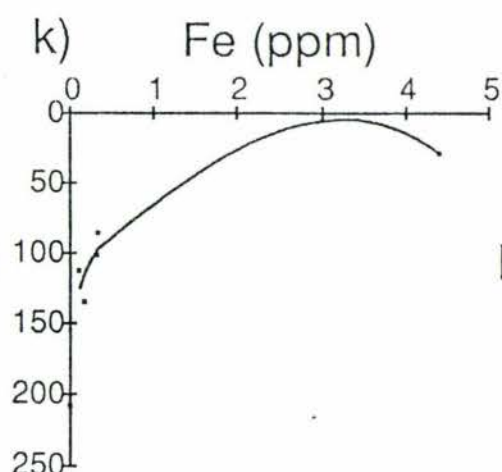
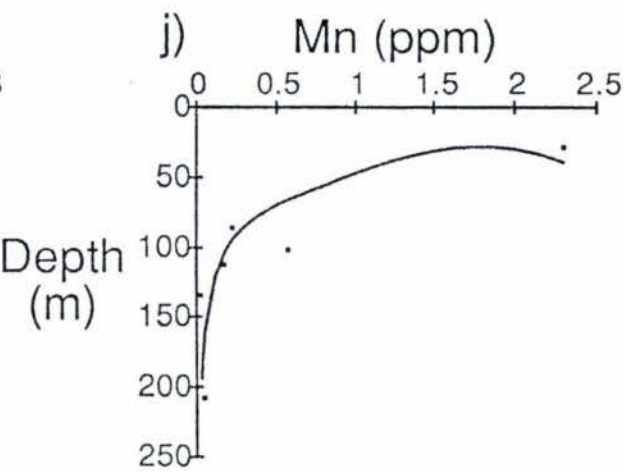
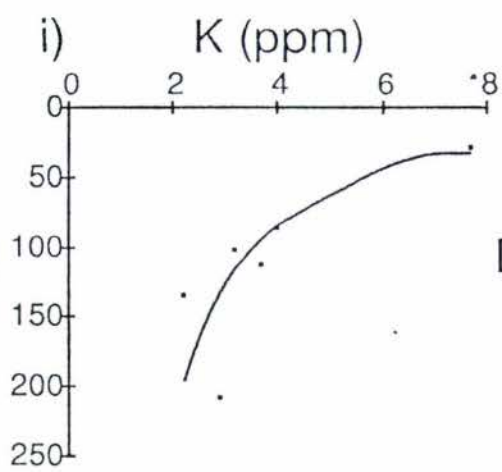
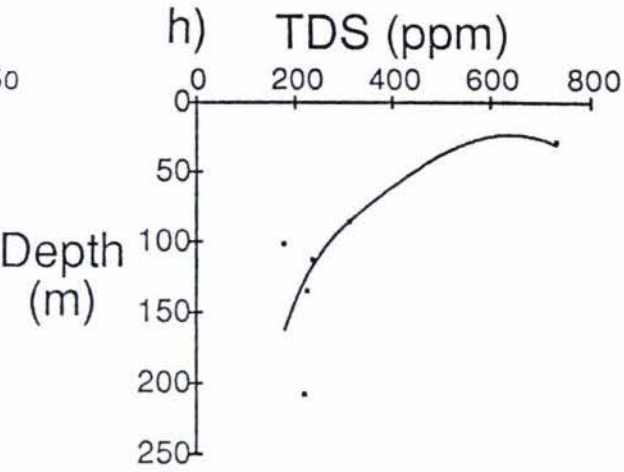
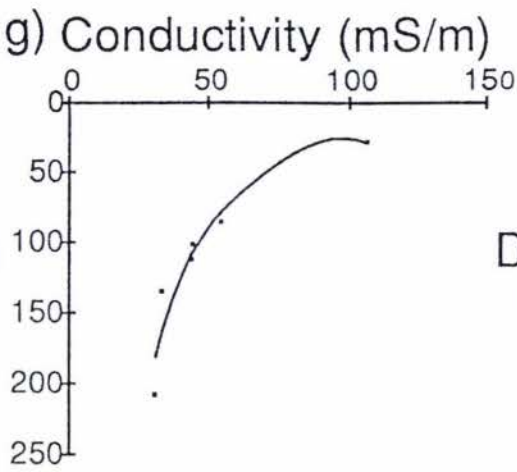


Figure 4.21 Graphs of chemical parameters versus depth.

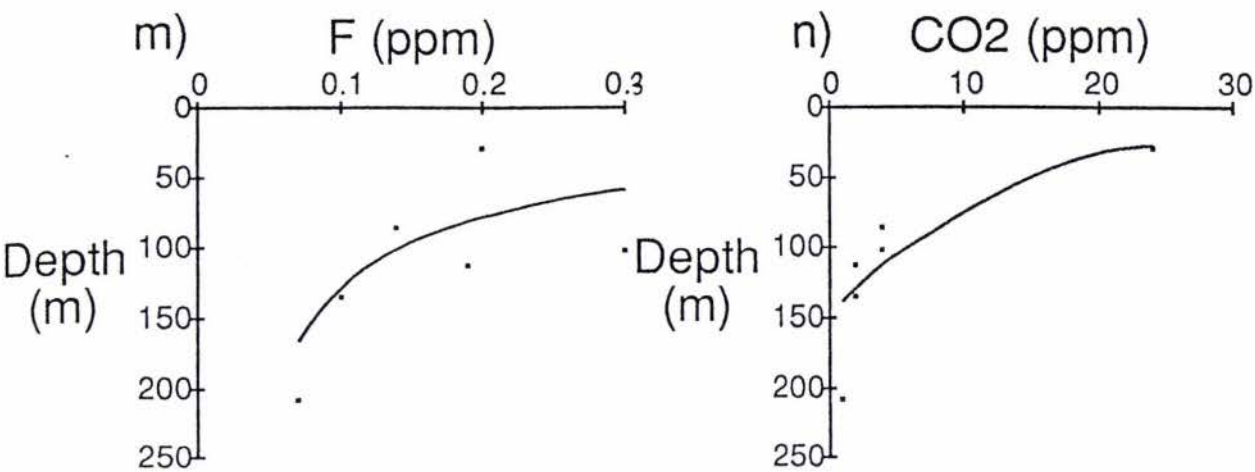


Figure 4.21 Graphs of chemical parameters versus depth.

very important in the Manawatu because the area is located very close to the coast, it is relatively flat, and strong westerly winds predominate allowing sea-spray to drift large distances. Chloride is also applied as a constituent of some fertilizers and being a non-reactive anion has a very high mobility in groundwater and may directly enter shallow groundwaters.

4.4 CONDUCTIVITY DIAGRAMS

Conductivity, as discussed earlier, is the ability of water to conduct electricity and is the sum of the electrical conductivities of the cations and anions in solution. Conductivity is one of the easiest properties of groundwater to measure and can be measured in the field. Measurement normally consists of introducing a conductivity metre into the water, passing a current between the two electrodes and measuring the resistance of the water. The resistance is measured in ohms and the reciprocal of resistance is the conductivity with the old units of mhos (ohm spelled backwards). These units are still very common but are being replaced with the new unit called Siemens (S).

Conductivity is directly related to the total dissolved solids in the water. Ideally the concentrations of all the dissolved cations and anions in solution added together will equal the total dissolved solids. When this was done for this study it was found that the summation value was consistently higher than the measured value of TDS (see Table 4.1). A brief discussion about the reasons for this discrepancy follows.

The laboratory procedure for the measurement of TDS involves firstly filtering the water sample through a prescribed size filter paper, (Whatman GF/C 4.7 cm was used in this case), weighing a 50 ml or 100 ml sample of filtered water into a pre-weighed Gooch crucible which has been heated to 180 °C for one hour and kept in a desiccator until required. The water is evaporated off by heating the sample to 180 °C for one hour. The crucible is then cooled in a desiccator to balance the temperature and is then reweighed. The difference in weight is the amount of TDS per 50 ml or 100 ml sample. This

Table 4.1 Comparison between measured total dissolved solids and summation total dissolved solids.

Measured TDS	Summation TDS	Measured TDS	Summation TDS
326	468	178	245
226	329	295	406
356	549	395	524
117	392	290	397
237	403	130	202
732	876	195	246
332	448	276	378
371	529	228	261
221	284	177	227
209	454	278	384
178	396	315	444
227	310	135	204
310	501	135	202
172	220	176	259
301	480	198	244
326	446	186	233
224	281	180	215
225	321	184	394
182	231	123	246
287	398	172	228
273	389	321	613
482	814	184	295
413	897	184	214
631	973	173	217
400	778	275	592
331	528	176	216
200	293	249	328
343	457	169	233
357	575	186	226
250	355	169	412
368	500	492	1144
263	370	274	413
266	403	558	987
278	431	213	357
287	427	183	211
261	428	213	236
271	392	152	286
260	402	274	378
219	327	239	317
80	634	256	404
146	230	115	234
177	281	732	1459

method may not always represent the true TDS as some volatiles such as sulphate and bicarbonate may escape when the temperature is increased to >100 °C. Ideally rotary evaporation would be used which uses low temperature evaporation and thus reduces the risk of volatiles being lost, but this method is fairly expensive and not readily available in most laboratories. The major error in the evaporation method of determining TDS is the error in the weighing of the sample before and after evaporation. For example if the 100 ml sample of filtered water plus the crucible which weighs 10.000 g weighs 110.00 g (assuming a balance which measures to two decimal places) before evaporation and weighs 10.03 g then the weight of the TDS is 0.03 g and the concentration of the TDS is $0.03 \text{ g}/100.00 \text{ g} = 300 \text{ ppm}$. Allowing for an accuracy of $\pm 0.005 \text{ g}$ in the balance then the error in the TDS concentration would be $\pm 50 \text{ ppm}$ (17 %), which means that the TDS may vary between 250 - 350 ppm. Also because the water is evaporated in one hour at 180 °C the sample would boil with some loss due to splashing possible.

