Rainfall recharge models of the Heretaunga Plains

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ABSTRACT

Hawke's Bay Regional Council (HBRC) is currently reviewing water resources in the Heretaunga Plains as part of the Greater Heretaunga/Ahuriri Catchment Area plan change process. As rainfall recharge is a key component of water resources in the region, GNS Science has completed an assessment of rainfall recharge to groundwater in the Heretaunga Plains and the Ahuriri Estuary catchments. This work has been completed as a component of the National Institute of Water and Atmospheric Research (NIWA) Waterscape programme.

Three rainfall recharge models (SOILMOD, Rushton and the genetic program) were applied to assess rainfall recharge on a daily basis between 1972 and 2006. Inputs to the model were generated from estimates of climate and soil propoerties. Daily rainfall and potential evapotranspiration values were derived from NIWA's Virtual Climate Station Network (VCSN), and soil profile available water was derived from Landcare Research's soils database.

Daily rainfall recharge was estimated in five zones: zone 1 (the unconfined area of the Heretaunga Plains); zone 2 (the confined Heretaunga Plains aquifer located south of the Ngaruroro River, including Hastings City); zone 3 (the confined Heretaunga Plains aquifer located north of the Ngaruroro River, including parts of Napier City); zone 4 (the Ahuriri area, including Bay View) and zone 5 (south of the Tukituki River near the coast, including the Te Awanga coastal strip).

Average modelled rainfall recharge between 1972 and 2006 for all zones was 2.7 m^3/s (SOILMOD), 2.2 m^3/s (Rushton) and 1.6 m^3/s (genetic program). Rainfall recharge estimates by the SOILMOD and Rushton models were similar, aside from zone 2 where significant runoff was calculated using the Rushton model. Modelled rainfall recharge is highly variable. For example, modelled rainfall recharge ranged from approximately 100 to 500 mm/yr at Bridge Pa in the unconfined zone, and rainfall recharge through heavy soils may be zero in dry years. Rainfall recharge is also highly seasonal, with zero rainfall recharge typical of the summer months.

The following recommendations suggest further actions that could be completed to support information requirements of the Greater Heretaunga/Ahuriri Catchment Area plan change process:

1. calculation of full-catchment water budgets with development of NIWA's TOPNET model to estimate groundwater recharge and groundwater flow and application of this model to the Greater Heretaunga/Ahuriri Catchment Area;
2. that HBRC staff continue to interact with researchers in regards to policy development for the allocation of groundwater, and integrated allocation of surface water and groundwater; and
3. continued monitoring of rainfall recharge and ground-level rainfall at three sites (Bridge Pa, Fernhill and Maraekakaho) located in the unconfined zone of the Heretaunga Plains.

KEYWORDS

Heretaunga Plains, groundwater resources, rainfall recharge, groundwater budget

1.0 INTRODUCTION

The management of resources in the Heretaunga Plains, Hawke's Bay, is currently under review by Hawke's Bay Regional Council (HBRC) through the Greater Heretaunga/Ahuriri Catchment Area plan change process (Hudson, 2013). This review includes assessment of water, land and air resources within four catchments relevant to the Heretaunga Plains (Figure 1.1):

- Karamu Stream catchment;
- Ahuriri Estuary catchment, which is part of HBRC's "Napier catchment";
- Ngaruroro River catchment; and
- Tutaekuri River catchment.

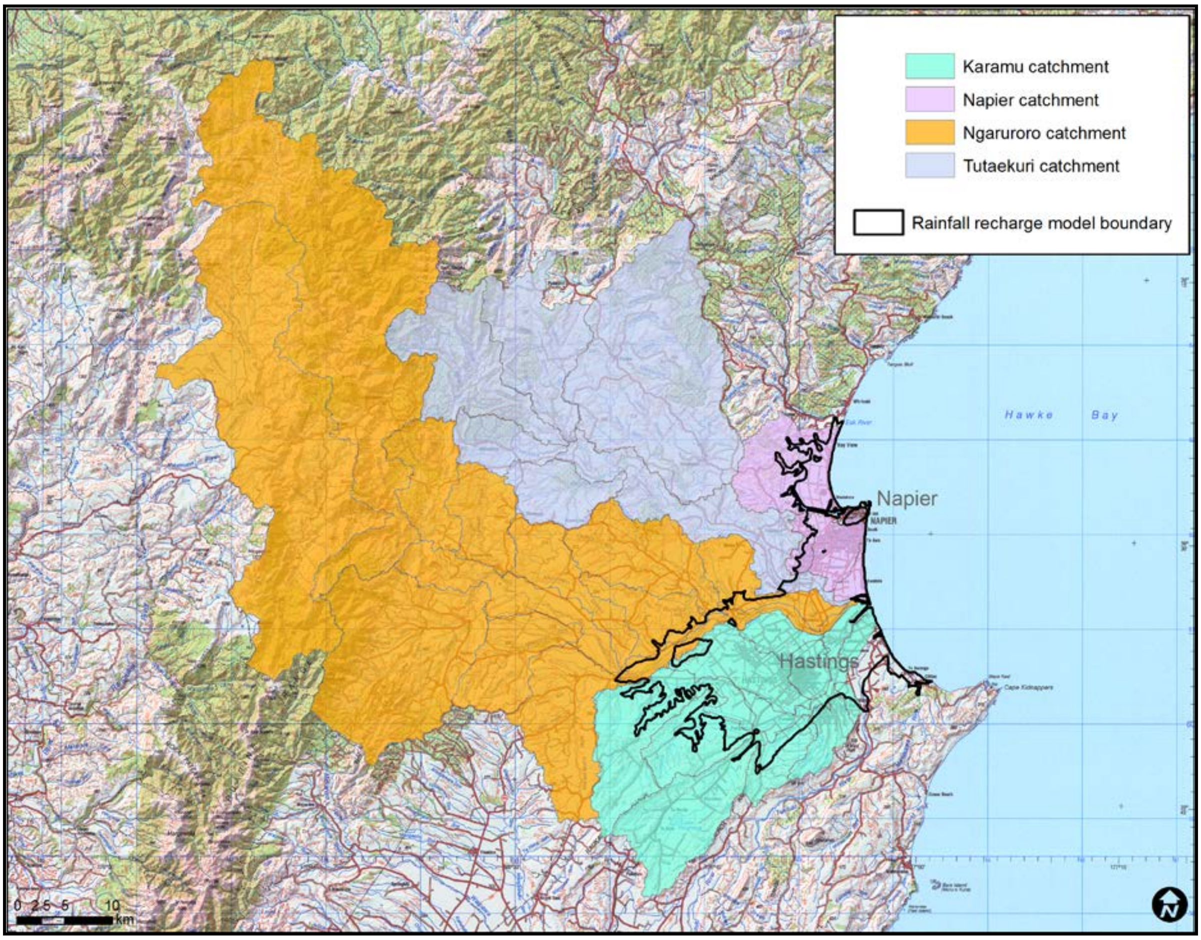

Figure 1.1 Surface catchments relevant to the Greater Heretaunga/Ahuriri Catchment Area plan change process, as defined by HBRC (Hudson, 2013).

Groundwater in the Heretaunga Plains is a key resource for the Hawke's Bay Region. This resource supports a large volume of agricultural production, is used by food processing industries (Luba, 2001), and is the sole source of drinking water for the populations of Napier and Hastings cities. An assessment of recharge to groundwater is part of the Greater Heretaunga/Ahuriri Catchment Area plan change process. Recharge to groundwater is sourced from rivers, particularly the Ngaruroro River, and from rainfall (Dravid and Brown, 1997). Statistics on the location, rates, and variability of groundwater recharge are of key importance in the management of the groundwater system.

In this report, an assessment of rainfall recharge to groundwater in the study area, including the Heretaunga Plains and the area surrounding the Ahuriri Estuary (Figure 1.2), is provided. Note that the study area includes part of the Heretaunga Plains that is located south of the Tukituki River near the coast, and the coastal strip to Te Awanga. Therefore, the study area is wider than the Greater Heretaunga/Ahuriri Catchment Area.

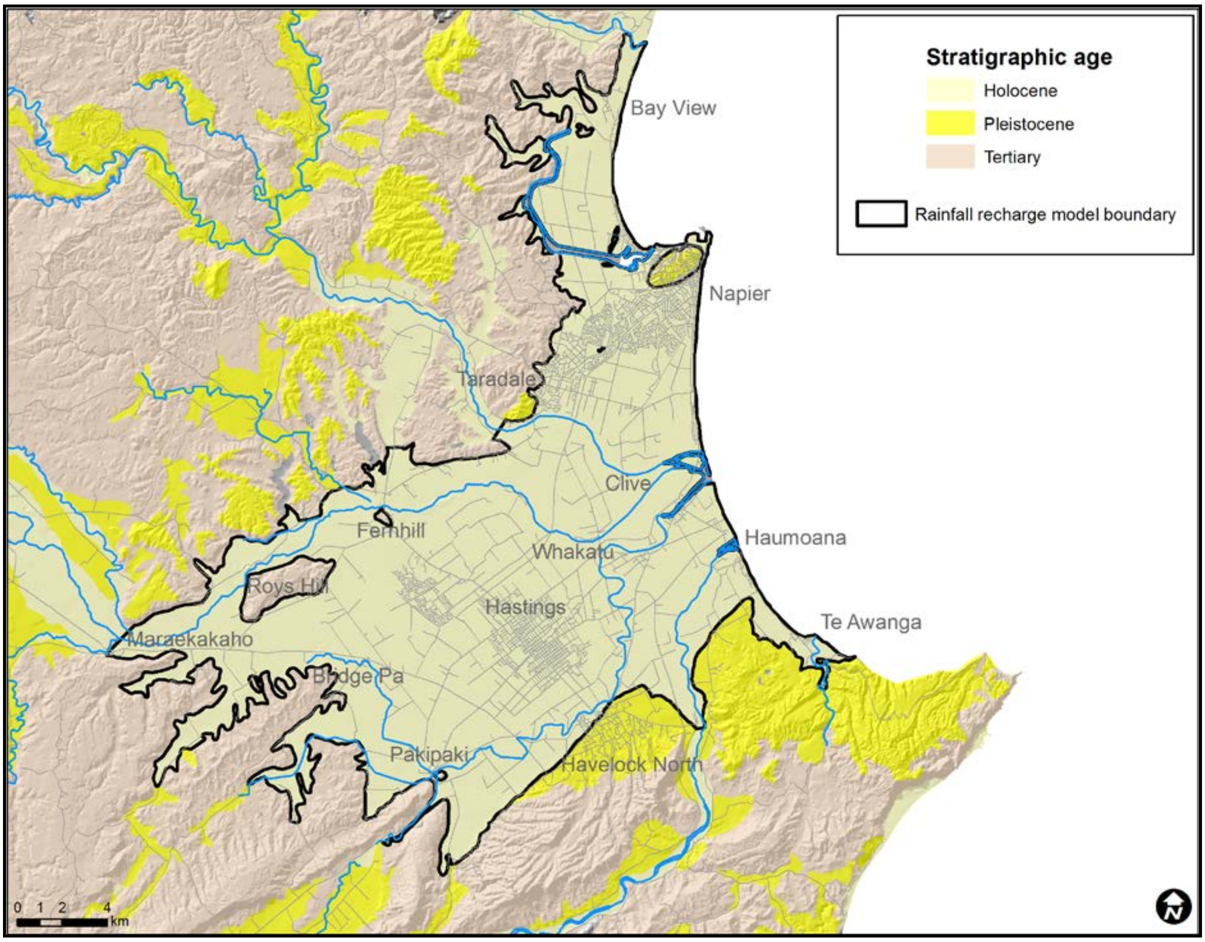

Figure 1.2: Rainfall recharge model boundary that encompasses the Greater Heretaunga/Ahuriri Catchment Area.

This project was completed as part of the National Institute of Water and Atmospheric Research (NIWA)'s Waterscape programme. Rainfall recharge was estimated using climate data from NIWA (Tait et al., 2012) and soil properties from Landcare Research (2013). Three rainfall recharge models were used to calculate rainfall recharge at a daily time step for the period 1972 to 2006. These models (SOILMOD, Rushton and the genetic programme) were chosen because they have had application to groundwater recharge assessments in New Zealand (e.g., Scott, 2004; Wilson 2012; and Hong and White, 2005, respectively). This report describes the following components of the Heretaunga rainfall recharge study: methods used to generate the input data sets for the rainfall recharge models; methods used by the models; and the results as daily estimates, and average volumetric flow rates, of rainfall recharge within five zones in the study area.

2.0 HERETAUNGA PLAINS GROUNDWATER AND CLIMATE

2.1 HYDROGEOLOGY

The Heretaunga Plains is formed from predominantly Holocene sediment (Figure 1.2), including inter-leaved and inter-fingered river channels, overbank floods and estuarine and marine Quaternary sediments (Figure 2.1). These sediments, some more than 250 m thick, were deposited in the actively subsiding Heretaunga tectonic depression during a period of fluctuating sea level (Luba, 2001). The base of the Quaternary sediments is formed by early Pleistocene and late Pliocene marine sediments. The principal aquifers are paleo-river channels containing gravels, sands and silts, which are transported by the river systems (the contemporary Tutaekuri, Ngaruroro and Tukituki rivers), and shore-line gravels formed by long-shore drift. The aquifers are separated by relatively impermeable sediments (marine muds, clays, and silts), and interspersed with volcanic ash, pumice, and peat layers. There is a transition from unconfined to confined aquifer conditions from west to east across the plains, associated with a transition from river channel sediments to inter-bedded river, estuarine and marine sediments.

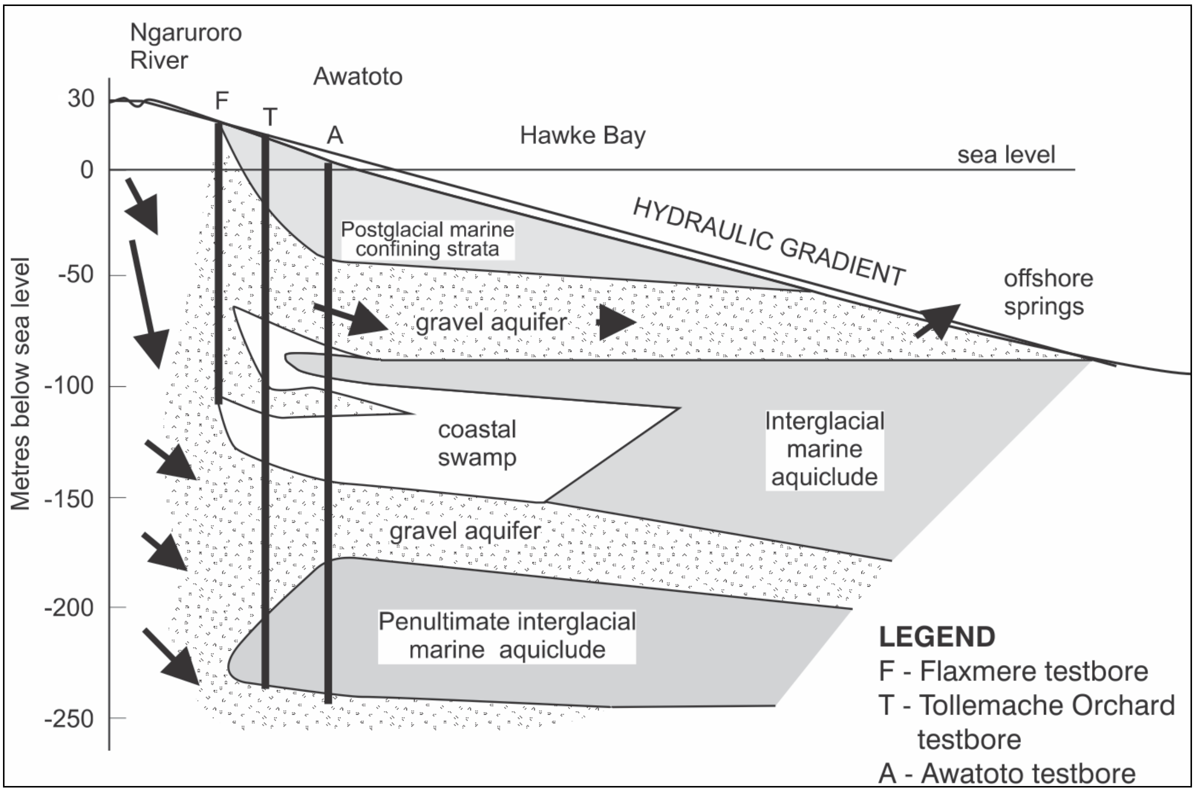

Figure 2.1 Hydrogeology of the Holocene aquifers in the Heretaunga Plains (Luba, 2001).

Groundwater levels in the unconfined aquifers are approximately a maximum of 50 m below ground level (BGL) in the west to approximately 7 m BGL near the coast (Luba, 2001). Dravid and Brown (1997) identified five aquifer systems in the Heretaunga Plains, and total groundwater storage in these aquifers is approximately 1.1 billion m^3 over a total area of 145 km^2. The five aquifer systems are:

- Main System. This aquifer system stores approximately 1 billion m^3 of groundwater and consists of three subunits:

- a major recharge area storing roughly 900 million m^3 and covering 30 km^2, between Roys Hill and Fernhill to Flaxmere, with a maximum estimated depth of 150 m;
- a minor recharge area storing about 90 million m^3 of water, covering about 15 km^2, from south of Roys Hill to Maraekakako along the Ngatarawa Valley, with a maximum estimated depth of 50 m; and
- a series of complex interconnected confined aquifers, including offshore extensions, which store an estimated 60 million m^3 of water, with a thickness of about 200 m and areal extent of about 300 km^2.