The measured total dissolved solids are plotted against conductivity (see figure 4.22). This shows a linear relationship, with a correlation coefficient of 0.92. On the same graph the summation totals are plotted, showing a better linear relationship with a correlation coefficient of 0.99. It can be seen from this graph that the summation values are approximately double the measured TDS values. This graph is very useful in the field for determining the TDS of a water by just measuring the conductivity of the water.

Another very useful graph to use in the field is one where conductivity is plotted against individual cations and anions. Graphs of calcium, magnesium, sodium, potassium, chloride, and alkalinity versus conductivity were made and all show good linear relationships (see figures 4.23(a-f)). These cations and anions normally make up more than 98% of the total constituents in the groundwaters in this study area. All the graphs have correlation coefficients of greater than 0.84 (the graph for potassium). Using these graphs it is possible to predict various cation and anion concentrations of the groundwaters in the Manawatu region by measuring only the conductivity of the water. It must be stressed that these graphs will only give an estimate and the accurate method of determining the concentrations is by analysing water samples in a laboratory.

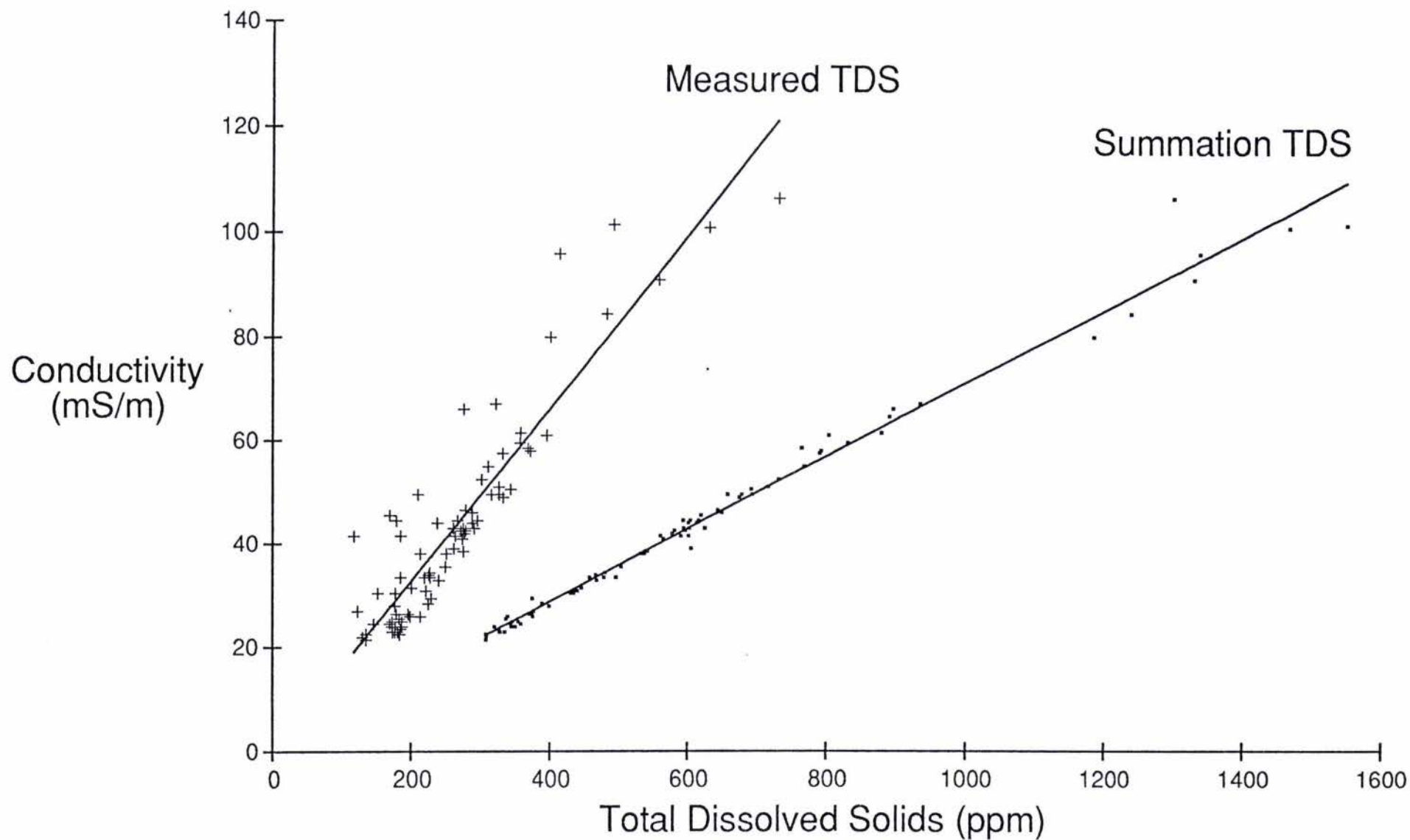
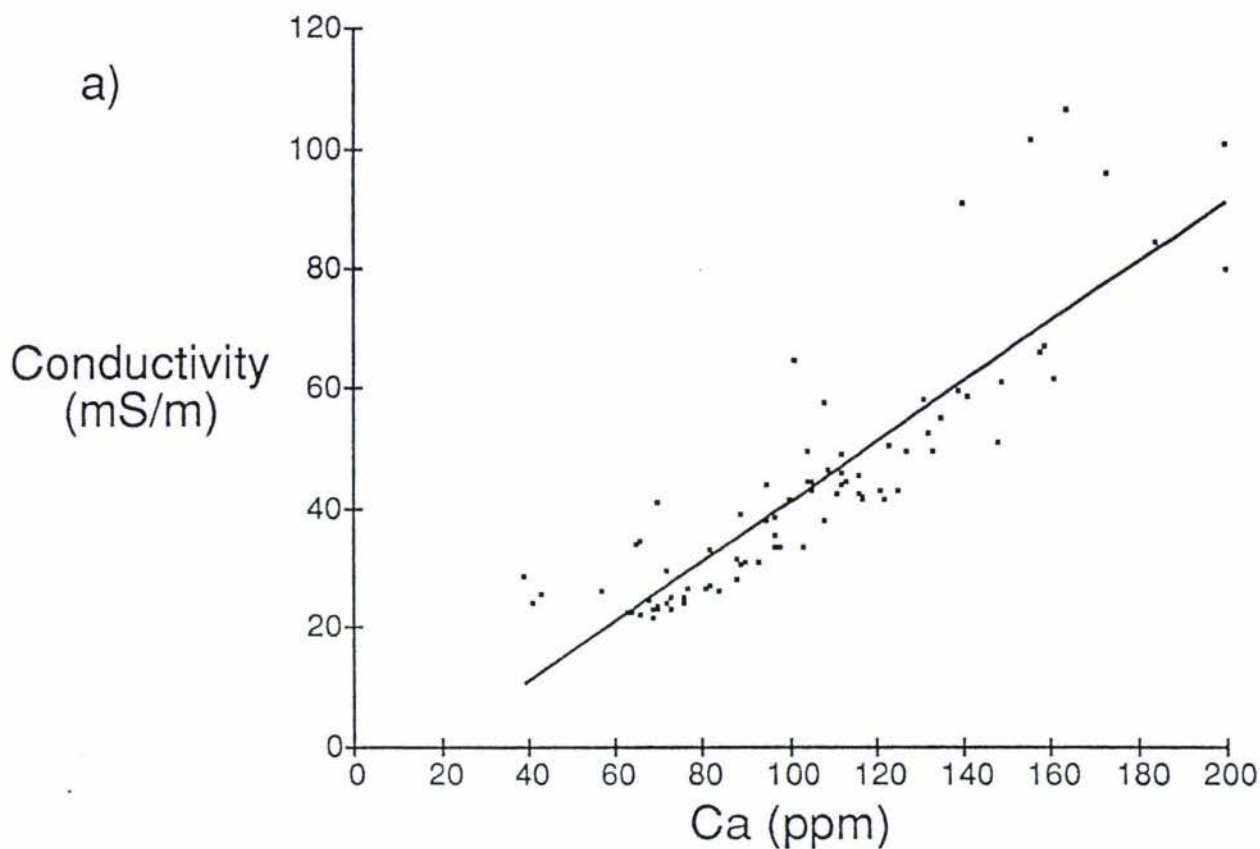


Figure 4.22 Graph of conductivity versus measured total dissolved solids and summation total dissolved solids.

a)



b)