- Moteo Valley. A partly artesian aquifer storing approximately 2 million m^3 of groundwater, with a maximum depth of 30 m over an aerial extent of 10 km^2. The aquifer extends south from the Tutaekuri River valley upstream of Puketapu, to near Fernhill.
- Tukituki. A shallow gravel aquifer containing approximately 6 million m^3 of groundwater. The aquifer covers about 20 km^2 with an average depth of 20 m.
- Esk (Whirinaki – Bay View). An unconfined coastal aquifer storing about 10 million m^3 of groundwater, with an average thickness of 10 m. The aquifer extends over an area of approximately 5 km^2, north from Napier Hill – Park Island to Bay View and across the Esk River to the Whirinaki area.
- Peripheral Limestone. A collection of water-bearing limestones on the southern, western and northern margin of the Heretaunga Plains, including cavities and fractures that store an estimated 27.5 million m^3 of groundwater.

2.2 HAWKE'S BAY CLIMATE

The Hawke's Bay region "has a generally dry, warm climate because it is sheltered on the west by the North Island's main axial mountain ranges" (Pollock, 2012). Annual sunshine is in the range 2,100 to 2,200 hours, with more in the Heretaunga Plains, and maximum summer daytime temperature is typically in the range 19–24°C. Rainfall in the mountains and southern Hawke's Bay is in the range 1,200 to 2,400 mm/yr with Heretaunga Plains typically receiving less than 800 mm/yr (Pollock, 2012).

2.3 PREVIOUS WORK ON GROUNDWATER BUDGET AND RAINFALL RECHARGE

Dravid and Brown (1997) defined a 'groundwater balance' for the Heretaunga Plains, with groundwater budget components including recharge from rainfall (Table 2.1). Rainfall recharge was estimated by Dravid and Brown (1997) for soils in the unconfined aquifer areas and simulated using the SWIM (Soil Water Infiltration Model). The model was applied to two periods of two years duration, including a wet period (1975 – 1977) and a dry period (1993-1995). The range of annual rainfall in these four years was 7.4 – 22.3 million m^3/yr. The rainfall recharge estimate in Table 2.1 was then calculated as 5 million m^3/yr to "account for the simplification of soil areas and soil hydraulic properties". Rainfall recharge of 5 million m^3/yr is equivalent to approximately 0.16 m^3/s.

Table 2.1 Groundwater budget components in the Heretaunga Plains (Dravid and Brown, 1997).

Groundwater budget components (million m^3/yr)			
Inflows		**Outflows**	
Source	**Flow**	**Sink**	**Flow**
Ngaruroro River	157.7	Public water supply	24.1
Tutaekuri River	25.2	Rural domestic	2
Rainfall	5	Industry	11
		Irrigation	23.9
		Frost protection	2
		Drainage dewatering	3
		Springs	119.8
		Submarine outflow	unknown
Total	187.9	Total	185.8

3.0 METHODS

3.1 MODEL GRID

A model grid was developed with 1 ha grid cells (100 m x 100 m cells) over the study area. An ArcGIS fishnet grid with a horizontal resolution of 100 m x 100 m was generated covering the entire model area. The regular grid was defined by its bottom left corner (Easting 2820000, Northing 6156000) and top right corner (Easting 2854200, Northing 6194200) and was generated using the ArcGIS 'Create Fishnet' tool (ArcToolbox → Data Management Tools → Feature Class → Create Fishnet).

The Feature ID (FID) for each grid cell, which is automatically assigned by ArcGIS, was used to link the fishnet grid with the grid cell centre points used in the modelling process. Then, the 100 m x 100 m cells that were within the model area were selected (Figure 1.2). This selection includes all cells that were within the model area, either wholly or partly, using ArcMap (ArcMap → Selection →Select by Location → Target Layer features intersect Source Layer features).

3.2 GENERAL WATER BUDGET

A general water budget equation describes the relationships between water inflow, water outflow and water storage within a defined area of a catchment (Scanlon et al., 2002; Scanlon, 2012), as demonstrated in Figure 3.1.

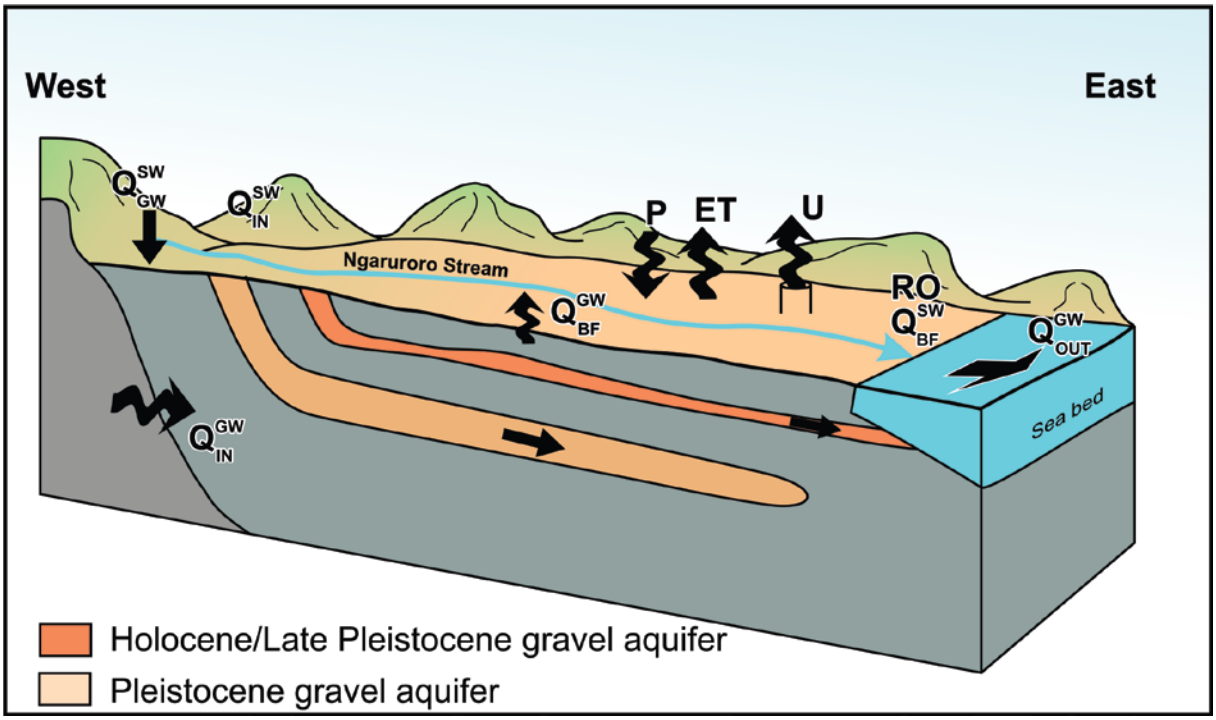

Figure 3.1 Conceptual model of water budget components and groundwater flow in the Heretaunga Plains aquifers.

These zones include the following:

$$\text{water inflow} = \text{water outflow} \quad (1)$$

i.e.,

$$P + Q_{IN} = ET + Q_{OUT} + \Delta S \quad (2)$$

Water inflows include:

P precipitation

Q_{IN} water flow into the area which is the sum of Q^{SW}_{IN} (baseflow, interflow and runoff) and Q^{GW}_{IN} (groundwater flow)

Water outflows include:

ET evapotranspiration from the area

Q_{OUT} water flow out from the area

ΔS change in water storage (S)

With:

$$Q_{OUT} = Q^{SW}_{IN} + Q^{SW}_{BF} + RO + Q^{GW}_{OUT} \tag{3}$$

$$Q^{GW}_{OUT} = U + Q^{GW}_{COUT} \tag{4}$$

Q^{SW}_{BF} surface water baseflow from the area, i.e., Q^{GW}_{BF} (groundwater flow to baseflow)

RO surface water runoff from the area

Q^{GW}_{OUT} groundwater outflow, including consumptive groundwater use (U) and groundwater discharge across the coastal boundary (Q^{GW}_{COUT})

Expanding Equation 2 for surface water and groundwater terms, assuming that S is zero (i.e., all flows are the same over time) and interflow is zero, has:

$$P + Q^{SW}_{IN} + Q^{GW}_{IN} = ET + Q^{SW}_{IN} + Q^{SW}_{BF} + RO + U + Q^{GW}_{COUT} \tag{5}$$

This equation simplifies, by cancelling terms associated with surface water inflow to the area, to a water budget for Heretaunga Plains area:

$$P + Q^{GW}_{IN} = ET + Q^{SW}_{BF} + RO + U + Q^{GW}_{COUT} \tag{6}$$

This report is concerned with estimates of rainfall recharge to groundwater on the Heretaunga Plains and Ahuriri catchment areas. Therefore, a calculation of a full water budget (i.e., Equation 6) is beyond the scope of this report. However, the rainfall recharge models (Section 3.5) assess components of the water budget.

Precipitation (P) was calculated by NIWA's Virtual Climate Station Network (VCSN) based on rainfall observations at individual rainfall recording sites. These datasets were then interpolated throughout New Zealand for the period 1972 to 2006, including sites located in the Hawke's Bay Region (Figure 3.2) at a daily time step (Tait et al., 2012). The spatial resolution of this dataset is 0.05 degrees of latitude and longitude, or approximately 5 x 5 km.

Evapotranspiration (ET) was calculated as potential evapotranspiration (PET) in the VCSN for the period 1972 to 2006 at a daily time step (Tait et al., 2013). Rainfall recharge models commonly calculate actual evapotranspiration (AET) at a daily time step, with specific consideration of soil type (i.e., profile available water, Section 3.4), but without specific consideration of land use and land cover.

Runoff (RO) is likely to be a relatively small component of total surface flow in the relatively flat Heretaunga Plains area, but may be significant in the areas with heavier soils. Although runoff has been estimated using one of the rainfall recharge models (the Rushton model, Section 3.5.2), a full analysis of runoff in the study area is beyond the scope of this project.

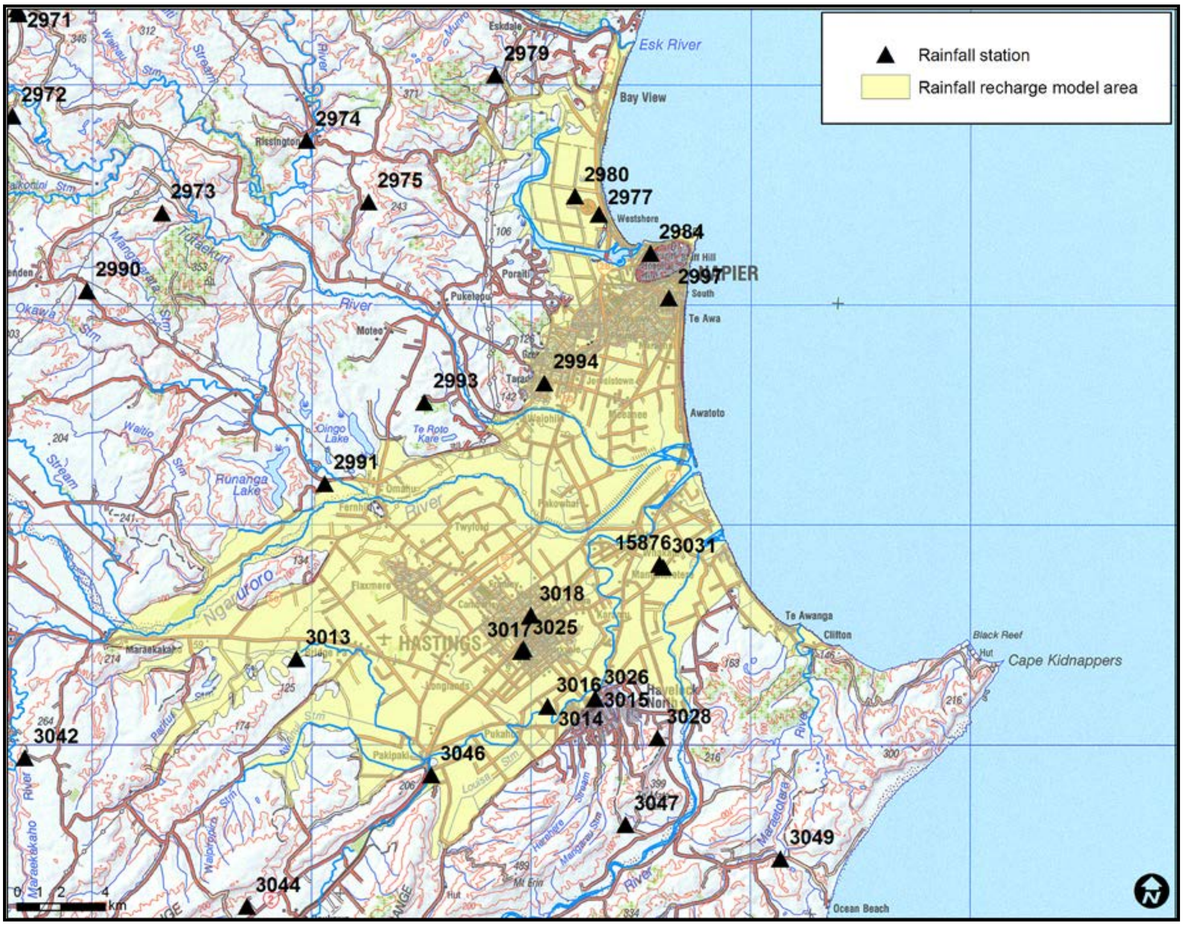

Figure 3.2 Selected Hawke's Bay rainfall recording sites used in the estimate of NIWA's VCSN rainfall model.

3.3 PROFILE AVAILABLE WATER

Profile available water (PAW) data was obtained from Landcare Research (2013). The dataset is part of the National Soils Database that includes the minimum, maximum and average available water for a soil profile up to a depth of 0.9 m, or to the potential rooting depth, whichever is the lesser.

For the ease of GIS data processing, the data was downloaded as an ArcGIS Shapefile with New Zealand Map Grid as the spatial reference system. The shapefile was then converted into a grid in ArcMap with a 10 m horizontal resolution. The 10 m PAW grid was then overlain with the 100 m fishnet grid and average PAW was calculated for each fishnet grid cell (ArcToolbox → Spatial Analyst → Zonal → Zonal Statistics as a table). Note that PAW is set to zero for two land uses (river beds and urban) on the Landcare Research database, as shown in Figure 3.3.

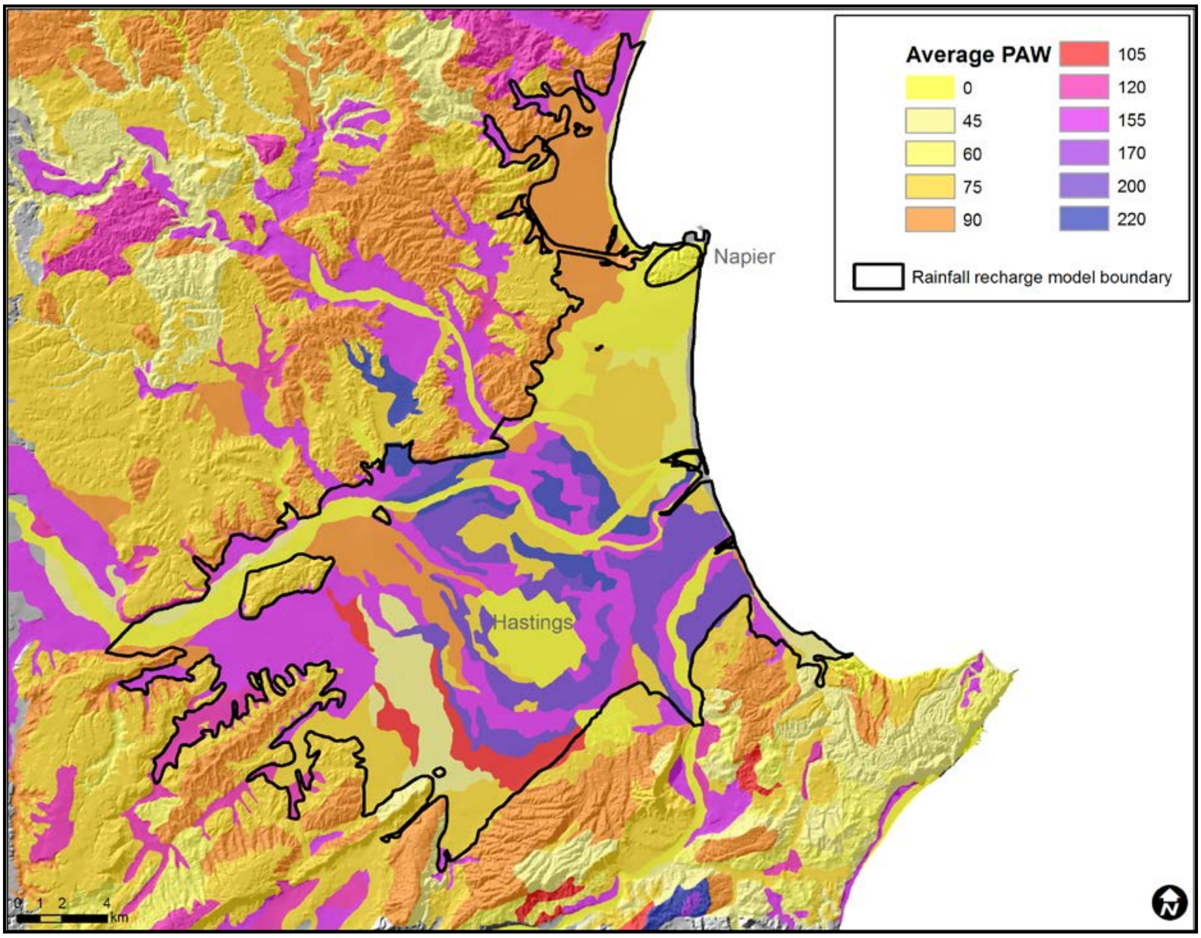

Figure 3.3 Profile available water (mm) in the Heretaunga Plains area as recorded in the LRIS portal.