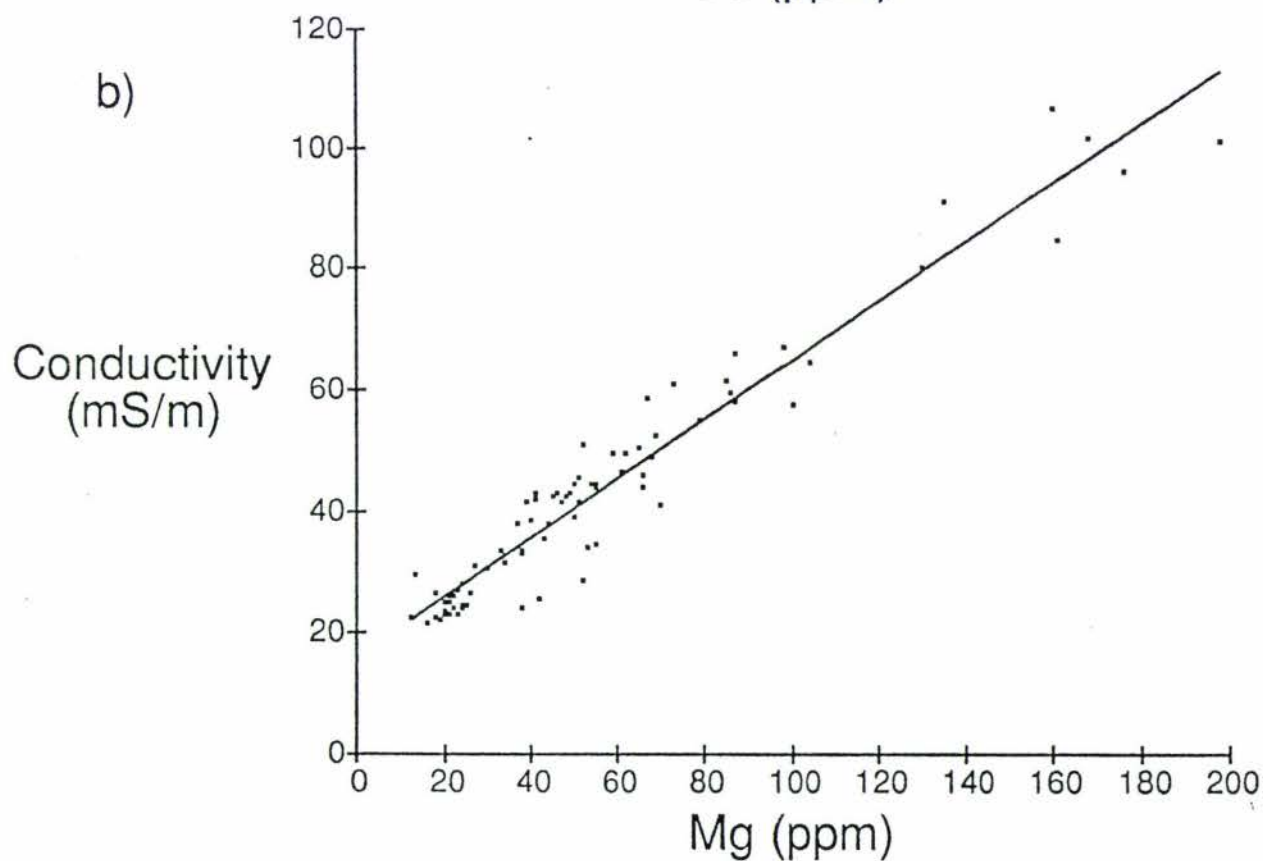


Figure 4.23 Graphs of the major cations and anions versus conductivity.

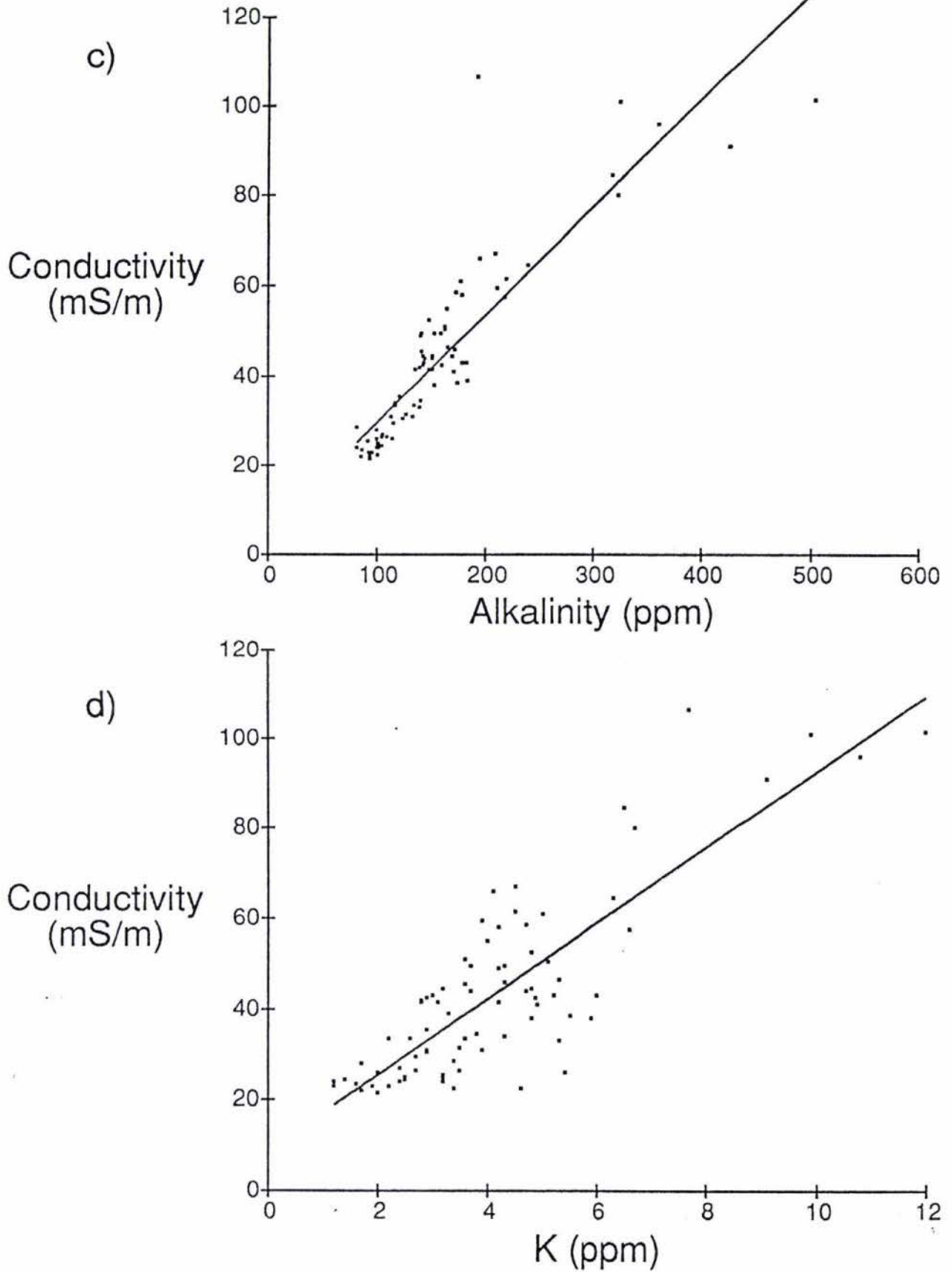


Figure 4.23 Graphs of the major cations and anions versus conductivity.