PAW was adjusted after the ArcMap gridding procedure. PAW was set for river beds as 45 mm, aiming to represent dry river beds with a value measured on Holocene Springston Formation gravel located near the Waimakariri River in Christchurch (White et al., 2003). PAW was adjusted to 250 mm for urban land use aiming to represent very heavy soils and stormwater drainage in the built-up areas. In addition, a gradient of PAW values is calculated by the ArcMap procedure that interpolates PAW values to model cells. For example, interpolated PAW values were between 0 mm and the adjacent zone value at the boundaries of river beds. PAW in these cells were also adjusted with: PAW set to 60 mm adjacent to river beds; and PAW set to adjacent zone value at the boundaries of urban areas.

3.4 RAINFALL RECHARGE MEASUREMENTS

Three rainfall recharge monitoring sites were installed on the Heretaunga Plains from July 2011 – July 2012 (Lovett and Cameron, 2013). The sites are situated on the unconfined zone of the Heretaunga Plains aquifer system, and are located at Bridge Pa, Maraekakaho and Fernhill, respectively (Figure 3.4). Each monitoring site consists of three rainfall recharge lysimeters (700 mm deep, 500 mm diameter), a ground level rain guage, an instrumentation enclosure, instrumentation and a telemetry system (Figure 3.5). Rainfall recharge is calculated from the volume of rainfall that infiltrates through the soil column.

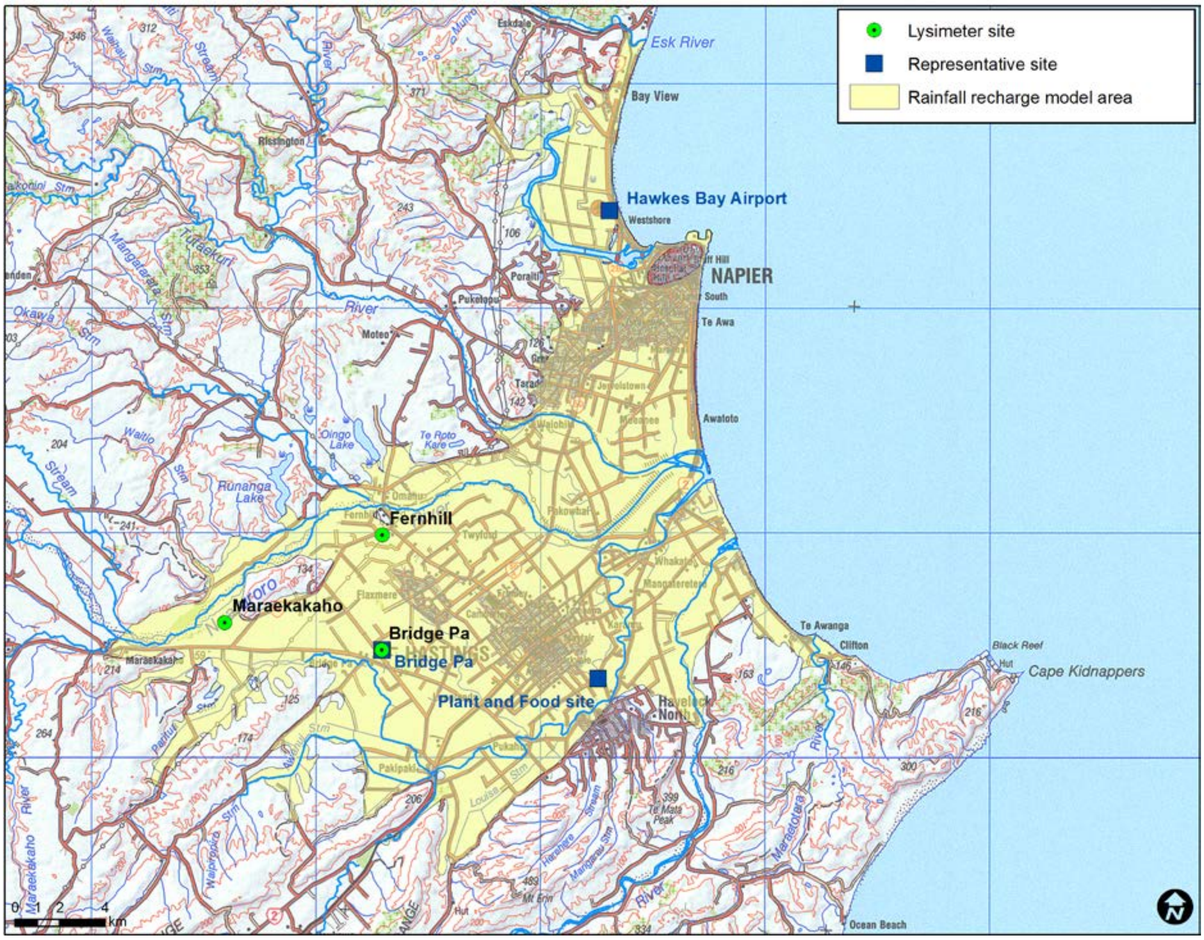

Figure 3.4 Location of the three rainfall recharge lysimeter sites, and three representative sites used to summarise rainfall recharge model calculations.

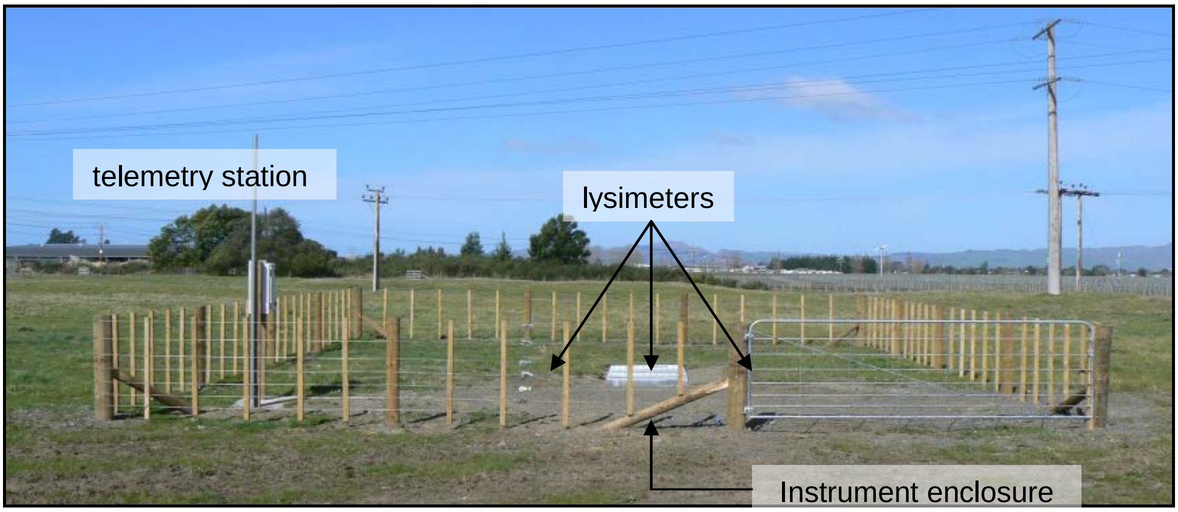

Figure 3.5 Fernhill Substation rainfall recharge monitoring site.

The Bridge Pa site was installed in July 2011, and datasets are availabile from August 2012 (Table 3.1). At the Maraekakaho site, installation was competed in June 2012 and datasets are available from September 2012. Installation at the Fernhill site was completed in July 2012, and datasets are available from September 2012. Due to instrument errors, several gaps occur throughout the period of availabile data at each site. In particular, both Bridge Pa and Fernhill sites have a data gap from 21/11/2012 to 04/12/2012. Similarly, there are several gaps in the dataset for the period 21/11/12 – 05/12/12 for the Maraekakaho site.

Table 3.1 Summary of rainfall recharge monitoring site installation and recording dates.

Location	Installation date	Dataset
Bridge Pa	11/07/2011	03/08/2012 – present
Maraekakaho	11/06/2012	07/09/2012 – present
Fernhill	25/07/2012	06/09/2012 – present

3.5 RAINFALL RECHARGE MODELS

Three rainfall recharge models (SOILMOD, Rushton, Genetic Programme) have been applied for this report, with the aim to estimate the variability of rainfall recharge estimates. Inputs to each of these models included:

- daily rainfall and daily PET in the period 1972 to 2006 in each 100 m x 100 m model cell calculated in Thiessen polygons, i.e., model cells were assigned the daily rainfall and daily PET values of the nearest VCSN sites; and
- average PAW in each cell.

3.5.1 SOILMOD

SOILMOD is used to calculate a daily soil water budget assuming no runoff (Scott, 2004):

$$S_i = S_{i-1} + R_i + IRR_i - AET_i - RR_i \qquad (7)$$

Where:

S_i soil moisture at day i

R_i rainfall at day i

IRR_i irrigation at day i

AET_i actual evapotranspiration at day i

RR_i groundwater recharge at day i

In this model, AET is varied as a function of soil water storage (White et al., 2003):

$$AET_i = PET_i * (S_{i-1}/FC)/(1-VC/\ PET_i) \qquad (8)$$

Where:

FC soil moisture field capacity

VC vegetation cover factor

Applications of the SOILMOD rainfall recharge model (Scott, 2004) have included estimation of rainfall recharge observations in Canterbury (Thorpe and Scott, 1999; White et al., 2003) and estimation of rainfall recharge at the sub-regional scale (White et al., 2003; Scott, 2004). Estimates of groundwater recharge from rainfall and irrigation have been used by Environment Canterbury to calculate groundwater allocation limits at the sub-regional scale (Scott, 2004).

3.5.2 Rushton

The Rushton model uses a soil moisture balance with the concept of “near-surface” storage (Rushton et al., 2006). “Near-surface” storage is “introduced to account for continuing ET on days following heavy rainfall even though a large soil moisture deficit exists" (Rushton et al., 2006). This has been applied to successfully represent the daily rainfall recharge observations in Canterbury (Hong and White, 2005) by Wilson (2012).

Ruston et al. (2006) supply algorithms to complete this calculation in an appendix to their paper; these calculations are used in the Heretaunga Plains rainfall recharge model, with the exception of RO. The Heretaunga Plains model uses the USDA Soil Conservation Service (SCS) runoff model described in Rawls et al. (1992), following Wilson (2012).

Estimation of rainfall recharge includes calculation of four discrete values:

1) **Infiltration to the soil zone**: calculation of RO uses soil zone parameters including the maximum potential retention after runoff begins (SRN) (Table 3.2). The infiltration equation uses P, RO and an empirical factor (FRACSTOR) to estimate infiltration (Rushton et al., 2006).
2) **Total actual evaporation:** estimated using infiltration, soil moisture deficit (SMD) and PAW (Rushton et al., 2006).
3) **Soil moisture balance**: calculated from model estimates including the soil moisture deficit on the previous day, infiltration and AET.
4) **Rainfall recharge**: occurs where SMD is less than zero.

Table 3.2. Typical soils and associted infiltration rates and model parameters.

Rainfall Recharge zone (Figure 3.6)	Soil type (example)[1]	Infiltration rate	Typical soil texture	SRN[2]	FRACSTOR[3]
1	Pakipaki	High	Sandy loam	391	0.4
2	Hastings	Low	Silt, clay loam	88	0.7
3	Farndon	Moderate	Silt loam	160	0.55
4	Meeanee	Moderate	Silt loam	160	0.55
5	Omarunui	Moderate	Sandy loam	160	0.55

[1] Griffiths (2001).
[2] Calculated from hydrologic soil groups with grass cover greater than 75% for high, moderate and low infiltration rates (Rawls et al., 1992).
[3] Estimated from Rushton et al. (2006) and Wilson (2012).

3.5.3 Genetic programme

The genetic programme method (GPM) relates observations of rainfall recharge to rainfall, PET and PAW (Hong and White, 2005). This method derives equations from observations of rainfall recharge and rainfall which were collected from four lysimeter sites located on the Canterbury Plains for the period 01/05/1999 – 30/04/2002. The best-fit equation for observations in the period 01/05/2002 – 30/04/2003 had rainfall recharge positively correlated to rainfall and negatively correlated to PET and PAW.

The GPM model used in the Heretaunga Plains rainfall recharge is that developed from observations of daily rainfall recharge, rainfall and PET from Canterbury Plains lysimeters in the period 01/05/1999 to 30/04/2003 (Zemansky et al., 2010):

$$RR = P * ((47.13)/(16.15+(PET*PAW)/0.5016–PET + PAW/1.014)^{P}) \qquad (9)$$

3.5.4 Model implementation

Model calculations are completed in the following steps:

- input VCSN data including: VCSN site number, day number, daily rainfall and daily PET;
- input Heretaunga Plains rainfall recharge model inputs including: cell identifier, rainfall recharge zone number, VCSN site number for cell and average PAW;
- complete model calculations; and
- generate output files including: daily rainfall recharge (all models), AET (SOILMOD and Rushton models) and RO (Rushton model) in units of mm/day; zone-aggregated rates of rainfall recharge (all models), AET (SOILMOD and Rushton models) and RO (Rushton model), in units of m^3/s.

The model is implemented in FORTRAN (including procedures to generate the input files), and the model output is processed with Excel and MATLAB.

3.5.5 Ground-level rainfall correction

Standard rain gauges typically record less rainfall than what hits the ground. For example, ground-level rainfall was greater than measured rainfall in a standard rain gauge by approximately 10% at Winchmore (Canterbury; Thorpe and Scott 1999), and by approximately 3% at Kaharoa, Bay of Plenty (White et al., 2007). Therefore, as part of rainfall recharge modelling, a ground-level rainfall correction should be applied to rainfall measured in standard rain gauges. For example, a 10% correction to rainfall measurements was applied by Scott (2004).

This report does not generally apply ground-level rainfall corrections as the models aim to make conservative estimates of rainfall recharge. However, the effects of ground-level rainfall corrections on average rainfall recharge calculated by SOILMOD are assessed for zone 1 of the Heretaunga Plains model.

3.6 SUMMARY STATISTICS

Rainfall, PET and rainfall recharge statistics are summarised for model cells at three representative sites (Figure 3.4) and in five zones (Figure 3.6). The three representative sites were chosen using the following criteria:

- Bridge Pa is located within the unconfined aquifer zone (Dravid and Brown, 1997), and therefore rainfall recharge estimates may represent rainfall recharge to the unconfined Heretaunga Plains aquifer. PAW at the site is 45 mm, and therefore, the soil at Bridge Pa is representative of very light soils in the Heretaunga Plains (Figure 3.3). Bridge Pa is also the location of a HBRC rainfall recharge monitoring site and a climate station.
- The Hawke’s Bay Airport site represents soils near the coast north of the Tutaekuri River. PAW at this site is 90 mm which is similar to the soils in the Napier City area (Figure 3.3). In addition, a climate station is located at the airport.
- Rainfall recharge through heavy Heretaunga Plains soils are represented by the Plant and Food Research site (Figure 3.4). PAW at the site is 200 mm which is typical of soils south of the Tutaekuri River and between Hastings and the coast (Figure 3.3). The Plant and Food site is also the location of much crop-related research, including water demand by apples (Green, 2013).

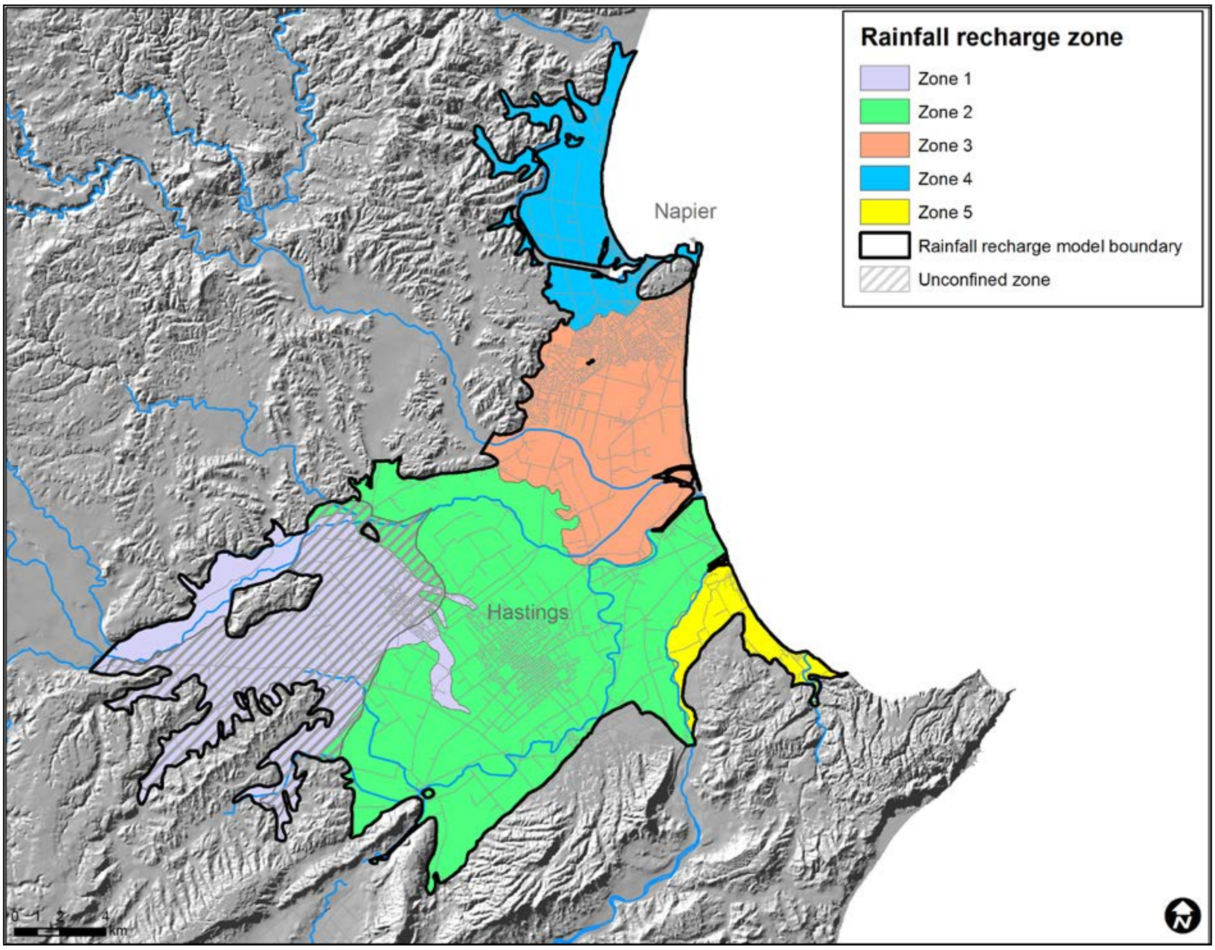

Figure 3.6 Rainfall recharge zones in the Heretaunga Plains and the unconfined zone as defined by Hawke's Bay Regional Council (Berry, 2012).

The study area was separated into five zones that were used to aggregate rainfall and rainfall recharge statistics (Figure 3.6):

- zone 1: largely the unconfined area of the Heretaunga Plains including the major recharge zone (between Fernhill and Roys Hill), the minor recharge zone (approximately between Bridge Pa and Maraekakaho) and relatively low PAW soils west of Hastings City;
- zone 2: the area of the Heretaunga Plains aquifer between the unconfined area and the coast, and generally south of the Ngaruroro River including the locations of wells that supply groundwater to Hastings City;
- zone 3: the area of the Heretaunga Plains aquifer generally north of the Ngaruroro River including Twyford and Napier City south of Napier Hill, including the locations of wells that supply groundwater to Napier City;
- zone 4: the Ahuriri area, including Bay View with a southern boundary that approximates the Ahuriri Estuary boundary before the Napier Earthquake (Dravid and Brown, 1997); and
- zone 5: the area south of the Tukituki River near the coast including the coastal strip between Haumoana and Te Awanga.

Rainfall in the rainfall recharge model area is summarised as the sum of daily rainfall (as m^3/s) in each of the 39,752 model cells in the period 1972 – 2006, divided by the number of days in the simulation period (12,784 days), and converted to mm/day and mm/yr. Annual rainfall is also calculated and three years during the period 1972 – 2006 are defined from these statistics, i.e., driest on record, average on record and wettest on record.

Annual average rainfall in the rainfall recharge model area is then expressed as a cumulative probability curve, also known as cumulative distribution function (CDF). Monthly rainfall and PET statistics in the rainfall recharge model area, calculated from daily figures, are represented by box-and-whisker plots including medians, quartiles and outliers.

Rainfall recharge model input data (i.e., rainfall and PET) and model estimates of AET and rainfall recharge (RR) are summarised with the SOILMOD calculations at the representative sites. Summary annual statistics include cumulative probability curves at the sites. Daily statistics at these sites are also summarised over the driest, average and wettest years as cumulative daily plots.

Annual rainfall and annual rainfall recharge in the five recharge zones are summarised with cumulative probability curves and tables. Typical patterns of rainfall recharge in the zones during the year are demonstrated with plots of cumulative daily rainfall recharge in zone 1 over the driest, average and wettest years.

4.0 RESULTS

4.1 PROFILE AVAILABLE WATER

PAW was revised, as per Section 3.3, in river beds and urban areas (Figure 4.1). This map was used in the generation of rainfall recharge models.

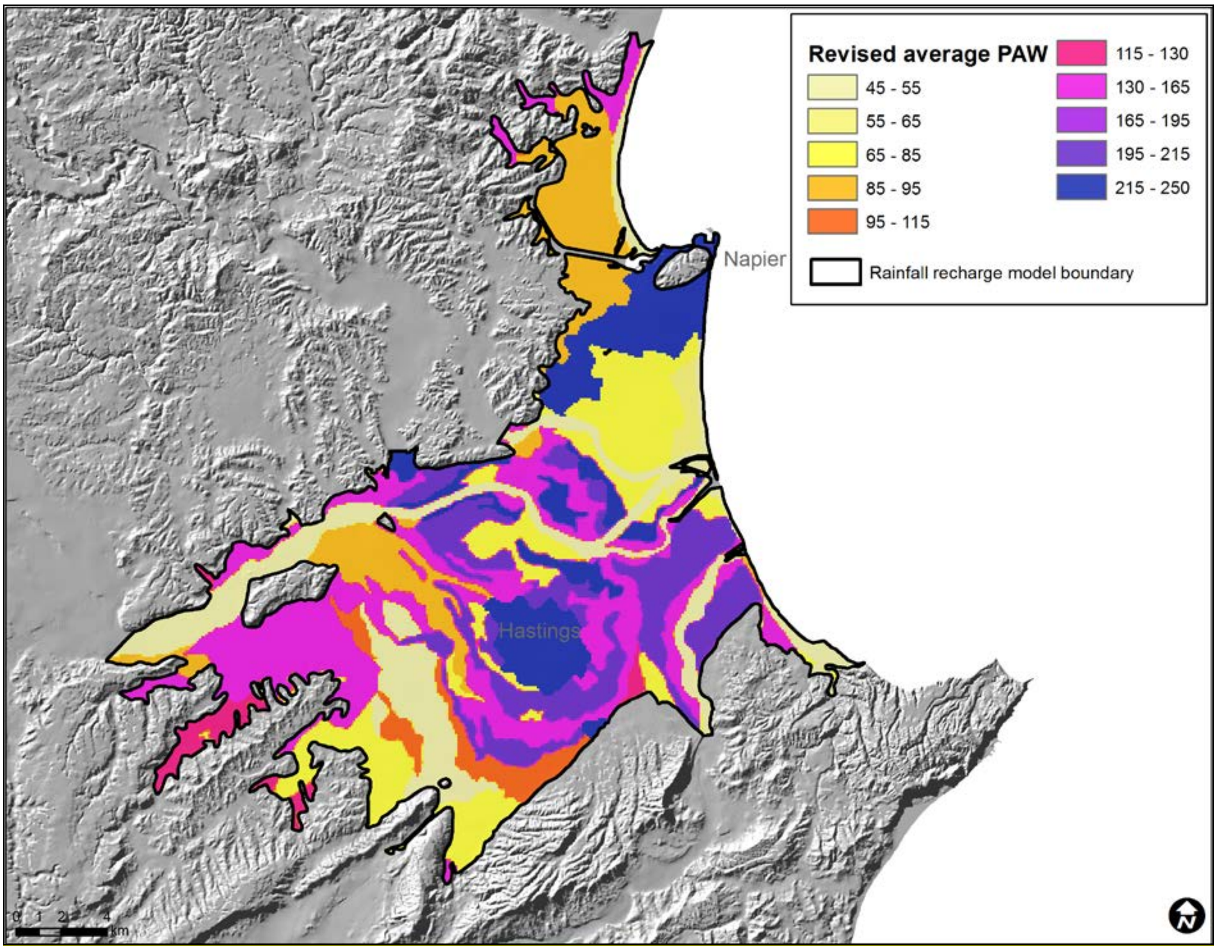

Figure 4.1 Revised PAW (mm) in the Heretaunga Plains area as adjusted from LRIS data for river beds and urban areas.

4.2 RAINFALL RECHARGE MEASUREMENTS

Measurements are available from the three lysimeter sites (Table 3.1). Rainfall recharge was recorded in two of these sites in winter 2012. However, Berry (2013) noted "major problems with instrumentation" at the sites with incorrect operation of the rain gauges used to measure rainfall recharge and ground-level rainfall. Therefore, these data were not used as a check on model estimates of rainfall recharge. Further collection of rainfall recharge and ground-level rainfall data is essential, and therefore maintenance of the sites is recommended (Section 6.0).

4.3 RAINFALL AND PET IN THE MODEL AREA

Annual rainfall in the period 1972 – 2006, as measured at the 33 VCSN sites nearest to the Heretaunga Plains rainfall recharge model cells, ranges from approximately 729 – 1028 mm/yr (Figure 4.2). Average annual rainfall in the period 1972 to 2006, at Napier (Hawke's Bay Regional Airport) and Hastings City Centre, are approximately 816 mm and 741 mm, respectively.

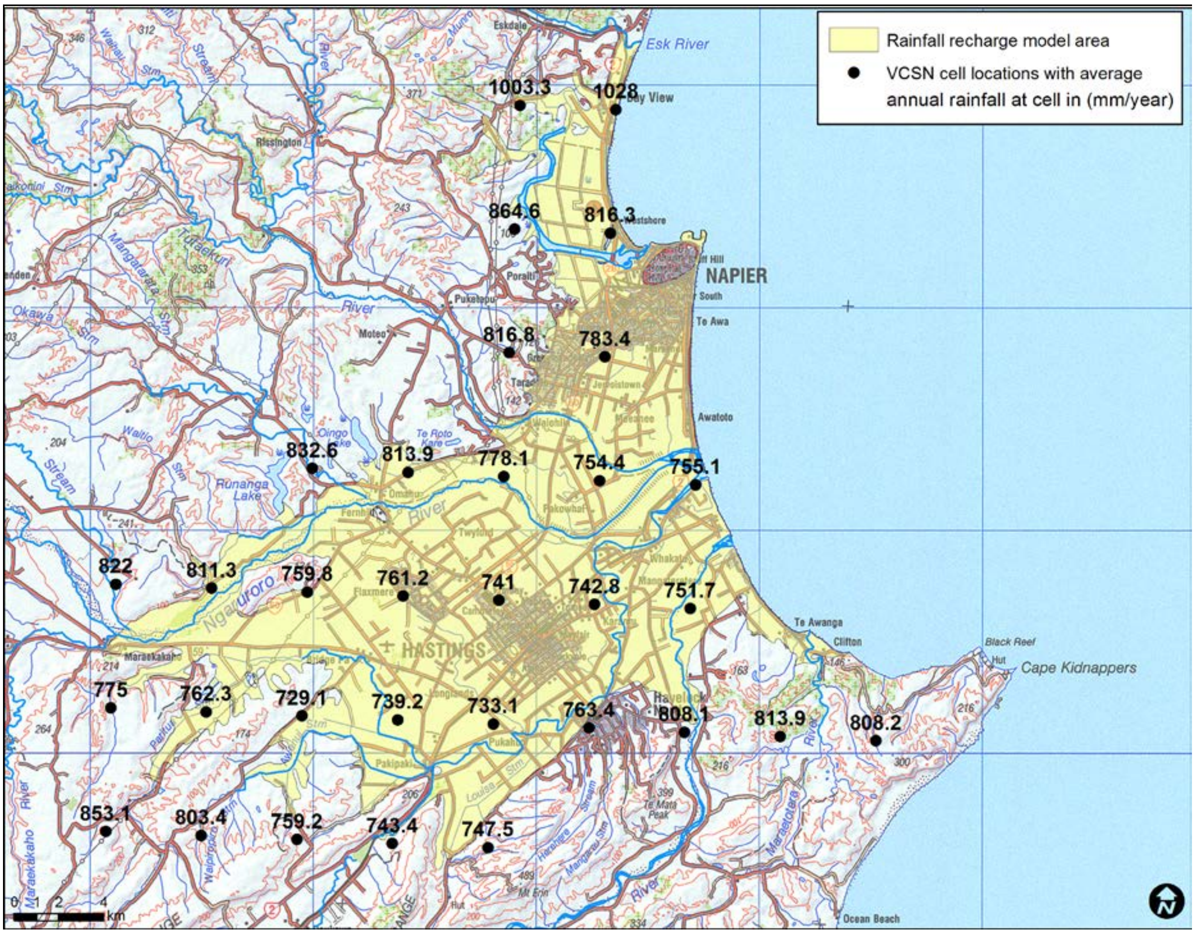

Figure 4.2 NIWA's VCSN cell locations in the vicinity of the rainfall recharge model area and average annual rainfall in the period 1974 to 2006 (mm/yr).

Median annual rainfall within the Heretaunga Plains rainfall recharge model area is 779 mm/yr (i.e., the 50 percentile; Figure 4.3). Calendar year 2004 had an annual rainfall of 766 mm/yr, which was close to the median annual VCSN rainfall in the 1972 – 2006 period. The driest calendar year was 1994 (rainfall 464 mm/yr) and the wettest year was 1974 (rainfall 1027 mm/yr). The largest daily rainfall on the Heretaunga Plains in the 1972 – 2006 period was recorded in 1974. Estimated average rainfall during a large rainfall event on 15/06/1974 over the model area was 137 mm/day (or approximately 630 m^3/s during the day), and flooding was recorded at Napier (Hawke's Bay Emergency Management, 2013). In comparison, estimated average rainfall associated with Cyclone Bola was approximately 36 mm/day (or 167 m^3/s during the period), over the three days from the 06/03/1988 – 08/03/1988.

Monthly median rainfall over the study area is typically largest in June and July, which conincides with the lowest montly median PET (Figure 4.4). The potential for rainfall recharge to groundwater is greatest in the winter months when rainfall is larger than PET. In contrast, median rainfall in summer is considerably lower than summer median PET. Therefore, the potential for rainfall recharge in summer is low.

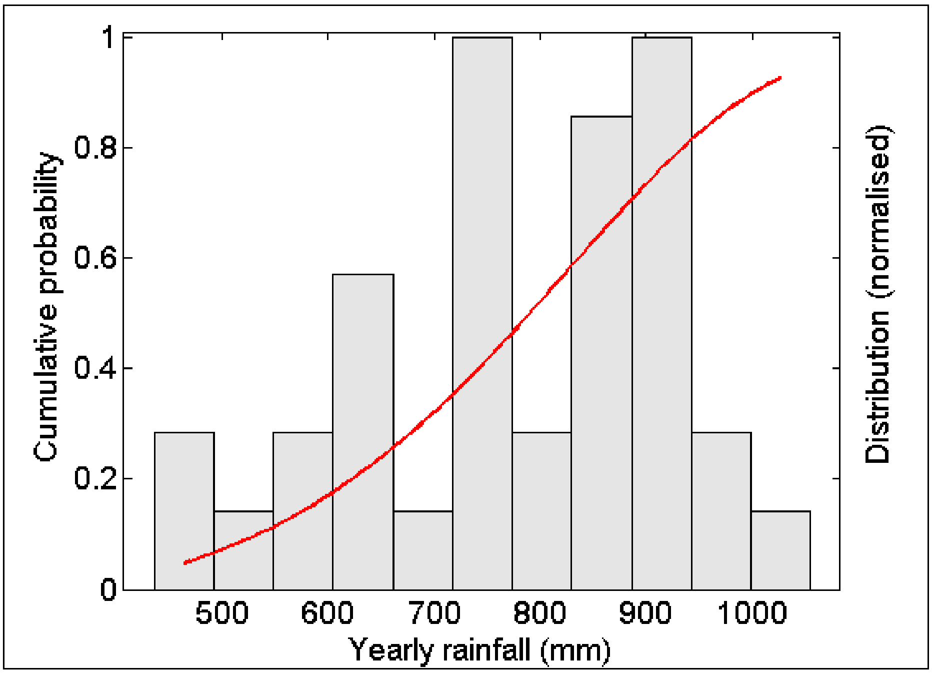

Figure 4.3 Annual rainfall cumulative probability curve in the Heretaunga Plains rainfall recharge model area, 1972 to 2006.

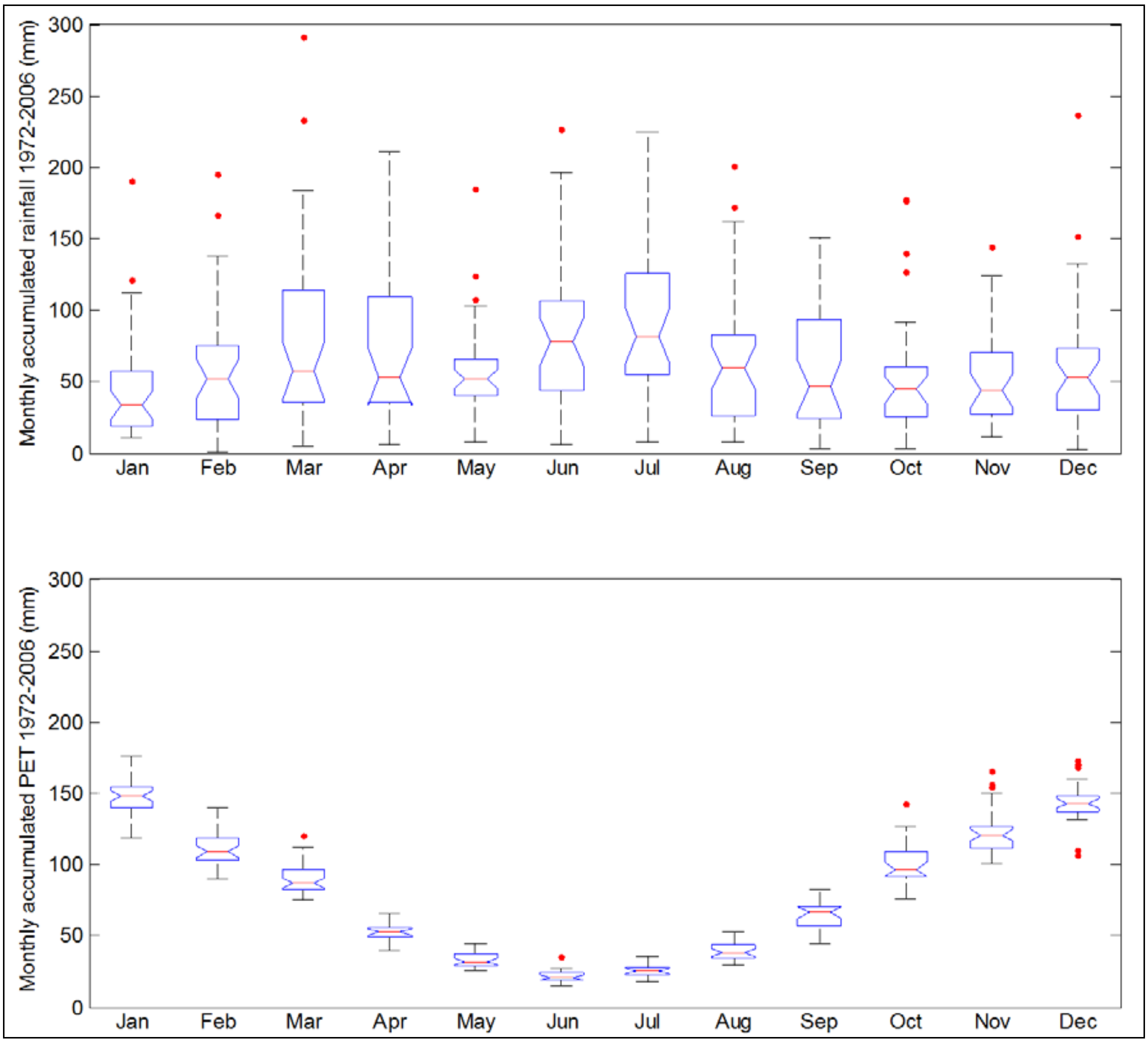

Figure 4.4 Monthly rainfall (top) and monthly PET (bottom) in the model area over the period 1972 – 2006. The red line in the notch indicates the median, while the bottom and top of the blue box are the 25 and 75 percentiles. The black whiskers indicate the extremes and the red dots are outliers.