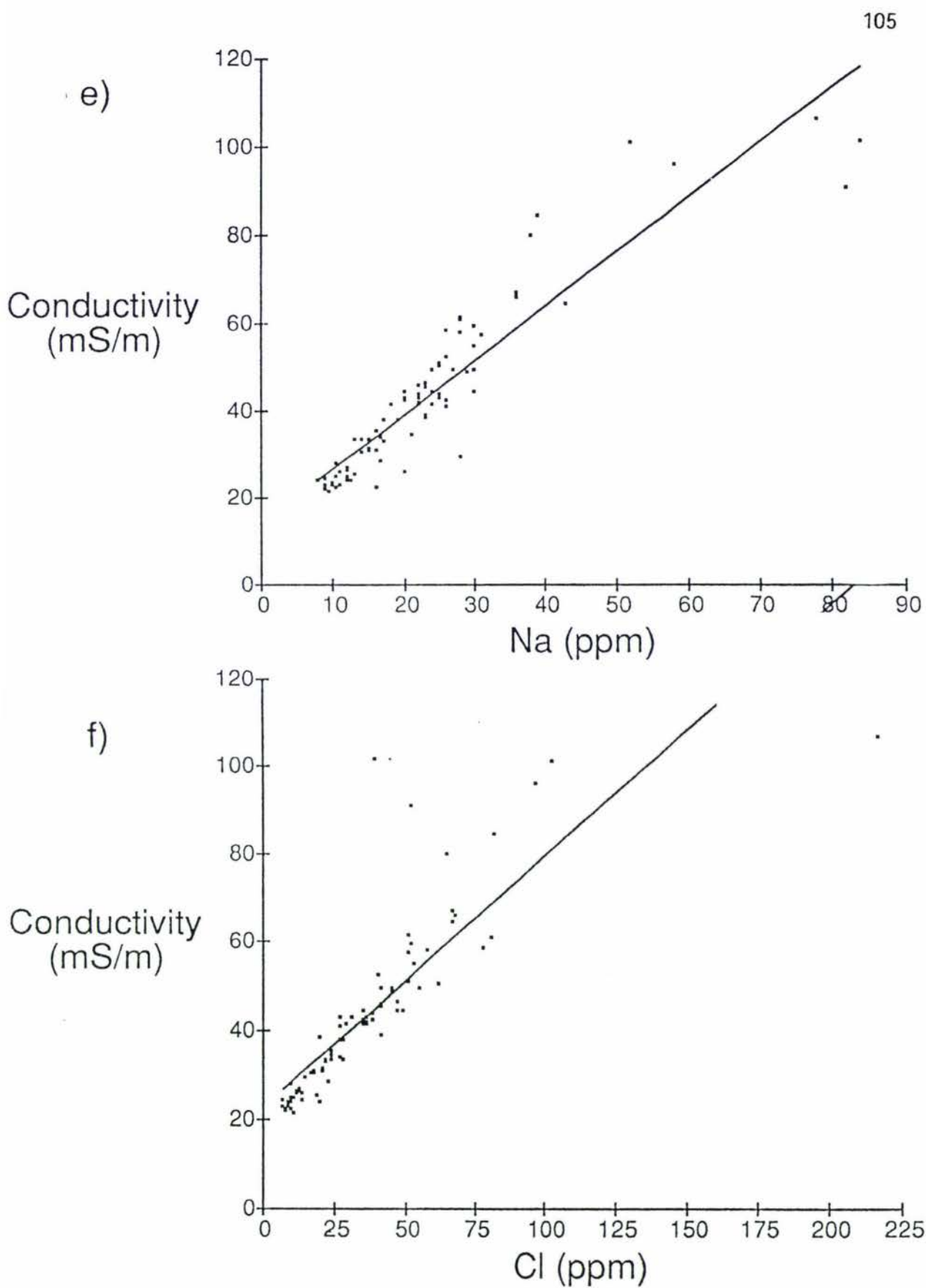


Figure 4.23 Graphs of the major cations and anions versus conductivity.

CHAPTER FIVE - CONCLUSIONS

The Manawatu River and to a lesser extent the Pohangina River have cut down into the marine strata of the South Wanganui Basin and their vallies are now entrenched within a flight of terraces formed by both aggradation and degradation during the Pleistocene and Holocene. Three aggradational terraces are described and correlated with the Ohakean, Ratan, and Porewan terraces in the Rangitikei River Valley. All the aggradational terraces were formed during the Otiran Glaciation and consist of predominantly greywacke gravel with some spilite and argillite which was brought down from the axial ranges. The oldest of the aggradational terraces is the Porewan terrace which was described as the Forest Hill Terrace by Fair (1968) who attributed the terrace to have formed during the Oturian Interglacial. The Porewan terrace exists on both sides of the Manawatu River Valley. On the south-eastern side of the valley the Porewan terrace exists as a narrow strip from Forest Hill Road up to the Manawatu Gorge; on the north-western side of the valley the distribution is not precisely known but it does occur around the township of Ashhurst. The Porewan gravels were thought to be accumulating between 65,000 and 75,000 years B.P.. Two loess units overlie the Porewan gravels, the basal loess unit is known as the Ratan loess and the upper loess is known as the Ohakean loess as the loess was accumulating during the formation of the Ratan and Ohakean terraces respectively.

The second advance of the Otiran Glaciation resulted in the formation of the Ratan terrace. This terrace only has one loess, the Ohakean loess, overlying the predominately greywacke Ratan gravels. The Aokautere ash, the 22,500 years B.P. marker horizon, is present within the Ohakean loess. The Ratan gravels were thought to have accumulated between 30,000 and 40,000 years B.P.. The Ratan terrace is present on both sides of the valley.

The third advance of the Otiran Glaciation resulted on the formation of the Ohakea terrace which was thought to have accumulating between 13,000 and 25,000 years B.P.. In many areas there is no loess cover but in some locations a small blanket of Holocene loess overlies the predominately greywacke gravels. The Ohakean terrace covers an extensive area around the

township of Ashhurst and also on the south-eastern side of the valley a large area between Aokautere and the Manawatu Gorge. Other remnants exist on both sides of the river valley. The Holocene terraces are located adjacent to the present rivers and consist of sands, silts, clays, and gravel. These terraces are degradational and have cut into the older aggradational terraces. The history of the Manawatu River is responsible for the distribution of the Ohakean terrace. It was previously flowing to the north of the valley and has over time migrated south-eastwards to be at present eroding the Ohakean terrace on this side of the valley.

Investigations into the distribution of lithologies in the area by way of cross-sections revealed that the nature and history of the Manawatu and Oroua Rivers has resulted in a sequence of clay, silt, sand, and gravel deposits which is exceedingly complex in detail. This has been the main factor influencing the distribution and nature of the aquifers of the region. Water is normally extracted from the coarsest deposits with 75% of the bores in the area obtaining water from gravel layers, 15% from sand layers, and 10% from sand/gravel mixtures. The clay and silt deposits form and act as confining or semi-confining layers which are only slightly permeable. Because of the nature and distribution of the lithologies in the area the water bearing strata are thought to be interconnected both vertically and horizontally making the entire system a "leaky" aquifer system. Depth ranges were identified as being the closest resemblance to separate and distinct aquifers of which three were used: bores which obtained water between 0-60 m, 60-120 m, and bores penetrating greater than 120 m depth below the ground surface. Nearly all the bores in the area are naturally flowing artesian bores which supports the idea that the entire area is a discharge zone. Piezometric information was used to prepare maps showing isopiezometric contour lines. These maps showed that groundwater movement occurs from east to west with an influx of groundwater from the Oroua and Pohangina catchments and from the Tararua Range area. This groundwater movement is similar for all the depth ranges. In general the static water levels in any particular area increase with depth and this is also indicative of the area being a discharge area. Recharge of the aquifer system is thought to be from two different types, one is from atmospheric precipitation which falls directly onto the land surface and percolates directly into the groundwater system and secondly recharge from the rivers and streams which flow through the area. The most

likely area from which the first type of recharge may occur is from the Tararua Range, Ruahine Range, the eastern and western flanks of the Pohangina Anticline, and the hills and ranges further to the north of the study area. River recharge is probably responsible for the recharge of the shallower aquifers. Large amounts of water can be lost by this method as is illustrated by the water loss through the Manawatu Gorge where some 6,500 litres per second is lost over the White Horse Rapids.

Discharge rates increase with the depth of extraction with an average of 570 m³/day for the 0-60 m depth range, 1120 m³/day for the 60-120 m range and 1440 m³/day for bores greater than 120 m depth. Transmissivities throughout the area range between 150-2000 m²/day and the storativity of the aquifers in the area range between 1.1×10^{-4} and 3.2×10^{-4} . The use of groundwater as a source of water has increased dramatically over the past 15 years. In 1977 groundwater accounted for 40% of total water used in this area as compared with nearly 90% in 1989. There are some 15 different uses for which groundwater is used, the main uses being spray irrigation, freezing works, and institutional supplies. The estimated water extraction from the aquifer system in this study area is 120,000 m³/day (43×10^6 m³/year).

The study of the groundwater chemistry of an area gives important indications of the geological history of the enclosing rocks, the velocity and direction of water movement, evidence of pollution and pollution sources, and uses of the groundwater in the area. Throughout the study area total alkalinity, calcium, chloride, electrical conductivity, potassium, magnesium, manganese, sodium, and total dissolved solid concentrations and values showed an overall increase from the east of the study area to the west along the direction of groundwater flow. Free carbon dioxide, fluorine, and iron showed no trend but have areas of high concentrations and areas of low concentrations. Only sulphate showed an increase in concentration from west to east. There are many anomalies to the major trends but these can be attributed to local conditions and the local geology. The average concentrations for the individual chemical parameters are total alkalinity - 157 ppm, calcium - 104 ppm, chloride - 36 ppm, free carbon dioxide - 11 ppm, conductivity - 43 mS/m, fluorine - 0.16 ppm, iron - 2.1 ppm, potassium - 4.1 ppm, magnesium - 55 ppm, manganese - 0.38 ppm, nitrate - 0.02 ppm, sodium - 23 ppm, sulphate - 10 ppm, and total dissolved solids - 256 ppm. Within a particular area the

concentrations of all the chemical parameters decreases with depth. This can be attributed to the upward movement of groundwater from deeper depths to shallower depth through the "leaky" aquifer system. In general the chemical concentrations for various regions is as follows: the lowest concentrations occur in the area adjacent to the Manawatu River. The Kairanga and Bunnythorpe regions tend to have medium concentrations, and the highest concentrations occur to the west of the Oroua River. Conductivity, which is simple to measure in the field, can be used to estimate the concentrations of all the major chemical parameters. Calcium, magnesium, sodium, potassium, chloride, total alkalinity, and total dissolved solids were found to have extremely good linear relationships when plotted against conductivity.

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APPENDIX ONE

PROFILE DESCRIPTIONS

PROFILE #1 - Ohakea terrace Section (see figure A.1)

Location: At the end of Orr's Road near Ashhurst Timber Ltd.

Grid Reference: NZMS 260 T24/407939.

0-5cm	Ap	Brown (10YR 4/6) silt loam; moderately developed fine nut breaking to medium crumb structure, friable; many roots.
5-30cm	Bwg	Bright yellowish brown (10YR 6/6) silt loam; weakly developed medium nut breaking to very fine crumb structure, firm; many faint bright yellowish brown (10YR 7/6) mottles; some roots.
30-50cm	Cg	Dull yellow orange (10YR 7/4) sandy loam; slightly hard massive appearance breaking down to coarse blocky structure; abundant distinct yellow orange (10YR 7/8) mottles.
50+cm	2C	Gravels, mainly greywacke with some spilite and argillite; size range from <2cm to >15cm diameter, well rounded; some areas are matrix supported whereas others are clast supported; much iron staining towards top of gravels.