4.4 RAINFALL RECHARGE MODEL CALCULATIONS AT REPRESENTATIVE SITES

Statistics of annual estimates of rainfall, and SOILMOD estimates of AET and rainfall recharge, at the representative sites (Figures 4.5, 4.6 and 4.7; Appendix 1) are summarised in Table 4.1. Annual average rainfall recharge was highest at Bridge Pa and lowest at the Plant and Food site. This is because AET was least at Bridge Pa due to low PAW at the site, i.e., the soil moisture capacity is more readily filled with rainfall and there is low runoff associated with soils at Bridge Pa.

Table 4.1 PAW and statistics (25, 50 and 75 percentile values) for annual rainfall, and SOILMOD calculations (AET and rainfall recharge) for the representative sites, 1972 to 2006.

Location	PAW (mm)	Annual rainfall (mm/yr)			Annual AET (mm/yr)			Annual rainfall recharge (mm/yr)		
		25	50	75	25	50	75	25	50	75
Bridge Pa	45	637	773	890	418	470	517	198	299	394
Hawke’s Bay Airport	90	706	826	936	516	578	641	147	234	329
Plant and Food	200	641	782	895	544	601	669	49	152	266

Rainfall statistics are similar at the three sites (Table 4.1). However, rainfall recharge estimates differ markedly between the sites. The difference between rainfall recharge estimates is greatest for the 25 percentile of annual rainfall recharge. For example, rainfall recharge at Bridge Pa was approximately four times that at the Plant and Food site (25 percentile), whereas the difference was approximately two times with the 50 percentile estimates.

Rainfall recharge was rare in January and December at all sites (Figures 4.8, 4.9 and 4.10). However, significant differences in the annual pattern of rainfall recharge between the representative sites is demonstrated by monthly statistics (Figures 4.8, 4.9 and 4.10). In particular, the interval of rainfall recharge at the Plant and Food site was much narrower than at the other sites. Rainfall recharge at the Plant and Food site typically occured over only four months (June, July, August and September), whereas the recharge at Bridge Pa typically occured over 10 months, and recharge at Hawke’s Bay Airport typically occured over seven months, albeit at very low rates in some of these months.

Low rates of rainfall recharge at the Plant and Food site, relative to the other sites, are also demonstrated by cumulative rainfall recharge plots (Figures 4.11, 4.12 and 4.13). For example, there was no rainfall recharge at the Plant and Food site in 1994 (the driest year in the simulation period). The onset of rainfall recharge was June 2004 (average year) and June 1974 (dry year). In contrast, rainfall recharge generally commenced earlier in the calendar year at the Bridge Pa and Hawke’s Bay Airport sites, Figure 4.11 and Figure 4.12, respectively.

Large rainfall events have an important contribution to total rainfall recharge. For example, the large rainfall event on 15/6/1974 was associated with a significant proportion of annual rainfall recharge in the 1974 year at all sites (Figures 4.11, 4.12 and 4.13).

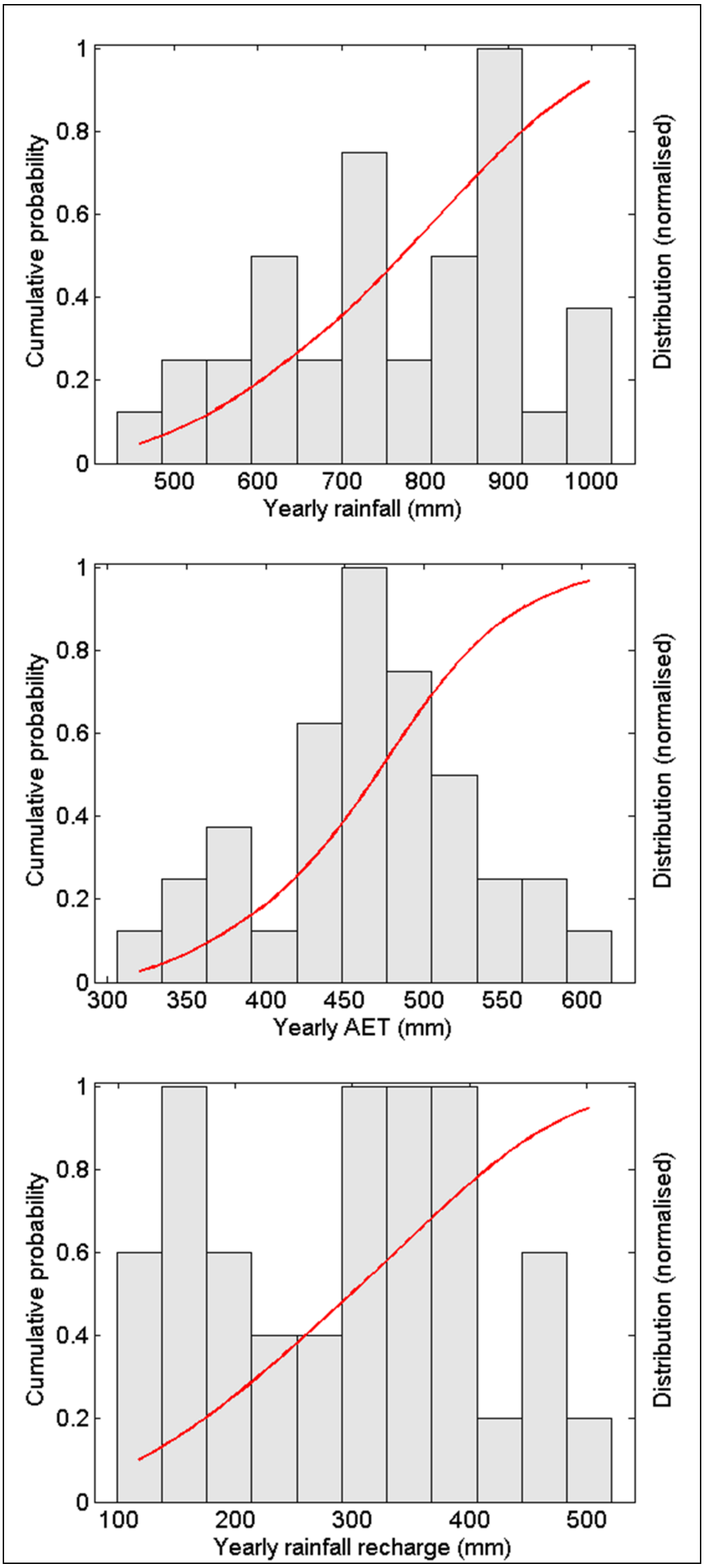

Figure 4.5 Cumulative probability and distribution of yearly sums of rainfall with calculations of AET and rainfall recharge using the SOILMOD model at the Bridge Pa location for the period 1972 to 2006. The red line corresponds to the modelled cumulative probability curve. The grey bars represent the normalised distribution of yearly rainfall, PET, AET and rainfall recharge.

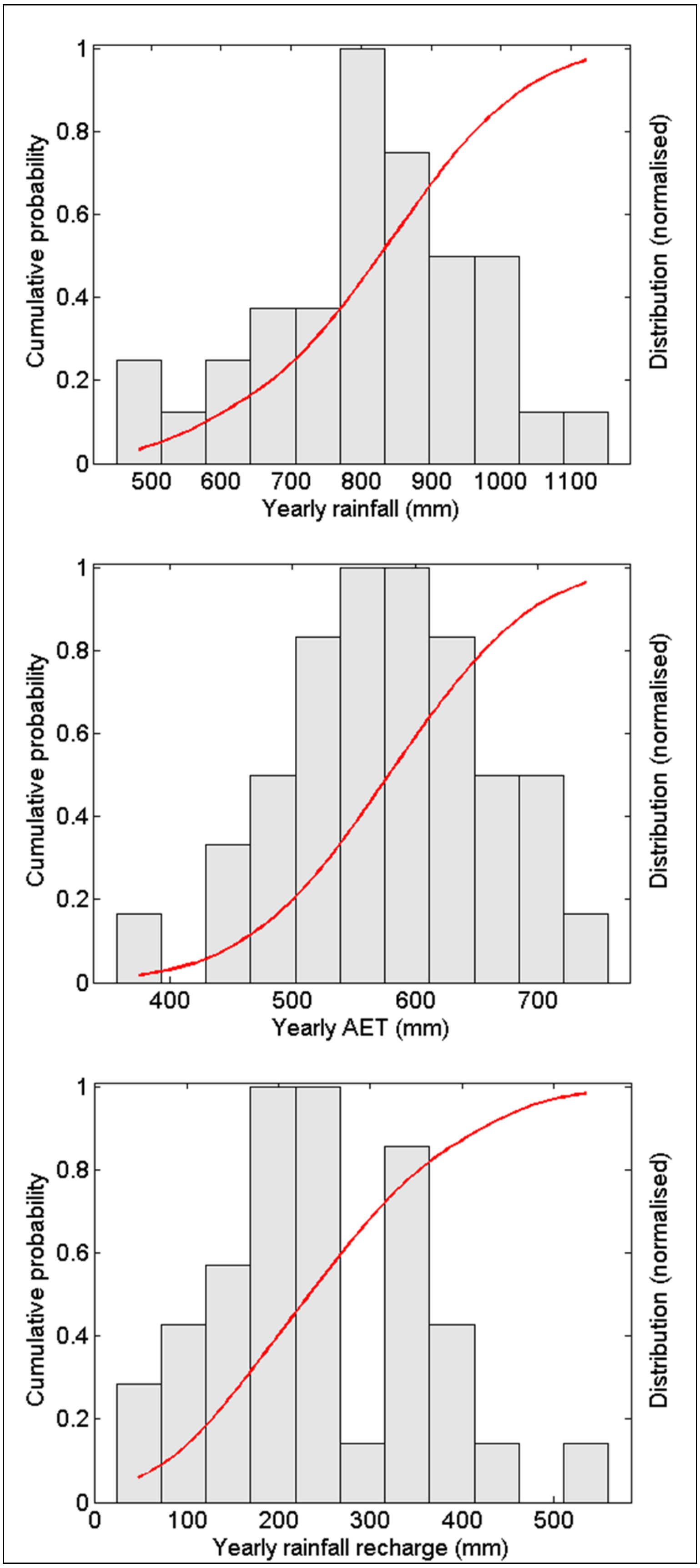

Figure 4.6 Cumulative probability and distribution of yearly sums of rainfall with calculations of AET and rainfall recharge using the SOILMOD model at Hawke's Bay Airport for the period 1972 to 2006. The red line corresponds to the modelled cumulative probability curve. The grey bars represent the normalised distribution of yearly rainfall, PET, AET and rainfall recharge.

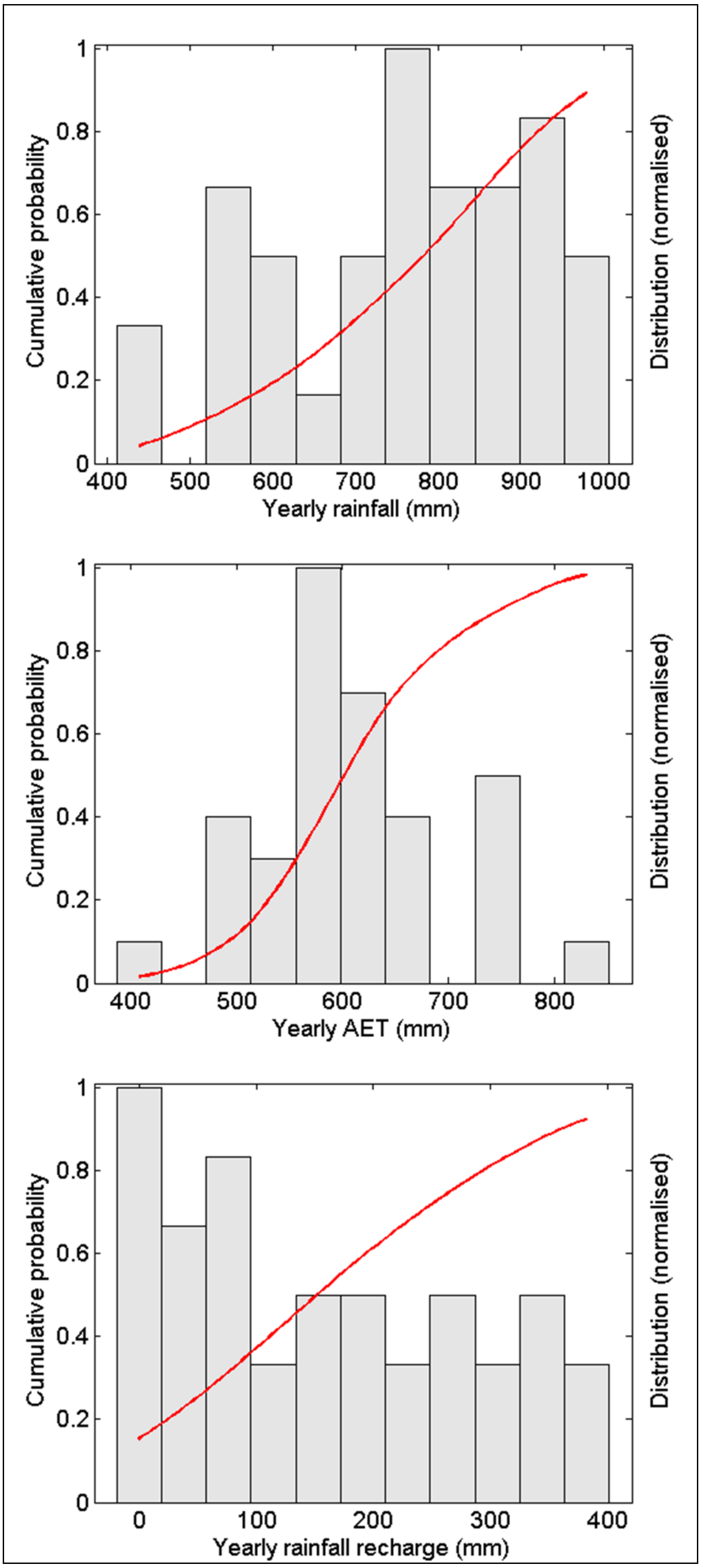

Figure 4.7 Cumulative probability and distribution of yearly sums of rainfall with calculations of AET and rainfall recharge using the SOILMOD model at the Plant and Food location for the period 1972 to 2006. The red line corresponds to the modelled cumulative probability curve. The grey bars represent the normalised distribution of yearly rainfall, PET, AET and rainfall recharge.

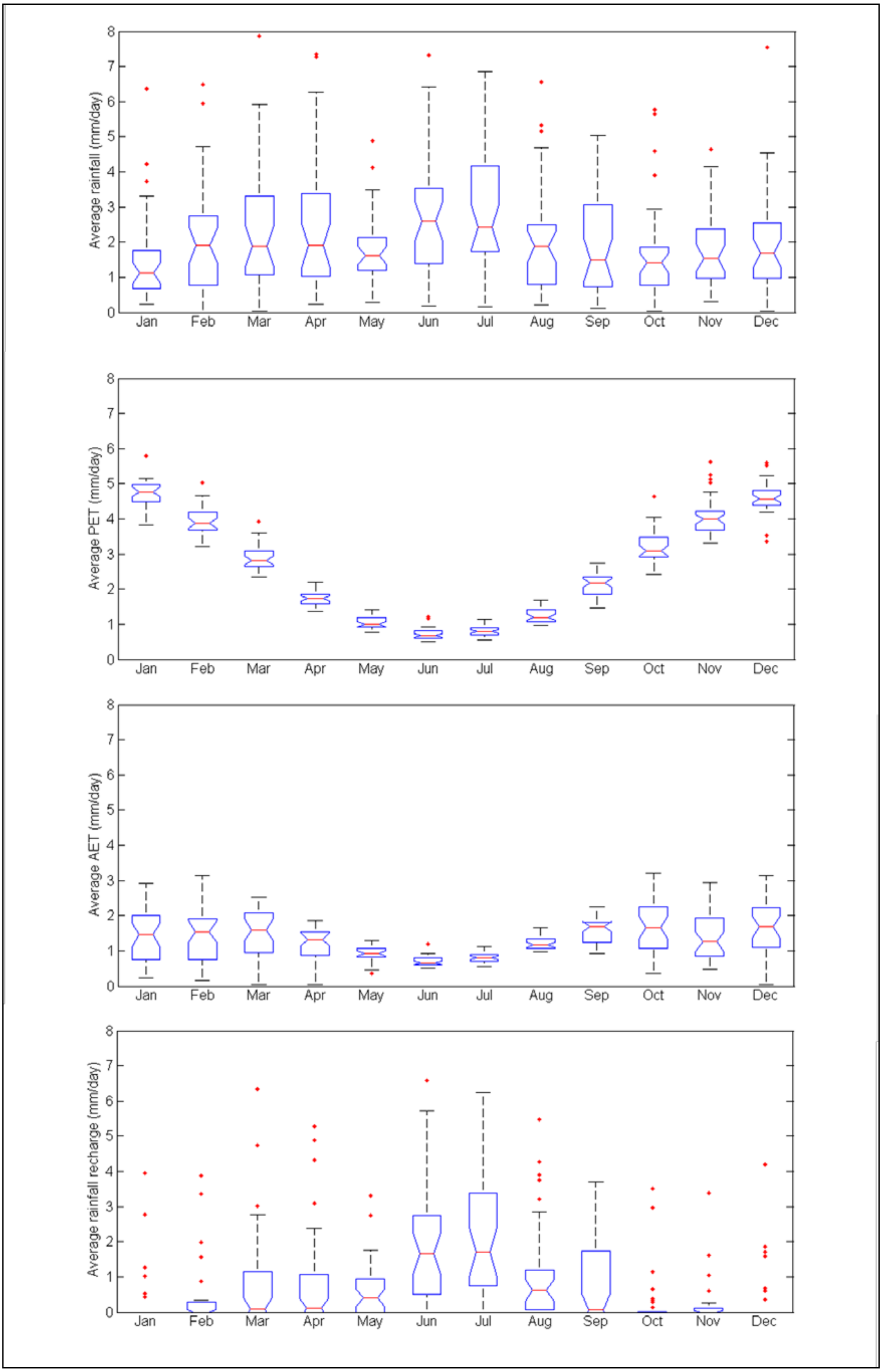

Figure 4.8 Bridge Pa location including monthly average rainfall and PET with calculations of AET and rainfall recharge using the SOILMOD model for the period 1972 – 2006. The blue boxes indicate the 25 and 75 percentiles. The red line at the notch of the blue box indicates the median. The whiskers are the extremes (i.e., in the 0 – 25 and 75 – 100 percentile range) of the distribution and red points are outliers.