PROFILE #2 - Tua Paka Section (see figure A.2)

Location: Opposite Tua Paka Farm, on Aokautere-Ashhurst Road.

Grid Reference: NZMS 260 T24/423936

0-20cm	Ap	Dull yellow orange (10YR 6/4) silt loam; moderately developed medium nut breaking to fine crumb structure, very friable; abundant roots.
20-30cm	ABg	Dull yellow orange (10YR 7/4) silt loam; moderately developed medium nut breaking to fine nutty structure, firm; few faint medium yellow orange (10YR 7/8) mottles; some roots.
30-80cm	Bwg	Dull yellow orange (10YR 7/3) silty clay loam; moderately developed coarse nut breaking to medium nutty structure, hard; many distinct large yellow orange (7.5YR 7/8) mottles; few roots.
80-120cm	Cg	Light grey (7.5YR 8/2) sandy loam; structureless and very hard; many large distinct yellow orange (7.5YR 7/8) mottles.
120-130cm	Aokautere Ash:	Light grey (7.5Y 8/2) fine sandy silt; well cemented, massive structure breaking to fine crumb.
130-170cm	Cg	Light grey (7.5YR 8/2) sandy loam; structureless and very hard; many large distinct yellow orange (7.5YR 7/8) mottles.
170+cm	2C	Gravels, mainly greywacke with some spilite and argillite; iron stained at top of gravels decreasing with depth; orientation tends to be horizontal; sizes range from <1cm to >15cm diameter, well rounded.



Figure A.1 Profile #1 - Ohakea terrace section.



Figure A.2 Profile #2 - Tua Paka section.

PROFILE #3 - Freyberg High School Section (see figure A.3)

Location: In side quarry of old brickworks behind Freyberg High School.

Grid Reference: NZMS 260 T24/334932.

0-20cm	Ap	Dull yellow orange (10YR 6/3) silt loam; moderately developed blocky breaking to medium crumb structure; abundant roots and very friable.
20-60cm	Bwg	Light yellow (2.5Y 7/3) silt loam; approximately 35% bright reddish brown (5YR 6/8) medium diffuse mottles; weakly developed medium to large block breaking to medium to fine blocky structure; many roots.
60-108cm	Bg1	Yellow orange (7.5YR 7/8) mottles predominate (60-70%), very distinct and large; light yellow (2.5Y 7/3) silt forms rest of horizon; moderately developed medium block breaking to medium to fine blocky structure; some roots.
108-120cm	Aokautere Ash:	Light grey (7.5Y 8/2) fine sandy silt; well cemented, massive structure breaking to fine crumb.
120-145cm	Bg2	Yellow orange (7.5YR 7/8) mottles predominate (60-70%), very distinct and large; light yellow (2.5Y 7/3) silt forms rest of horizon; moderately developed medium block breaking to medium to fine blocky structure.
145-185cm	Bg3	Bright brown (7.5YR 5/6) loam with approximately 10% dark reddish brown (5YR 3/3) concretions and approximately 10% dull yellow orange (10YR 7/4) mottles; moderately developed medium block breaking to fine blocky and medium crumb structure.
185-205cm	Bw	Brown (10YR 4/6) silty clay loam; well developed medium block breaking to fine blocky structure; slightly plastic.

- 205-210cm 2C Well rounded gravel layer; mainly greywacke with some spillite and argillite; sizes vary from less than 1cm to greater than 5cm diameter; nearly all show some evidence of rust staining.
- 210-230cm 3C Yellowish brown (10YR 5/8) coarse sand and some silt; very weakly cemented with no structure, poorly sorted.
- 230->600cm 4C Gravel; well rounded with sizes ranging from less than 1cm to greater than 15cm diameter with the majority being within the range 5-6cm diameter; in places the gravel is matrix supported and in others it is clast supported; the matrix is predominantly medium sand and silt; most of the horizon is poorly consolidated with much rust staining; the majority of the gravels are horizontally orientated and are poorly sorted.

PROFILE #4 - Ashhurst Section (see figure A.4)

Location: Roadcutting about 300m from the intersection of Wyndam and

Grid Reference: NZMS 260 T24/435986

0-5cm	Ah	Dull yellow (2.5Y 6/4) silt loam; moderately developed fine nut breaking to very fine crumb structure; very friable with many roots.
5-40cm	Bwg1	Light yellow (5Y 7/3) very fine sandy silt; profuse medium bright brown (7.5YR 5/8) mottles; moderately developed medium nut breaking to fine blocky structure; some roots.
40-52cm	Aokautere Ash:	Light yellow (5Y 7/3) sandy silt; very weakly developed medium nut breaking to medium to fine crumb structure, moderately consolidated.
52-130cm	Bwg2	Light grey (5Y 7/2) sandy silt veins within orange (7.5YR 6/8) matrix; very hard and massive.
130-150cm	2Bcw	Bright brown (7.5YR 5/6) silt; approximately 20% light yellow (2.5Y 7/3) silt; some small iron concretions; very strongly developed medium blocky breaking to medium and fine blocky structure.
150-250cm	2Bwg	Light yellow (2.5Y 7/3) clay loam; many (> 50%) large distinct bright brown (7.5YR 5/6) mottles; very hard and massive.
250-450+cm	3C	Gravels; very cemented and closely packed; mainly greywacke with some spilite and argillite; sizes range from less than 1cm to greater than 30cm diameter; well rounded with no apparent preferred orientation; mainly clast supported with the matrix being medium to fine sand; many of the gravels show rust staining.

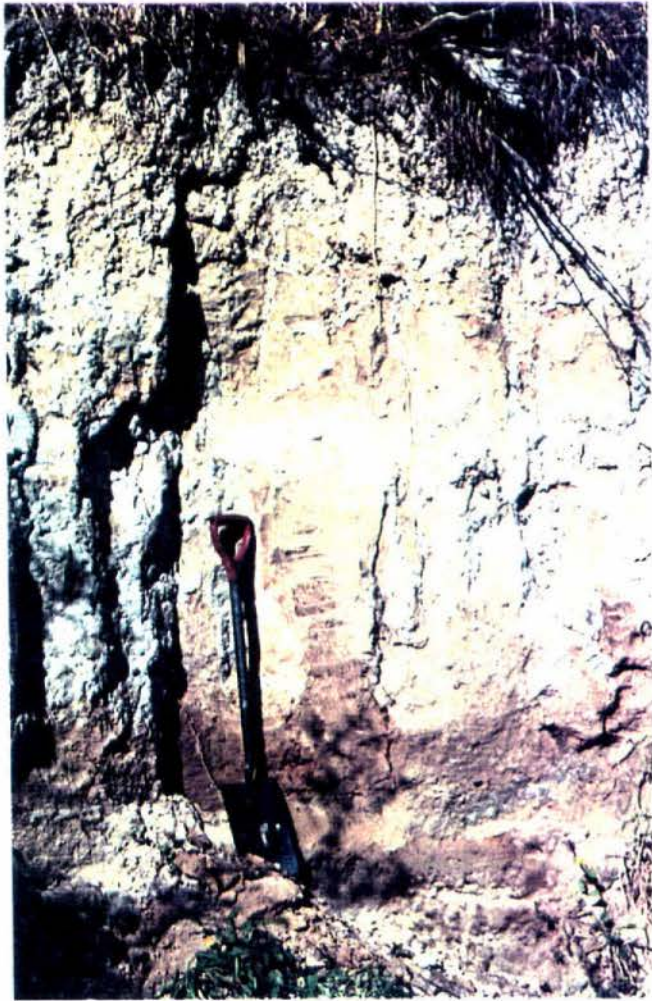


Figure A.3 Profile #3 - Freyberg section.

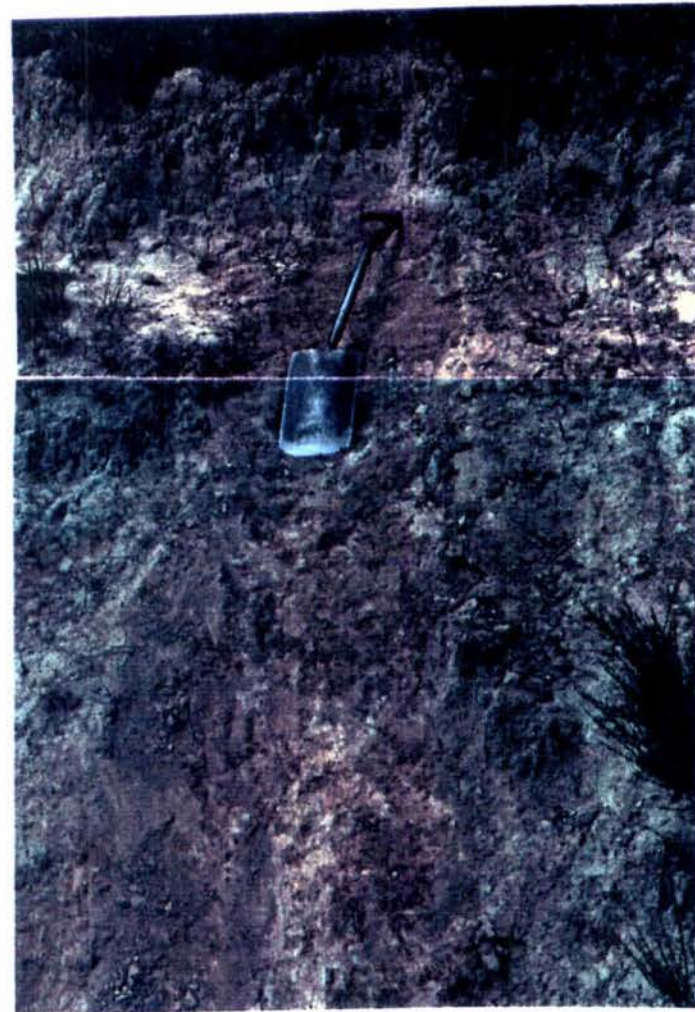


Figure A.4 Profile #4 - Ashhurst section.