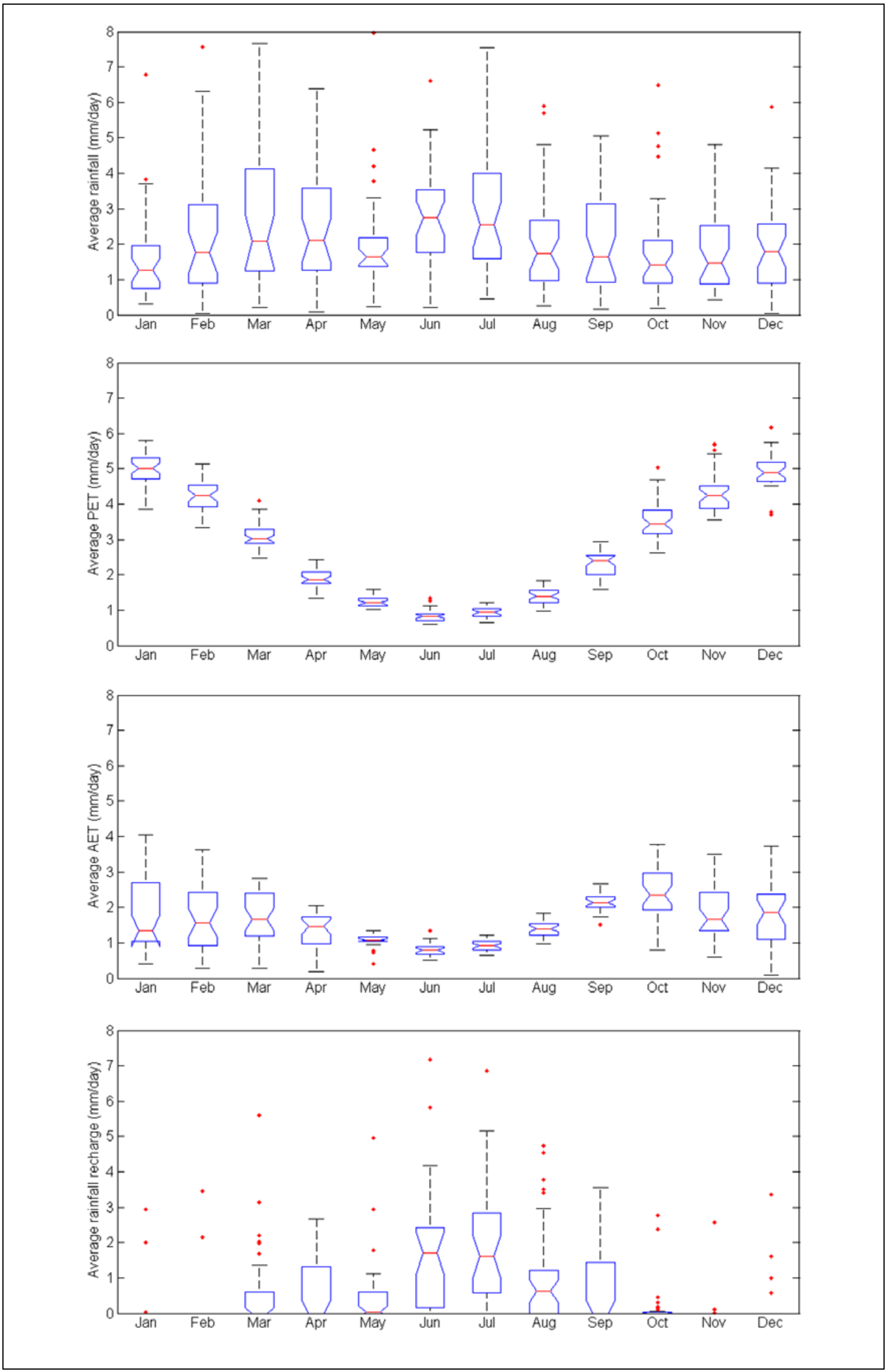

Figure 4.9 Hawke's Bay Airport location including monthly average rainfall and PET with calculations of AET and rainfall recharge using the SOILMOD model for the period 1972 – 2006. The blue boxes indicate the 25 and 75 percentiles. The red line at the notch of the blue box indicates the median. The whiskers are the extremes (i.e., in the 0 – 25 and 75 – 100 percentile range) of the distribution and red points are outliers.

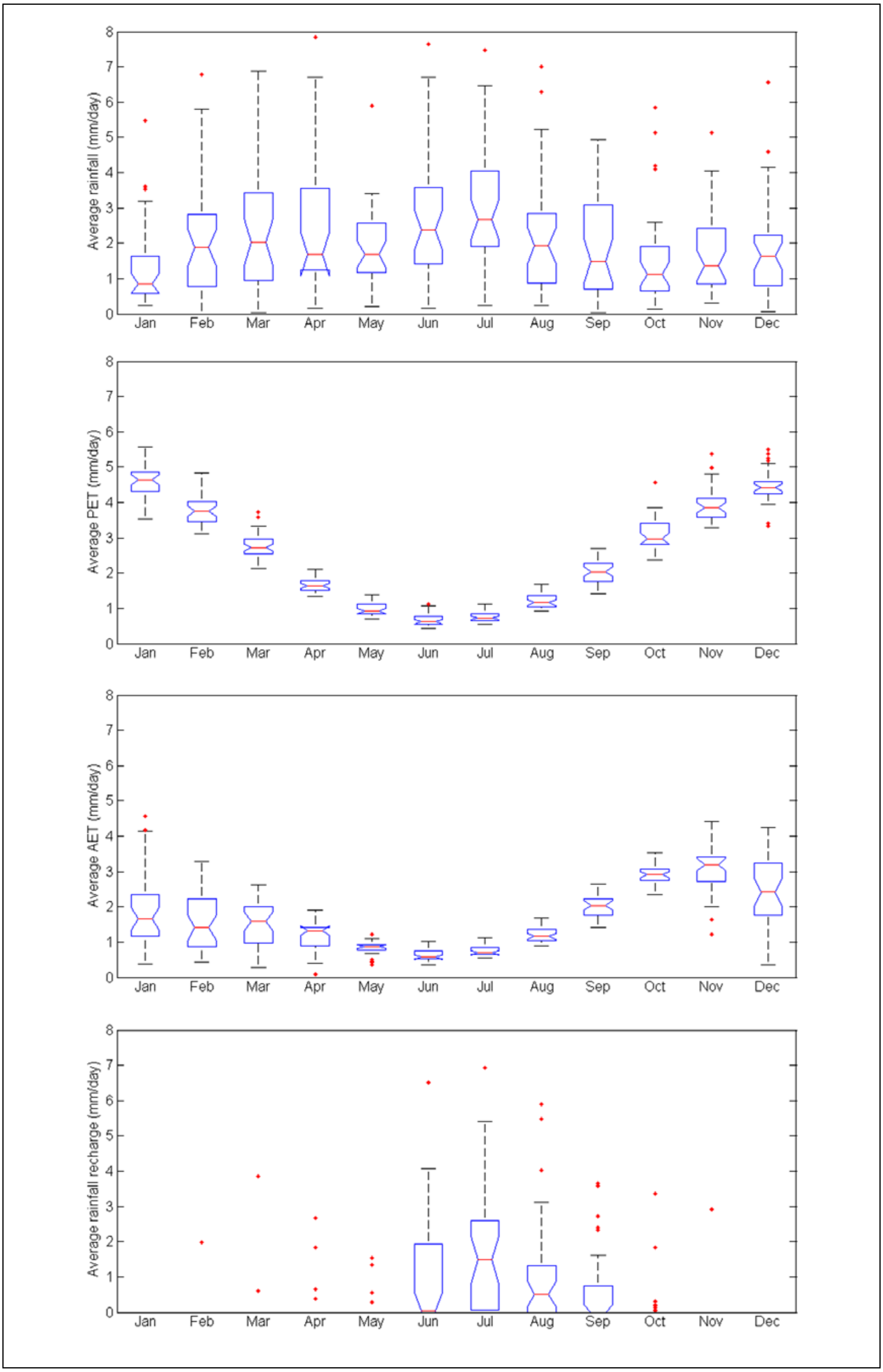

Figure 4.10 Plant and Food location including monthly average rainfall and PET with calculations of AET and rainfall recharge using the SOILMOD model for the period 1972 – 2006. The blue boxes indicate the 25 and 75 percentiles. The red line at the notch of the blue box indicates the median. The whiskers are the extremes (i.e., in the 0 – 25 and 75 – 100 percentile range) of the distribution and red points are outliers.

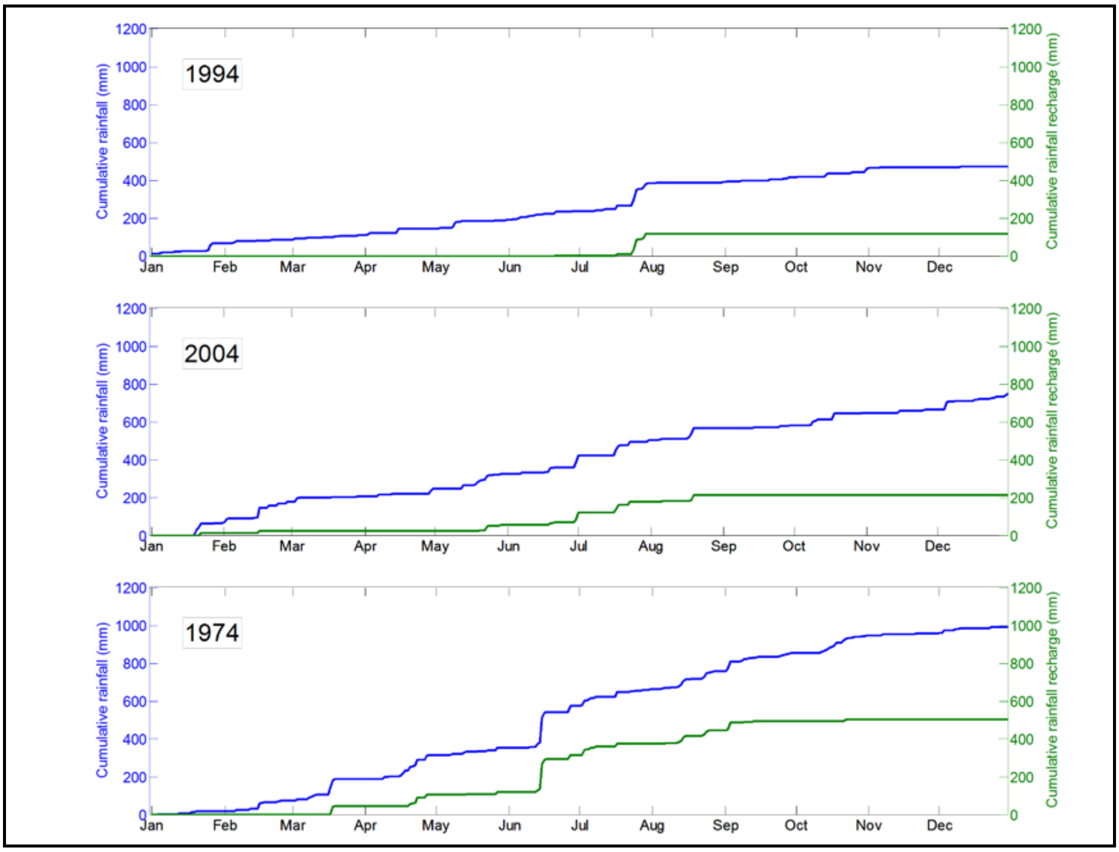

Figure 4.11 Cumulative rainfall (blue), and rainfall recharge (green) calculated using the SOILMOD model at the Bridge Pa location for a dry year (1994), average year (2004) and wet year (1974).

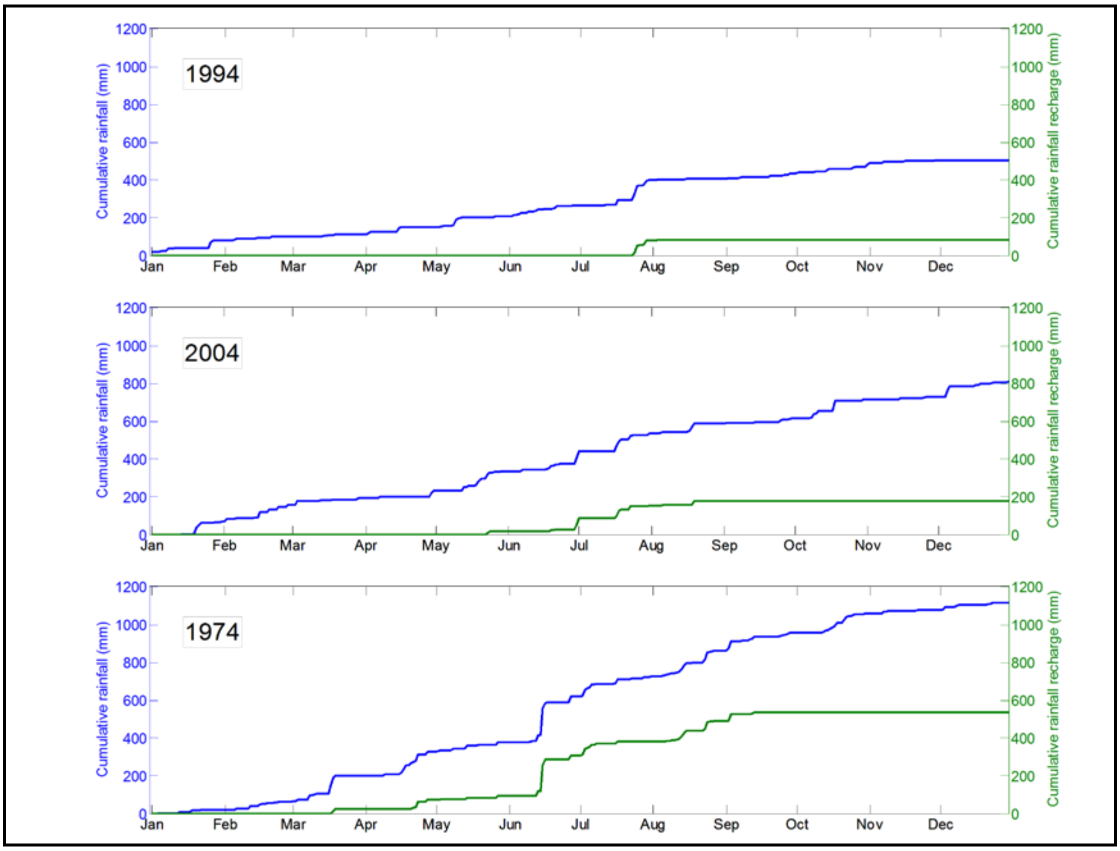

Figure 4.12 Cumulative rainfall (blue), and rainfall recharge (green) calculated using the SOILMOD model at the Hawke's Bay Airport location for a dry year (1994), average year (2004) and wet year (1974).