PROFILE #5 - Forest Hill Road Section (see figure A.5)

Location: Approximately 500 m up Forest Hill Road from the intersection of Forest Hill Road and Aokautere-Ashhurst Road

Grid Reference: NZMS 260 T24/397913

0-30cm	Ah	Dull yellowish brown (10YR 5/3) silt loam; well developed medium blocky structure, friable; many roots.
30-50cm	Bwg	Dull yellow orange (10YR 7/3) silty clay loam; moderately developed medium nut breaking to fine nut structure, firm; many distinct medium orange (5YR 6/8) mottles; some roots.
50-120cm	Cg	Dull yellow orange (10YR 7/3) silt; moderately developed coarse nutty structure, very hard; abundant medium to large distinct orange (5YR 6/8) mottles.
120-135cm	Aokautere Ash:	Light yellow (5Y 7/3) sandy silt; very weakly developed medium nut breaking to medium to fine crumb structure, moderately consolidated.
135-280cm	Cg	Dull yellow orange (10YR 7/3) silt; hard massive structure; abundant medium to large distinct orange (5YR 6/8) mottles.
280-300cm	2Bw	Reddish brown (5YR 4/8) hard concretions -80%; dull yellow (10YR 7/3) silt surrounding concretions; weakly cemented.
300-650cm	2C _{xg}	Dull yellow orange (10YR 7/3) silt; hard and massive with large columnar jointing; abundant large distinct orange (5YR 6/8) mottles.

650+ cm 3C Gravel, mainly greywacke with some spillite and argillite; sizes range from < 0.5cm to >15cm diameter; well rounded; orientation could not be identified due to nature of road cutting.

PROFILE #6 - Tokomaru Marine Bench Section (see figure A.6)

Location: Road cutting approximately 1km from Bunnythorpe township towards Palmerston North on Railway Road.

Grid Reference: NZMS 260 T24/337982.

0-30cm	Ap	Brown (10YR 4/4) silty clay; fine crumb structure; very friable; roots abundant.
30-160cm	Bg1	Dull yellow (2.5Y 6/3) silty clay loam; many large distinct bright reddish brown (5YR 5/6) mottles; ranging from approximately 10% in top of horizon to 60-70% at base of horizon; massive and moderately cemented; some roots.
160-300cm	Bg2	Light yellow (2.5Y 7/4) clay; few medium faint orange (7.5YR 6/8) mottles; massive and hard.
300-380cm	2Cg	Light yellow (2.5Y 7/4) fine sand; structureless and only slightly consolidated; many layers of orange (7.5YR 6/8) mottles.
380-400cm	3Cg	Light yellow (2.5Y 7/3) clay; very plastic and massive; some medium faint yellow orange (7.5YR 7/8) mottles.
400-420+cm	4C	Yellowish brown (2.5Y 5/3) medium sand; unconsolidated.

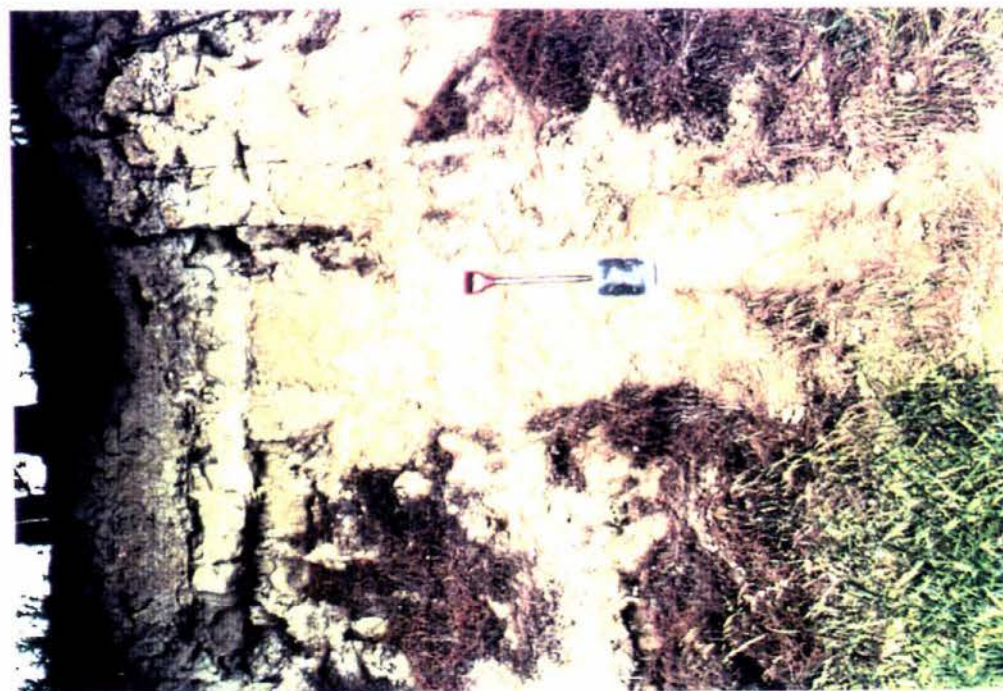


Figure A.5 Profile #5 - Forest Hill section.



Figure A.6 Profile #6 - Tokomaru Marine Bench section.

APPENDIX B - STATIC WATER LEVELS

Grid	Bore	Easting	Northing	Static Water Level (m)	Altitude Of Bore (m)	Piezometric Water Level (m)	Depth Of Bore (m)
325	081	1247	993	-0.5	31.2	31	89
326	001	1343	981	-6.5	63.2	57	117
326	011	1343	990	0.6	58.1	59	113
326	021	1328	995	-1.3	54.0	53	29
326	031	1316	1001	-2.0	50.8	49	14
326	051	1344	1002	-5.8	67.5	62	79
326	061	1340	993	3.0	50.8	54	118
326	091	1343	994	2.6	29.9	33	208
326	101	1394	978	-51.2	108.2	57	108
326	161	1394	983	-40.2	107.9	68	46
326	171	1350	979	1.0	57.8	59	102
326	181	1352	975	-5.0	64.2	59	135
326	191	1316	992	5.0	49.5	55	154
326	221	1321	998	5.0	49.9	55	135
326	311	1318	987	7.0	47.4	54	152
327	021	1435	985	-22.9	90.8	68	48
327	041	1410	978	-44.2	105.6	61	120
327	071	1436	991	-18.9	83.1	64	69
327	101	1426	991	-48.5	118.3	70	104
327	141	1419	981	-49.2	109.0	60	111
334	001	1216	964	-3.8	23.6	20	18
334	021	1218	918	4.3	12.7	17	95
334	031	1174	883	3.0	12.3	15	124
334	051	1197	970	-0.7	18.9	18	90
334	061	1207	973	0.6	20.3	21	30
335	001	1269	885	3.0	21.1	24	82
335	011	1273	948	7.0	14.3	21	92
335	021	1232	966	-1.5	23.	22	13
335	031	1279	904	3.0	23.3	26	48
335	041	1260	947	7.0	21.5	29	155
335	051	1241	871	5.2	16.8	22	126
335	061	1251	950	-5.0	20.4	15	17
335	071	1274	919	7.0	18.8	26	91
335	081	1296	920	2.0	26.7	29	80
335	131	1297	909	3.8	26.2	30	149
335	141	1268	906	3.5	17.2	21	50
335	161	1261	957	2.2	27.0	29	69
335	171	1246	893	4.4	13.0	17	69
335	181	1258	877	3.7	20.1	24	110
335	191	1260	879	12.0	18.2	30	176
335	201	1262	869	12.0	19.0	31	160
335	211	1266	903	5.8	18.1	24	92
335	221	1253	910	-0.6	14.5	14	114