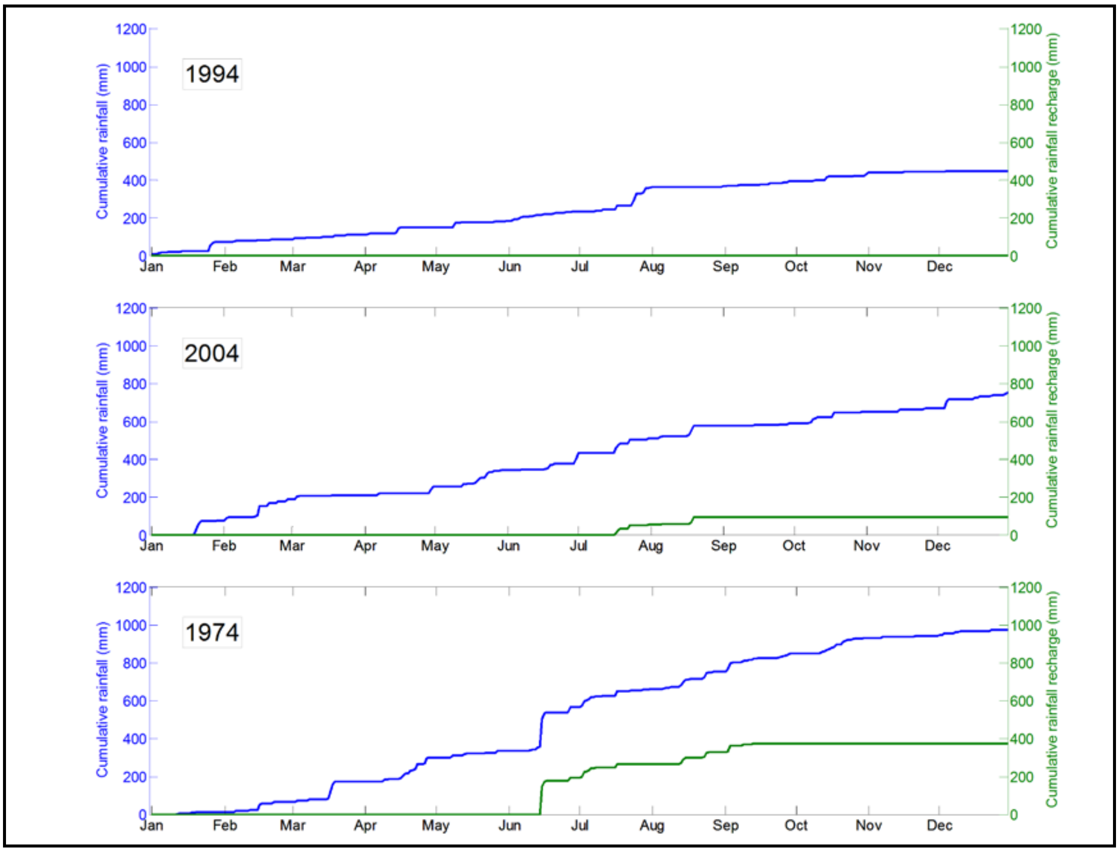

Figure 4.13 Cumulative rainfall (blue), and rainfall recharge (green) calculated using the SOILMOD model at the Plant and Food location for a dry year (1994), average year (2004) and wet year (1974).

4.5 RAINFALL AND RAINFALL RECHARGE MODEL CALCULATIONS IN RECHARGE ZONES

The average volumetric flow rate of rainfall on the model area is approximately 9.8 m^3/s (Table 4.2; and the 50 percentile total rainfall, Figure 4.14), with annual flow rates listed in Appendix 2. Zone 2 covers the largest area in the model domain. Therefore, the volumetric flow rate and standard deviation of rainfall, is largest in this zone.

Table 4.2 Statistics of rainfall rates in zones 1 to 5, including the total of all zones.

Zone	Rainfall (m^3/s)		
	Average	Median	Standard deviation
1	2.2	2.3	0.4
2	4.2	4.1	0.8
3	1.8	1.8	0.4
4	1.2	1.2	0.2
5	0.4	0.4	0.1
All zones	9.8	9.7	1.9

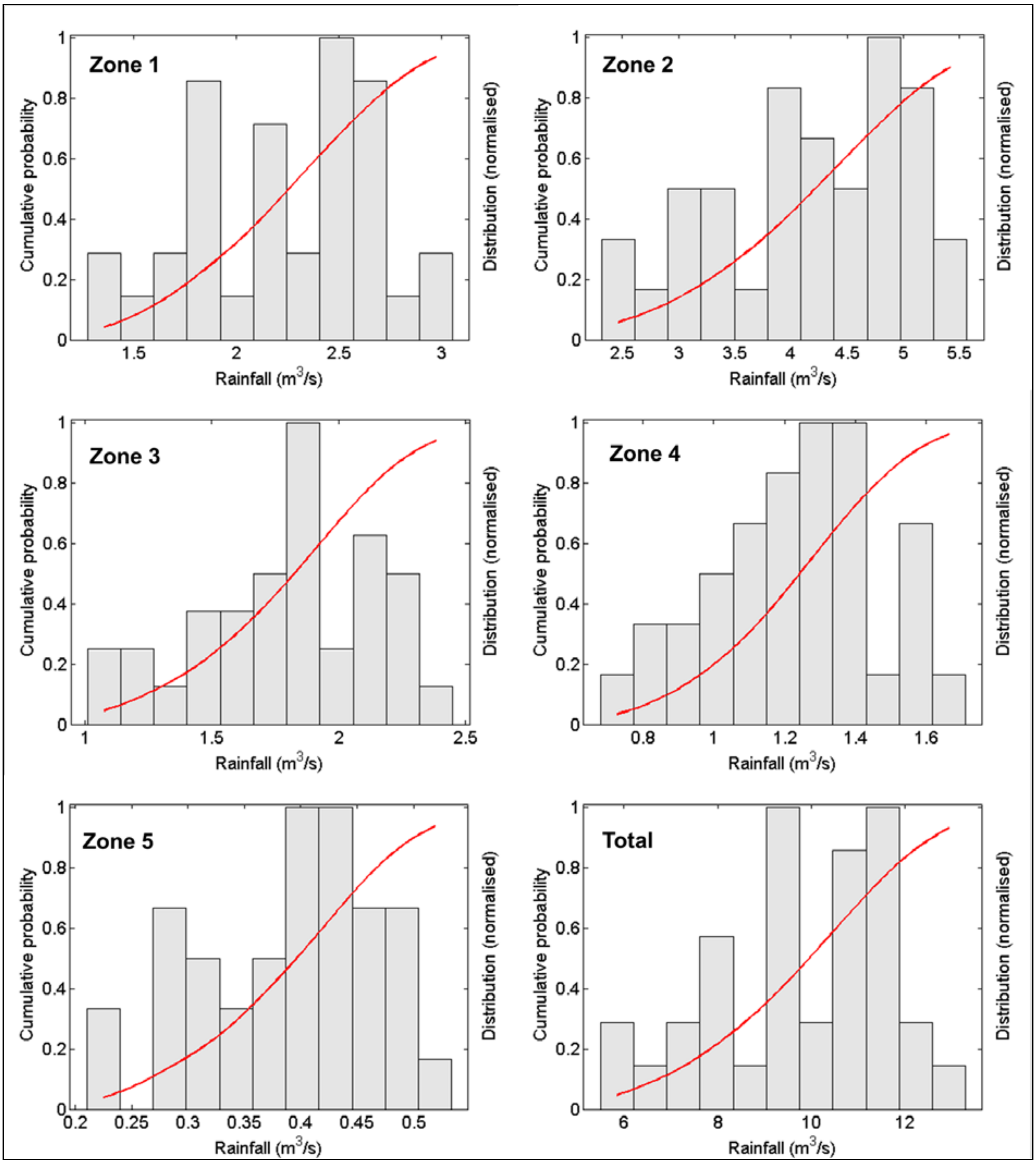

Figure 4.14 Yearly distribution of rainfall in zones 1 – 5 and the total, as volumetric flow rates. The cumulative distribution curve is plotted in red. Probabilities are normalised to their maximum.

Rainfall recharge model calculations of AET by SOILMOD and the Rushton model were similar (Tables 4.3 and Table 4.4, respectively). Average rainfall recharge calculated by these two models were also similar in zones 1, 3, 4 and 5. However, the the Rushton model (adapted with the Rawls et al., 1992 runoff calculation), had a lower average recharge in zone 2 than in SOILMOD. This is because the Rushton model calculated significant runoff in the zone. Rainfall recharge estimated by the GPM (Table 4.5) were typically the lowest of the three models. The variability of rainfall recharge calculated by the GPM is a little less than that calculated by other models (e.g., Table 4.6).

Table 4.3 Rainfall and SOILMOD estimates of model components as volumetric flow rates.

Zone	Average 1972 to 2006 (m^3/s)				
	P	**AET**	**RO**	**RR**	**Balance (P-AET-RR)**
1	2.2	1.6	na	0.6	0
2	4.2	3.1	na	1.1	0
3	1.8	1.3	na	0.5	0
4	1.2	0.8	na	0.4	0
5	0.4	0.3	na	0.1	0
Sum	9.8	7.1	na	2.7	0

Table 4.4 Rushton estimates of model components as volumetric flow rates.

Zone	Average 1972 to 2006 (m^3/s)				
	P	**AET**	**RO**	**RR**	**Balance (P-AET-RO-RR)**
1	2.2	1.6	<0.05	0.6	0
2	4.2	3.1	0.2	0.8	0.1
3	1.8	1.3	<0.05	0.4	0.1
4	1.2	0.8	<0.05	0.3	0.1
5	0.4	0.2	<0.05	0.1	0.1
Sum	9.8	7	0.2	2.2	0.4

Table 4.5 GPM estimates of model components as volumetric flow rates.

Zone	Average 1972 to 2006 (m^3/s)				
	P	**AET**	**RO**	**RR**	**Balance (P-AET-RO-RR)**
1	2.2	na	na	0.4	na
2	4.2	na	na	0.6	na
3	1.8	na	na	0.3	na
4	1.2	na	na	0.2	na
5	0.4	na	na	0.1	na
Sum	9.8	na	na	1.6	na

Table 4.6 Rainfall recharge statistics (25, 50 and 75 percentiles) estimated by the three models in zone 1.

Model	Annual rainfall recharge (m^3/s)		
	25	**50**	**75**
SOILMOD	0.4	0.6	0.9
Rushton	0.3	0.6	0.9
GPM	0.3	0.4	0.5

Rainfall recharge estimates provided by the three models were similar for dry (e.g., 1994), average (e.g., 2004) and wet (e.g., 1974) years (Figure 4.15). However, the GPM estimates of rainfall recharge were considerably less than the other two models in the wet year (1974). The similarity of rainfall recharge estimates calculated by SOILMOD and the Rushton model is demonstrated in Figure 4.16. This figure also demonstrates systematic differences between estimates for these two models and the GPM, which are consistent with lower rainfall recharge estimates at higher rainfall (Figure 4.15).

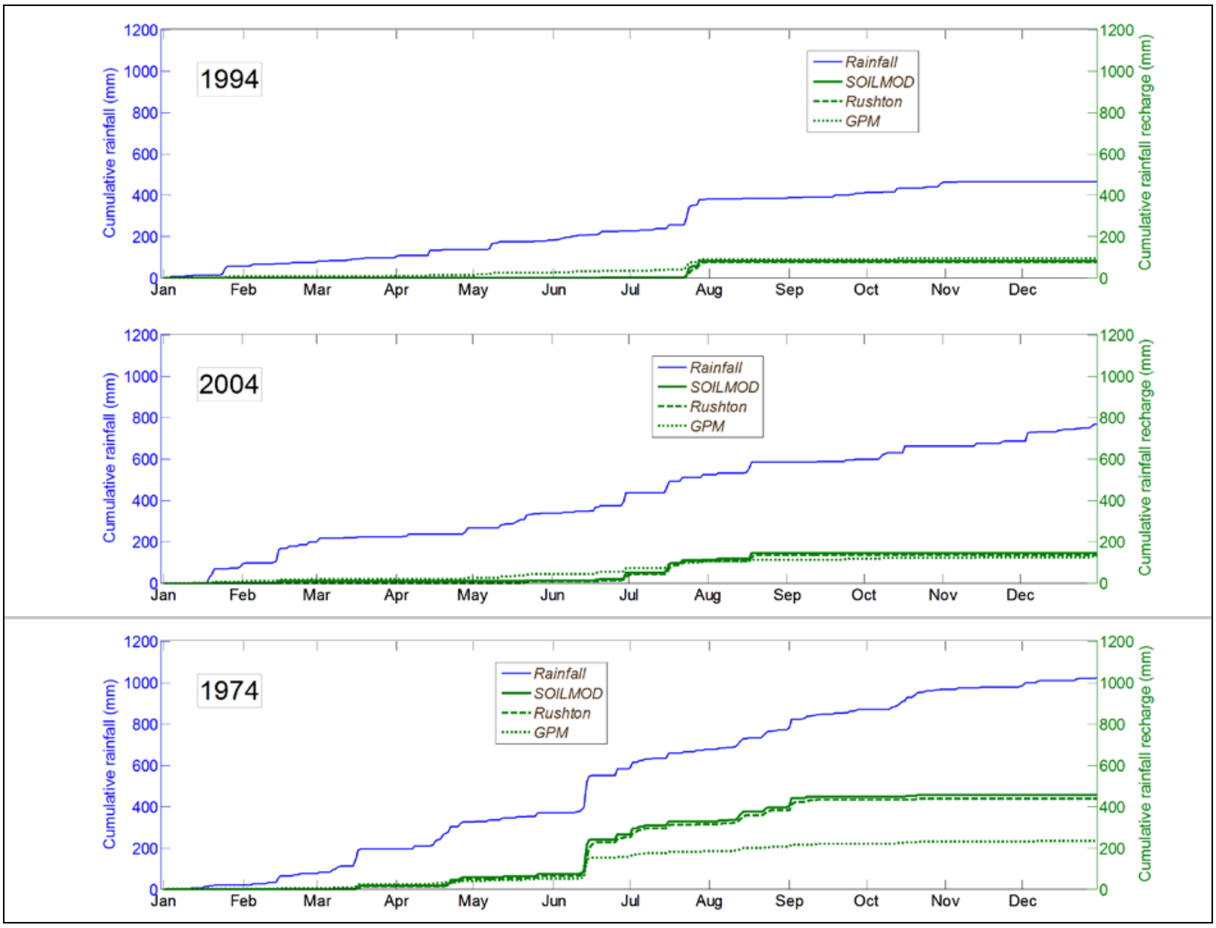

Figure 4.15 Time series of cumulative rainfall (blue) and rainfall recharge (green) using the three models in zone 1 during a dry (1994), average (2004) and wet (1974) year.

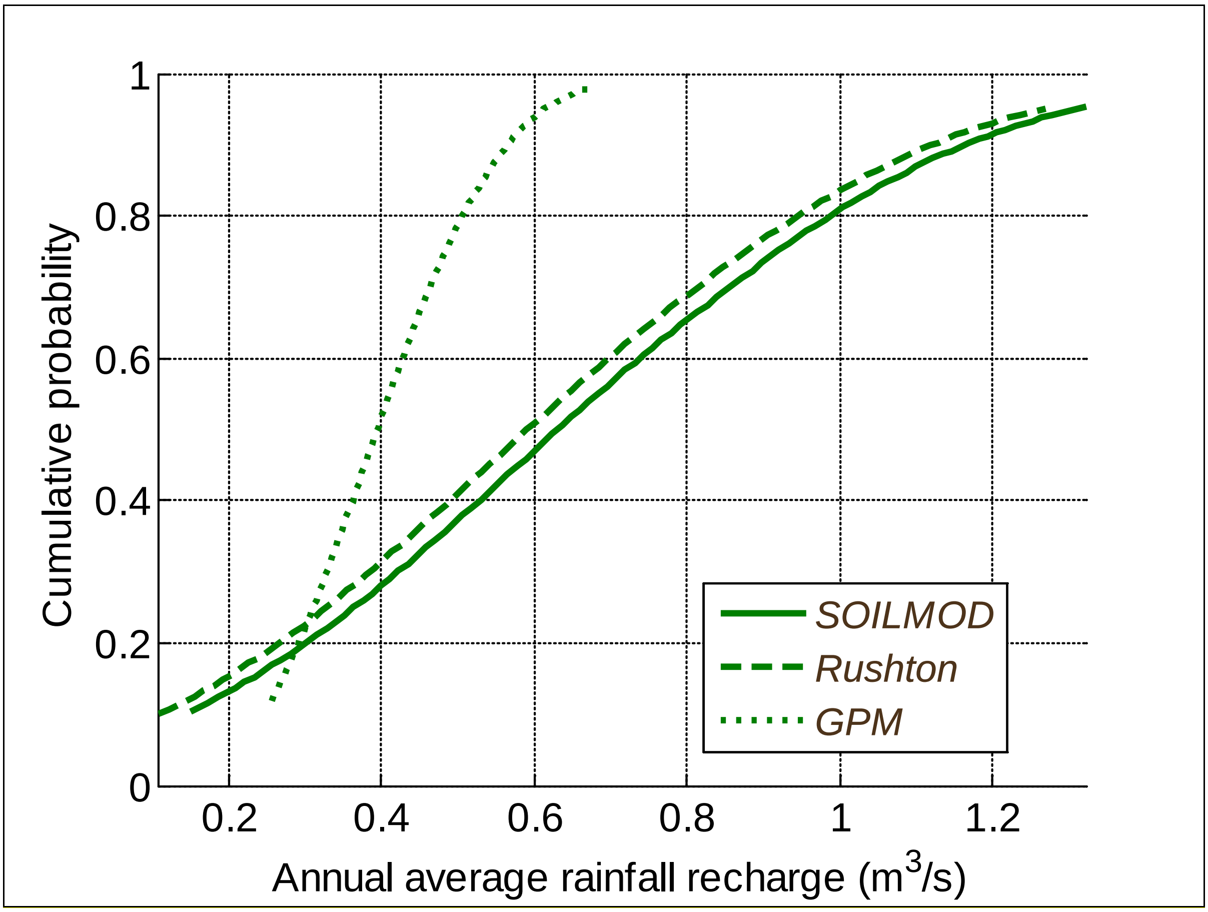

Figure 4.16 Cumulative probability curve of annual rainfall recharge in zone 1 estimated by the three recharge models for the period 1972 to 2006.

4.5.1 Ground-level rainfall correction

Estimates of rainfall recharge are influenced by the ground-level rainfall correction (Section 3.5.5), and are presented in Table 4.7. In this table, the ground-level rainfall correction is a factor applied to VCNS rainfall, i.e., a factor of 1.1 means that ground-level rainfall is 10% greater than VCNS rainfall (Table 4.7). Average rainfall recharge calculated with SOILMOD in zone 1 is 0.5 m^3/s and 0.8 m^3/s with factors of 0.9 and 1.1, respectively. These estimates demonstrate the disproportional impact of the ground-level rainfall recharge factor on rainfall recharge estimates. For example, a 10% increase in ground-level rainfall results in an approximate 30% increase in rainfall recharge. Therefore, careful application of correction factors is appropriate (Section 5.0).