Grid	Bore	Easting	Northing	Static Water Level (m)	Altitude Of Bore (m)	Piezometric Water Level (m)	Depth Of Bore (m)
335	231	1265	913	3.0	15.3	18	56
335	241	1261	887	5.7	17.4	23	104
335	251	1266	906	2.1	16.3	18	28
335	271	1284	952	3.7	26.5	30	82
335	281	1243	877	-3.0	15.9	13	19
335	301	1261	932	-2.6	19.7	17	33
335	321	1277	965	6.5	27.6	34	95
335	331	1268	874	10.5	21.9	32	141
335	341	1290	953	6.5	27.9	34	74
335	351	1261	884	14.0	17.0	31	171
335	371	1266	932	4.0	20.7	25	108
335	381	1295	955	4.4	27.0	31	69
335	391	1296	963	3.8	31.4	35	74
335	401	1246	946	-4.7	19.5	15	15
335	421	1262	921	-4.6	16.2	12	108
336	001	1329	946	4.0	43.7	48	125
336	011	1389	935	4.0	40.9	45	51
336	041	1383	937	4.0	42.2	46	78
336	051	1322	958	0.5	40.4	41	36
336	061	1365	886	1.3	78.5	80	59
336	071	1314	888	11.0	28.4	39	80
336	081	1315	896	20.8	28.3	49	167
336	111	1338	926	-4.6	44.9	40	146
336	121	1315	885	6.8	29.3	36	68
336	141	1364	924	0.0	38.3	38	43
336	161	1359	923	3.0	36.5	40	70
336	181	1356	907	8.8	36.5	45	72
336	191	1328	890	2.6	38.4	41	38
336	201	1314	925	-4.0	28.7	25	20
336	231	1310	909	3.4	27.7	31	111
336	241	1312	973	9.9	41.7	52	40
336	261	1345	927	1.5	36.5	38	144
336	271	1343	895	13.0	31.7	45	118
336	301	1316	920	3.3	31.0	34	100
336	311	1319	904	2.4	29.7	32	80
336	321	1388	947	12.0	44.9	57	98
336	351	1372	945	15.4	57.3	73	28
336	361	1371	941	8.0	44.1	52	113
336	391	1361	902	4.2	42.2	46	42
336	411	1381	929	11.0	40.1	51	70
336	421	1353	932	2.5	36.9	39	82
336	441	1321	887	7.0	29.8	37	72
336	451	1338	896	13.0	30.6	44	87
336	471	1328	973	0.3	45.5	46	48
336	481	1350	912	4.5	33.0	38	47
336	541	1349	931	3.3	36.8	40	76

Grid	Bore	Easting	Northing	Static Water Level (m)	Altitude Of Bore (m)	Piezometric Water Level (m)	Depth Of Bore (m)
336	551	1371	950	15.1	61.3	76	52
336	561	1393	949	12.0	44.9	57	61
336	571	1351	888	1.0	43.5	45	53
336	581	1367	942	7.9	43.8	52	120
336	591	1327	962	-5.3	46.4	41	31
337	001	1442	964	4.0	55.1	59	40
337	011	1414	955	4.5	46.5	51	27
337	021	1405	939	3.0	44.5	48	27
337	031	1417	946	15.0	48.5	64	83
337	041	1418	951	17.0	48.5	66	99
344	011	1206	834	-4.0	13.2	9	29
344	081	1169	843	-4.0	13.2	9	35
345	001	1267	853	12.0	24.2	36	135
345	011	1222	856	8.0	12.0	20	135
345	071	1242	861	2.5	15.6	18	87
+34	111	1243	854	5.0	16.1	21	109
345	131	1296	849	1.2	38.0	39	137

APPENDIX C - CHEMICAL DATA

Grid	Bore	Depth (m)	Easting	Northing	pH	Cond (mS/m)	TDS	Ca	Mg	Total Hardness
325	031	80	1303	982	8.20	51.0	326	148	52	200
325	081	89	1247	993	7.30	34.5	226	66	55	121
325	091	172	1267	986	7.60	59.5	356	139	86	225
325	121	165	1298	987	8.25	41.5	117	122	47	169
326	011	113	1343	990	8.10	44.0	237	112	55	167
326	021	29	1328	995	7.20	106.5	732	164	160	324
326	041	91	1392	999	7.25	49.0	332	112	68	180
326	061	118	1340	993	7.80	58.0	371	131	87	218
326	091	208	1343	994	8.20	31.0	221	93	27	120
326	101	108	1394	978	7.75	49.5	209	133	59	192
326	171	102	1350	979	7.90	44.5	178	104	50	154
326	181	135	1352	975	8.10	33.5	227	103	33	136
326	331	86	1335	996	7.90	55.0	310	135	79	214
327	001	96	1426	989	7.10	24.0	172	41	38	79
327	011	41	1444	991	7.45	52.5	301	132	69	201
327	041	120	1410	978	7.20	49.5	326	104	62	166
327	071	69	1436	991	6.70	28.5	224	39	52	91
327	081	106	1433	1000	7.10	34.0	225	65	53	118
327	091	110	1431	999	7.20	25.5	182	43	42	85
327	141	111	1419	981	7.50	44.0	287	95	66	161
334	021	95	1218	918	7.40	41.0	273	70	70	140
334	031	124	1174	883	7.50	84.5	482	184	161	345
334	041	99	1156	909	7.60	96.0	413	173	176	349
334	051	90	1197	970	7.50	101.0	631	200	198	398
334	071	67	1179	956	7.70	80.0	400	200	130	330
334	121	64	1158	876	7.60	57.5	331	108	100	208
335	001	82	1269	885	7.90	31.5	200	88	34	122
335	011	92	1273	948	7.50	50.5	343	123	65	188
335	041	155	1260	947	7.70	61.5	357	161	85	246
335	051	126	1241	871	7.70	38.0	250	108	37	145
335	091	77	1285	945	7.65	58.5	368	141	67	208
335	141	50	1268	906	7.50	41.5	263	100	51	151
335	161	69	1261	957	7.70	44.5	266	105	54	159
335	171	69	1227	905	7.35	46.5	278	109	61	170
335	221	114	1253	910	7.70	46.0	287	112	66	178
335	231	56	1265	913	7.10	39.0	261	89	50	139
335	241	104	1261	887	7.70	42.5	271	116	48	164
335	261	103	1246	933	7.60	43.0	260	105	46	151
335	291	237	1263	888	8.25	33.5	219	98	38	136
335	301	33	1261	932	6.90	64.5	80	101	104	205
335	311	85	1304	889	8.10	24.5	146	68	24	92
335	331	141	1268	874	8.10	30.5	177	89	30	119
335	351	171	1261	884	8.10	30.5	152	89	30	119
335	361	112	1285	884	8.10	26.5	178	77	26	103
335	371	108	1266	932	7.50	44.5	295	113	55	168
335	391	74	1296	963	7.70	61.0	395	149	73	222

Grid	Bore	Depth (m)	Easting	Northing	pH	Cond (mS/m)	TDS	Ca	Mg	Total Hardness
336	001	125	1329	946	8.20	43.0	290	125	41	166
336	041	78	1383	937	8.10	22.0	130	66	19	85
336	081	167	1315	896	7.95	26.5	195	81	18	99
336	141	43	1364	924	8.00	42.0	276	117	41	158
336	151	200	1336	865	8.15	29.5	228	72	13	85
336	181	72	1356	907	8.25	24.0	177	72	22	94
336	211	37	1371	940	8.00	42.5	278	111	45	156
336	241	40	1312	973	8.10	49.5	315	127	59	186
336	271	118	1343	895	8.10	22.5	135	64	18	82
336	301	100	1316	920	9.00	21.5	135	69	16	85
336	321	98	1388	947	8.10	28.0	176	88	24	112
336	361	113	1371	941	8.20	26.0	198	84	22	106
336	391	42	1361	902	8.00	25.0	186	76	21	97
336	401	43	1381	931	8.15	23.0	180	70	21	91
336	421	82	1353	932	8.10	41.5	184	117	39	156
336	441	72	1321	887	8.10	27.0	123	82	23	105
336	451	87	1338	896	8.10	25.0	172	73	20	93
336	471	48	1328	973	7.70	67.0	321	159	98	257
336	481	47	1350	912	8.10	33.5	184	97	33	130
336	491	96	1377	938	8.10	23.5	184	70	20	90
336	511	49	1356	914	8.25	23.0	173	69	20	89
336	591	31	1327	962	7.80	66.0	275	158	87	245
337	001	40	1442	964	8.30	23.0	176	73	23	96
337	011	27	1414	955	7.80	35.5	249	97	43	140
337	031	83	1417	946	8.25	24.5	169	76	25	101
337	041	99	1418	951	8.20	24.0	186	76	24	100
337	051	61	1412	962	7.60	45.5	169	116	51	167
344	031	32	1158	867	6.80	101.5	492	156	168	324
344	051	137	1211	847	7.70	43.0	274	121	49	170
344	081	35	1169	843	6.85	91.0	558	140	135	275
345	011	135	1222	856	7.50	38.0	213	95	44	139
345	041	164	1292	859	8.00	22.5	183	63	12	75
345	051	52	1253	834	7.90	26.0	213	57	21	78
345	061	63	1235	820	7.90	31.0	0	90	27	117
345	071	87	1252	861	7.80	38.5	274	97	40	137
345	111	109	1243	854	7.40	33.0	239	82	38	120

Grid	Bore	Fe	Mn	Na	K	Alkalinity	Cl	Sulphate
325	031	1.08	0.07	25.0	3.6	164	51	21
325	081	3.50	0.75	21.0	3.8	141	24	0
325	091	1.30	1.20	30.0	3.9	211	52	13
325	121	0.81	0.04	18.0	3.1	149	36	14
326	011	0.11	0.17	25.0	3.7	152	38	15
326	021	4.40	2.30	78.0	7.7	193	217	25
326	041	1.30	1.62	29.0	4.2	141	45	30
326	061	11.30	0.41	28.0	4.2	179	58	24
326	091	0.00	0.05	15.0	2.9	114	21	10
326	101	0.57	0.66	24.0	4.3	160	41	25
326	171	0.32	0.58	30.0	3.2	143	47	14
326	181	0.17	0.03	13.0	2.2	118	22	16
326	331	0.33	0.22	30.0	4.0	166	53	29
327	001	2.60	0.39	12.5	3.2	82	20	7
327	011	0.14	0.34	26.0	4.8	149	40	47
327	041	1.80	1.30	30.0	4.3	142	55	27
327	071	11.50	0.61	16.5	3.4	82	23	20
327	081	5.40	0.60	16.5	4.3	118	27	12
327	091	4.60	0.40	13.0	3.2	92	19	2
327	141	1.10	0.82	22.0	4.7	145	38	16
334	021	3.90	0.63	26.0	4.9	172	27	0
334	031	3.00	0.67	39.0	6.5	318	82	0
334	041	2.10	0.53	58.0	0.0	361	97	0
334	051	4.00	0.56	52.0	9.9	325	103	59
334	071	1.28	0.39	38.0	6.7	323	65	0
334	121	2.40	0.26	31.0	6.6	218	51	0
335	001	0.31	0.08	15.0	3.5	128	21	0
335	011	2.30	0.53	25.0	5.1	164	62	0
335	041	1.38	0.46	28.0	4.5	219	51	15
335	051	0.34	0.14	17.0	4.8	154	28	0
335	091	0.74	0.42	26.0	4.7	174	78	0
335	141	0.93	0.29	22.0	4.2	152	29	0
335	161	0.97	0.53	24.0	4.8	171	35	0
335	171	2.70	0.55	23.0	5.3	167	47	0
335	221	0.97	0.37	22.0	4.3	173	41	0
335	231	1.04	0.53	23.0	3.3	184	41	7
335	241	0.62	0.17	20.0	4.9	161	35	0
335	261	0.80	0.23	25.0	6.0	183	27	0
335	291	0.05	0.02	14.0	3.6	135	28	8
335	301	12.00	1.90	43.0	6.3	239	67	0
335	311	2.30	0.02	12.0	2.5	103	14	2
335	331	0.11	0.04	14.0	2.9	125	17	1
335	351	0.42	0.04	14.0	2.9	125	18	4
335	361	0.04	0.03	12.0	2.7	110	13	2
335	371	1.29	0.53	20.0	4.8	152	49	0
335	391	2.30	0.43	28.0	5.0	178	81	0

Grid	Bore	Fe	Mn	Na	K	Alkalinity	Cl	Sulphate
336	001	2.40	0.08	22.0	3.0	144	36	21
336	041	0.00	0.02	9.0	1.7	86	8	11
336	081	0.16	0.03	12.0	3.5	105	12	12
336	141	0.26	0.09	22.0	2.8	140	36	16
336	151	0.00	0.02	28.0	2.7	116	15	12
336	181	0.64	0.03	12.0	2.4	100	10	7
336	211	0.50	0.11	26.0	2.9	143	38	14
336	241	0.15	0.14	27.0	3.7	154	45	26
336	271	0.34	0.03	10.5	3.4	94	8	5
336	301	0.04	0.02	9.5	2.0	94	11	0
336	321	0.09	0.03	10.5	1.7	100	10	23
336	361	0.04	0.02	11.0	2.0	100	12	12
336	391	0.29	0.02	12.0	2.5	102	10	7
336	401	0.72	0.03	10.0	1.9	93	9	8
336	421	0.10	0.07	24.0	2.8	136	35	17
336	441	0.14	0.03	12.0	2.4	106	13	5
336	451	0.12	0.04	10.5	3.2	101	11	7
336	471	1.03	0.53	36.0	4.5	209	67	30
336	481	0.00	0.05	15.0	2.6	117	24	4
336	491	0.00	0.03	10.0	1.6	87	9	15
336	511	0.19	0.02	11.0	2.2	96	9	8
336	591	5.40	0.47	36.0	4.1	195	68	32
337	001	0.03	0.06	9.0	1.2	94	7	9
337	011	0.20	0.12	16.0	2.9	122	24	19
337	031	0.00	0.06	9.0	1.4	105	7	8
337	041	0.03	0.05	8.0	1.2	102	9	5
337	051	4.00	0.37	23.0	3.6	142	41	24
344	031	18.50	2.20	84.0	0.0	504	39	0
344	051	0.52	0.17	20.0	5.2	179	31	0
344	081	22.00	2.10	82.0	9.1	427	52	0
345	011	1.40	0.37	19.0	5.9	154	27	0
345	041	0.09	0.03	16.0	4.6	101	10	2
345	051	0.19	0.06	20.0	5.4	115	14	0
345	061	0.16	0.04	16.0	3.9	134	18	0
345	071	10.60	0.36	23.0	5.5	175	20	0
345	111	1.20	0.30	17.0	5.3	140	22	0

Grid	Bore	F	CO2	Nitrite	Nitrate	Sum of Cations (m eq.)	Sum of Anions (m eq.)
325	031	0.10	2	0	0	5.18	5.15
325	081	0.14	14	0	0	3.43	3.49
325	091	0.19	11	0	0	5.90	5.95
325	121	0.09	2	0	0	4.24	4.28
326	011	0.19	2	0	0	4.52	4.42
326	021	0.20	24	0	0	10.06	10.50
326	041	0.27	16	0	0	4.97	4.71
326	061	0.10	6	0	0	5.68	5.71
326	091	0.07	1	0	0	3.12	3.08
326	101	0.24	6	0	0	4.99	4.87
326	171	0.30	4	0	0	4.46	4.47
326	181	0.10	2	0	0	3.34	3.31
326	331	0.14	4	0	0	5.68	5.42
327	001	0.14	13	0	0	2.20	2.35
327	011	0.27	11	0.001	0.01	5.27	5.08
327	041	0.16	18	0	0	4.73	4.95
327	071	0.19	33	0	0	2.62	2.70
327	081	0.17	19	0	0	3.19	3.37
327	091	0.17	12	0	0	2.35	2.42
327	141	0.21	9	0	0	4.29	4.30
334	021	0.22	14	0	0	4.05	4.20
334	031	0.20	20	0	0	8.76	8.67
334	041	0.19	18	0	0	9.77	9.95
334	051	0.20	21	0	0	10.47	10.63
334	071	0.18	13	0	0	8.42	8.29
334	121	0.23	11	0	0	5.67	5.79
335	001	0.20	3	0	0	3.18	3.15
335	011	0.17	10	0	0	4.97	5.03
335	041	0.20	9	0	0	6.25	6.13
335	051	0.07	6	0	0	3.76	3.87
335	091	0.16	8	0	0	5.41	5.68
335	141	0.20	10	0	0	4.08	3.86
335	161	0.21	7	0	0	4.34	4.40
335	171	0.21	15	0	0	4.53	4.66
335	221	0.21	7	0	0	4.62	4.61
335	231	0.21	29	0.001	1.28	3.86	4.98
335	241	0.20	6	0	0	4.27	4.20
335	261	0.16	9	0	0	4.26	4.42
335	291	0.17	2	0	0	3.42	3.65
335	301	0.21	60	0.01	0	6.13	6.67
335	311	0.23	2	0	0	2.42	2.49
335	331	0.18	2	0	0	3.06	3.00
335	351	0.16	2	0	0	3.06	3.09
335	361	0.18	2	0	0	2.65	2.61
335	371	0.14	10	0	0	4.35	4.42
335	391	0.15	7	0	0	5.78	5.84

Grid	Bore	F	CO2	Nitrite	Nitrate	Sum of Cations (m eq.)	Sum of Anions (m eq.)
336	001	0.10	2	0	0	4.35	4.33
336	041	0.13	1	0	0	2.13	2.17
336	081	0.14	2	0	0	2.59	2.69
336	141	0.13	3	0	0	4.19	4.15
336	151	0.08	2	0	0	2.99	2.99
336	181	0.13	1	0	0	2.46	2.43
336	211	0.17	3	0	0	4.32	4.22
336	241	0.11	2	0	0	4.99	4.89
336	271	0.14	1	0	0	2.18	2.21
336	301	0.06	0	0	0	2.16	2.19
336	321	0.13	2	0	0	2.74	2.76
336	361	0.13	1	0	0	2.65	2.59
336	391	0.14	2	0	0	2.52	2.47
336	401	0.13	1	0	0	2.30	2.28
336	421	0.14	23	0	0	4.23	4.06
336	441	0.15	2	0	0	2.68	2.59
336	451	0.09	2	0	0	2.40	2.47
336	471	0.16	8	0	0	6.82	6.69
336	481	0.13	2	0	0	3.32	3.10
336	491	0.18	1	0	0	2.27	2.30
336	511	0.13	1	0	0	2.31	2.34
336	591	0.10	6	0	0	6.57	6.48
337	001	0.15	0	0	0	2.34	2.26
337	011	0.19	4	0	0	3.57	3.51
337	031	0.13	1	0	0	2.45	2.46
337	041	0.15	1	0	0	2.38	2.40
337	051	0.22	7	0	0	4.43	4.49
344	031	0.29	160	0	0	10.43	11.17
344	051	0.14	7	0	0	4.40	4.45
344	081	0.23	118	0.002	0	9.29	10.00
345	011	0.10	10	0	0	3.75	3.84
345	041	0.10	2	0	0	2.31	2.34
345	051	0.17	3	0.001	0	2.57	2.69
345	061	0.09	3	0.014	0.16	3.13	3.19
345	071	0.04	6	0	0	3.88	4.06
345	111	0.16	11	0	0	3.27	3.42