Table 4.7 Ground-level rainfall correction and average rainfall recharge calculated by SOILMOD in zone 1, 1972 to 2006.

Ground-level rainfall correction factor	Average rainfall recharge, zone 1 (m^3/s)
0.90	0.5
0.95	0.6
1.00	0.6
1.05	0.7
1.10	0.8

5.0 DISCUSSION

Three rainfall recharge models estimate average rainfall recharge in the Heretaunga Plains area between 1972 and 2006, in the range of 1.6 to 2.7 m^3/s (Tables 4.3, 4.4 and 4.5). This range is not large, indicating that the model calculations of rainfall recharge are similar over the 35-year period of simulation. Model calculations are generally similar in low and average rainfall conditions (Figure 4.15). However, the GPM calculates considerably lower rainfall recharge, relative to the other models, in wet years (e.g., 1974, Figure 4.15). This may be due to the development of the GPM at sites where annual rainfall was typically less than approximately 900 mm/yr. Therefore the GPM may not be suitable where annual rainfall is greater than about 900 mm/yr, i.e., in 7 of the 35 years between 1972 and 2006 (Figure 4.3)

The model comparison in this report is useful in estimating rainfall recharge for management purposes. For example, conservative estimates of rainfall recharge given by the GPM, and making no ground-level rainfall correction, may be suitable for setting groundwater allocation targets. In the future, other models of rainfall recharge could be tested in the Heretaunga Plains rainfall recharge area (Section 6.0).

Rainfall recharge and runoff estimates in this report have significant implications for the water budget of the Heretaunga Plains model area, suggesting that a new water budget should be developed before the budget can be used for water management purposes. The current water budget of the Heretaunga Plains by Dravid and Brown (1997; Table 2.1) includes a rainfall recharge estimate of 5 million m^3/yr, or approximately 0.16 m^3/s, from the unconfined zone. Estimates of average rainfall recharge on the unconfined zone (approximating zone 1, Figure 3.6) in this report, are between 0.4 – 0.6 m^3/s, and therefore considerably larger than that of Dravid and Brown (1997). Furthermore, in this report, rainfall recharge over the wider area of the Heretaunga Plains and Ahuriri is calculated. These estimates are important to include in a water budget because: rainfall recharge outside the unconfined zone probably contributes to base flow in streams; rainfall recharge probably contributes to groundwater that is pumped from shallow dewatering wells in the lower reaches of the Heretaunga Plains (Dravid and Brown, 1997); and rainfall recharge is probably the sole source of groundwater in the Ahuriri Estuary catchment.

The SOILMOD and Rushton models produce similar estimates of rainfall recharge across the range of Heretaunga Plains rainfall rates (e,g., Figure 4.15 and Figure 4.16). Therefore, the balance of rainfall and rainfall recharge is similar in the two models. Generally, the estimates of runoff rates provided by the Rushton model, using the runoff calculation of Rawls (1992), are low. Therefore, the AET estimates provided by SOILMOD are similar to the estimates of Rushton.

Runoff is an important component of the water budget (Equation 6). For example, runoff is significant in the lower reaches of the Heretaunga Plains where it may contribute 80% of the flow from shallow dewatering stations close to the coast (Dravid and Brown, 1997). However, runoff is only estimated with the Rushton model, with the runoff calculation of Rawls (1992). SOILMOD aims to represent rainfall recharge from flat land and assumes runoff is zero, whereas runoff is “embedded” in the GPM calculation but not calculated discretely. Therefore, runoff should be identified in a basin-wide water budget. The proposed extension of the rainfall recharge modelling project summarised in Section 6.0, includes calculation of runoff as part the NIWA’s Waterscape research programme.

Modelled rainfall recharge is highly variable, e.g., modelled annual rainfall recharge ranged from approximately 100 – 500 mm/yr at Bridge Pa (Figure 4.5) and rainfall recharge may be 0 mm through heavy soils in dry years (e.g., the Plant and Food site, Figure 4.13). Rainfall recharge is also highly seasonal with 0 mm rainfall recharge typical of the summer months (e.g., Bridge Pa, Figure 4.8) and the period October to May below heavy soils (Figure 4.10). In contrast, recharge from rivers is likely to be reasonably constant (White and Brown, 1995; White et al., 2012). Therefore, seasonal variability of groundwater levels in the Heretaunga Plains is most likely controlled by the variability of rainfall recharge and estimates of zonal rainfall recharge. Therefore, the timing of this recharge is important for management purposes.

Currently, little rainfall recharge monitoring data is available from the lysimeter network (Figure 3.4) to test rainfall recharge model predictions. These datasets are crucial to assess the quality of these models. Therefore, monitoring of these sites should continue for at least five years to build a suitable data set of rainfall recharge and ground-level rainfall observations.

6.0 RECOMMENDATIONS

The rainfall recharge modelling described in this report was undertaken as part of NIWA's Waterscape programme, with assistance from Hawke's Bay Regional Council (HBRC). The following recommendations suggest further actions that could be completed to support information requirements of the Greater Heretaunga/Ahuriri Catchment Area plan change process. Suggested actions are relevant to the Waterscape research programme and to HBRC (e.g., application, monitoring and policy).

Three models of rainfall recharge could be applied to the assessment of rainfall recharge, in addition to the models tested in this report. These models include:

- GPM, to be developed with Canterbury rainfall recharge data recorded between 1999 and 2011 (White et al., 2013);
- the Bayesian model (Hong and White, 2013) when it is further developed for basin-wide applications; and
- SPASMO, which has been applied at the Plant and Food site and apple orchards in Heretaunga Plains (Green, 2013).

An assessment of runoff in the Heretaunga Plains model area is relevant to the modelling of groundwater recharge and to estimates of water budgets for the area. This is best done in the context of full-catchment water budgets in the Greater Heretaunga/Ahuriri Catchment Area area (Figure 1.1). Full-catchment water budgets are best developed with NIWA's TOPNET model. Current strengths of TOPNET include linkages to the VCSN data set, representation of flows in sloping catchments and a developing ability for real-time flow prediction. However, this model has not been designed to represent groundwater recharge and flow.

Therefore, it is recommended that NIWA's TOPNET model is extended to include groundwater recharge and groundwater flow. This will require development of the system to represent: 1) groundwater recharge from rainfall (e.g., with one of the models described in this report) and from rivers; and 2) water budgets aggregated by recharge zone (e.g., Figure 3.6) and time interval (e.g., annual, seasonal, daily). This work has been proposed for the next phase of the Waterscape research programme (McMillan, 2013).

An assessment of the uncertainty of inputs to the rainfall recharge models (e.g., rainfall, PET and PAW) and to the TOPNET model would also be useful to quantify the uncertainty in model outputs. This assessment could follow from the current work in the Waterscape research programme.

In May 2013, one of the authors of this report (Westerhoff) commenced a PhD research programme on the use of satellite remote sensing data for regional-scale groundwater assessments. This research is part of the MBIE-funded Smart Aquifer Characterisation (SAC) project led by GNS Science. The SAC project aims to use satellite remote sensing data to calculate precipitation, evaporation and soil moisture, with the intention to fill information gaps. The study will consider several test case areas, and it is recommended that the Greater Heretaunga/Ahuriri Catchment Area is included in the PhD programme. This work will bring extra analysis to the estimation of rainfall recharge in the region.

Rainfall recharge monitoring in the Heretaunga Plains (Figure 3.4) by HBRC should continue. Currently, the record of rainfall recharge at these sites is too short to be of use in model calibration. However, the value of the record will grow over time and rainfall recharge measurements will be useful to calibrate various models once at least two additional years of monitoring exist. These measurements will also be invaluable should HBRC chose to adopt seasonally-adjustable groundwater allocation in the Heretaunga Plains.

The estimates of annual rainfall recharge in this report (Tables 4.3, 4.4 and 4.5) were all significantly larger than the published estimate of rainfall recharge to the Heretaunga Plains (approximately 0.16 m^3/s; Dravid and Brown, 1997). This result is particulary relevant to HBRC policy development as part of the Greater Heretaunga/Ahuriri Catchment Area plan change process. Therefore, it is recommended that HBRC interact with researchers in the consideration of Greater Heretaunga/Ahuriri Catchment Area policy options, including allocation of groundwater and integrated allocation of surface water and groundwater.

7.0 CONCLUSIONS

Hawke's Bay Regional Council (HBRC) is currently reviewing water resources in the Heretaunga Plains in the Greater Heretaunga/Ahuriri Catchment Area plan change process. As part of the National Institute of Water and Atmospheric Research (NIWA) Waterscape research programme, GNS Science has completed an assessment of rainfall recharge to groundwater in the Heretaunga Plains and the Ahuriri Estuary catchment.

Three rainfall recharge models (SOILMOD, Rushton and the genetic program) were applied to assess rainfall recharge on a daily basis between 1972 and 2006 using estimated model inputs of daily rainfall and potential evapotranspiration from NIWA's Virtual Climate Station Network (VCSN) and soil profile available water from Landcare Research's soils database.

Daily rainfall recharge was estimated in five zones: zone 1 (largely the unconfined area of the Heretaunga Plains); zone 2 (the area of confined Heretaunga Plains aquifer located generally south of the Ngaruroro River, including Hastings City); zone 3 (the area of confined Heretaunga Plains aquifer located generally north of the Ngaruroro River, including parts of Napier City); zone 4 (the Ahuriri area, including Bay View) and zone 5 (the area south of the Tukituki River near the coast, including the coastal strip).

Average rainfall recharge in all zones was 2.7 m^3/s (SOILMOD), 2.2 m^3/s (Rushton) and 1.6 m^3/s (genetic program) between 1972 and 2006. Rainfall recharge estimates by the SOILMOD and Rushton models are similar, apart from zone 2 where significant runoff was calculated by the Rushton model. Modelled rainfall recharge is highly variable, e.g., modelled rainfall recharge ranged from approximately 100 – 500 mm/yr at Bridge Pa in the unconfined zone, and rainfall recharge through heavy soils may be 0 mm in dry years (e.g., the Plant and Food site). Rainfall recharge is also highly seasonal with 0 mm rainfall recharge typical of the summer months.

This report recommends that full-catchment water budgets are developed with NIWA's TOPNET model including estimation of runoff from the Heretaunga Plains. To do this, it is recommended that the TOPNET model is extended to include groundwater recharge and groundwater flow.

The estimates of annual rainfall recharge in this report were all significantly larger than the published estimate of rainfall recharge to the Heretaunga Plains (Dravid and Brown, 1997). Therefore, this report recommends that HBRC interact with researchers in the consideration of Greater Heretaunga/Ahuriri Catchment Area policy options, including allocation of groundwater and integrated allocation of surface water and groundwater. It is also recommended that HBRC continues to monitor rainfall recharge and ground-level rainfall at three sites (Bridge Pa, Fernhill and Maraekakaho) located in the unconfined zone of the Heretaunga Plains.

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APPENDICES

APPENDIX 1: ESTIMATES OF ANNUAL TOTAL RAINFALL, PET, AET AND RAINFALL RECHARGE WITH SOILMOD AT REPRESENTATIVE SITES.

Table A 1.1 Bridge Pa location: annual rainfall, PET, AET and rainfall recharge.

Year	Rain (mm)	PET (mm)	AET (mm)	RR (mm)
1972	603.7	991.3	463.9	185.6
1973	738.5	949.7	469.1	261.8
1974	997.7	900.3	497.8	502.5
1975	855.6	943.7	505.9	311.5
1976	893.6	883.3	584.6	346.8
1977	873.1	909.3	473.9	399
1978	596	903.5	372.1	233.4
1979	896.2	889.6	398.9	454.2
1980	971.7	865.1	536	448.4
1981	861.3	858	495	390.3
1982	510	914.6	357.7	156.9
1983	576.4	905.3	420.4	162.7
1984	635	898.2	497.8	124.2
1985	823.8	923.9	426	400.8
1986	559.2	908.9	446	125.7
1987	742.3	926	467.8	275.4
1988	670.7	952.6	391	244.8
1989	727.1	875	436.6	322.1
1990	721.8	903.3	367.6	357.6
1991	852.7	858.4	466.9	348.7
1992	977	866.8	605.2	398.8
1993	649.2	871	489	153.5
1994	457.4	1052	359.5	118.1
1995	764.8	990.1	468.1	295.1
1996	895	992.4	501.9	358.5
1997	875.7	1034.3	528.1	387.3
1998	487.8	1134.8	319.9	168.5
1999	890.4	1018.2	528.8	363.2
2000	611.9	1019.6	425.6	185.1
2001	718.2	958.2	576.2	143.6
2002	779	1074.7	483.3	297.9
2003	867.1	1001.4	512.3	319.3
2004	747.4	995.2	560.4	211.4
2005	882.7	917	465.6	431.1
2006	932	1032.4	461	464

Table A 1.2 Plant and Food Research location: annual rainfall, PET, AET and rainfall recharge.

Year	Rain (mm)	PET (mm)	AET (mm)	RR (mm)
1972	581	980	762	8
1973	752	931	591	115
1974	979	869	636	373
1975	779	916	625	55
1976	955	867	830	166
1977	931	881	642	337
1978	568	863	509	83
1979	950	847	534	382
1980	938	834	616	205
1981	884	840	677	338
1982	520	884	481	73
1983	564	881	508	8
1984	603	869	611	16
1985	857	903	580	284
1986	556	885	561	11
1987	718	883	570	132
1988	817	889	585	223
1989	758	814	534	206
1990	826	868	538	329
1991	928	788	587	270
1992	965	819	655	259
1993	676	862	734	41
1994	438	1032	483	0
1995	749	969	564	165
1996	889	974	635	182
1997	948	988	750	288
1998	439	1091	408	30
1999	835	986	733	81
2000	611	967	577	51
2001	732	907	629	0
2002	727	1025	766	67
2003	782	950	567	170
2004	754	920	680	92
2005	822	839	588	231
2006	888	982	601	300

Table A 1.3 Hawke's Bay Airport location: annual rainfall, PET, AET and rainfall recharge.

Year	Rain (mm)	PET (mm)	AET (mm)	RR (mm)
1972	677	1039	609	157
1973	795	998	562	218
1974	1121	949	591	536
1975	925	1011	660	186
1976	927	936	739	237
1977	1007	999	636	396
1978	739	1004	523	233
1979	952	1018	531	388
1980	1009	964	618	352
1981	823	936	617	267
1982	610	1020	458	166
1983	544	995	483	63
1984	655	1011	591	48
1985	854	1016	513	351
1986	599	997	509	100
1987	737	1039	517	219
1988	859	1112	590	235
1989	880	1021	548	358
1990	815	1010	491	334
1991	784	1043	570	192
1992	1039	955	702	321
1993	727	948	614	120
1994	483	1114	439	82
1995	798	1021	565	227
1996	881	1024	605	212
1997	1023	1075	686	409
1998	514	1152	375	138
1999	897	1023	653	239
2000	677	1027	499	180
2001	856	988	695	132
2002	795	1124	628	199
2003	834	1056	553	228
2004	809	1112	681	176
2005	1006	1044	592	421
2006	918	1151	557	352

APPENDIX 2: ANNUAL RAINFALL EXPRESSED AS AVERAGE VOLUMETRIC FLOW RATE BY ZONE.

Table A 2.1 Yearly average volumetric flow rate of rainfall in each zone and the total for all zones.

Year	Rainfall (m^3/s)					
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	All zones
1972	1.8	3.2	1.4	1	0.3	7.7
1973	2.1	4.1	1.7	1.2	0.4	9.5
1974	3	5.4	2.4	1.7	0.5	13
1975	2.6	4.5	2	1.4	0.4	10.9
1976	2.6	5	2.1	1.4	0.5	11.6
1977	2.5	4.9	2.2	1.5	0.5	11.6
1978	1.9	3.2	1.5	1.1	0.3	8
1979	2.7	5	2.2	1.4	0.5	11.8
1980	2.9	5.2	2.2	1.6	0.5	12.4
1981	2.6	4.7	1.9	1.2	0.4	10.8
1982	1.5	2.8	1.3	0.9	0.3	6.8
1983	1.7	3	1.2	0.8	0.3	7
1984	1.9	3.3	1.4	1	0.3	7.9
1985	2.5	4.5	1.9	1.3	0.4	10.6
1986	1.7	3	1.3	0.9	0.3	7.2
1987	2.2	3.9	1.6	1.1	0.3	9.1
1988	1.9	4.1	1.8	1.4	0.4	9.6
1989	2.1	4.1	1.8	1.3	0.4	9.7
1990	2	4.2	1.8	1.2	0.4	9.6
1991	2.5	4.8	1.9	1.2	0.4	10.8
1992	2.8	5.3	2.3	1.5	0.5	12.4
1993	1.8	3.6	1.6	1.1	0.3	8.4
1994	1.4	2.5	1.1	0.7	0.2	5.9
1995	2.3	4.1	1.8	1.2	0.4	9.8
1996	2.5	4.9	2.1	1.4	0.5	11.4
1997	2.4	5.1	2.3	1.5	0.5	11.8
1998	1.4	2.5	1.1	0.8	0.2	6
1999	2.6	4.7	2	1.3	0.4	11
2000	1.8	3.4	1.5	1	0.3	8
2001	2.1	4	1.8	1.3	0.4	9.6
2002	2.3	4.1	1.8	1.1	0.4	9.7
2003	2.6	4.5	1.9	1.3	0.4	10.7
2004	2.2	4.1	1.7	1.2	0.4	9.6
2005	2.5	4.7	2.1	1.6	0.4	11.3
2006	2.7	5	2.1	1.4	0.4	11.6

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