3 RAINFALL AND RECHARGE – Matt Gibbs

3.1 SUMMARY

The strength of the economy, environment and community of the South East of South Australia is linked to its water resources, with groundwater being the main source of water (Paydar et al. 2009). Recharge to the groundwater system is therefore a fundamental component of the water balance for resource allocation in the South East (Brown et al. 2006). The aim of this study is to investigate the relationship between rainfall and recharge, as well as the relationship between rainfall and the groundwater level, for this region.

The Water Table Fluctuation method has been used to estimate the annual recharge rate at 41 wells in the South East of the state. Across the wells, the maximum depth to watertable is approximately 10 m, but typically in the 2 – 5 m range. By also considering the annual rainfall each year, the relationship between rainfall and recharge has been investigated. While the annual recharge rates fluctuate considerably, statistically significant relationships between annual rainfall and recharge were found at 25 of the wells. This increased to 31 wells when winter rainfall (falling between April and September) was used as the rainfall variable. By considering how the rainfall – recharge relationships varied over the study area, the management areas of Short, Kennion and Riddoch were identified as a high recharge zone for the region.

Of particular interest to this study is the recent decline in the watertable near the management areas of Coles and Short. This decline has coincided with a land use change (plantation forestry) in the area, as well as lower than average rainfall for a number of years. Since the introduction of forestry around the year 2000, there was no discernible change in the relationship between rainfall and recharge at groundwater observation wells associated with the land use change up to 2006. However, over the period 2007-2009, the observed recharge has been below that expected based on the long-term relationship with winter rainfall. On average, the observed recharge rate was 60% below that expected. This reduction in recharge was not observed at wells 10 – 20 km away associated with a pasture land use. However, due to the high variation in the observed recharge rates over the whole record, the reduction in the observed recharge at forestry wells is not statistically significant.

All changes in the groundwater level, not just increases determined to be recharge, have also been considered as part of this study. Historically, there is a strong relationship between winter rainfall and the depth to the groundwater table. Hence, annual winter rainfall and the depth to the groundwater table the previous year have been used to forecast the depth to the groundwater table the following year. For the four observation wells considered associated with the pasture land use, the relationships developed predicted the groundwater level within 95% confidence bounds over a 30 year period. For the four observation wells considered associated with the forestry land use, the relationships developed were also found to predict the observed groundwater level within 95% confidence bounds up to the year 2004. After this time, the observed groundwater level significantly declines from that predicted based on rainfall.

As the relationships developed produced accurate results for the pasture sites, as well as the forestry sites up to the year 2004, it is very unlikely (less than 0.1% chance) that the recent decline in the watertable observed at the wells associated with the forestry land use can be attributed to reduced rainfall alone. Also, for four pasture wells, on average the watertable has been stable (an increase of 0.03 m/yr over the period 2004-2009), where for the four forestry wells the watertable has declined by an average of 0.54 m/yr over the same period. As the wells considered in this component of the study are all in a similar geographic location, the most likely cause for the decline in the watertable observed only at the wells associated with forestry is this different land use.

Finally, the probability of the watertable rebounding from an initial deficit has been estimated for different scenarios. The scenarios considered include different recharge rates, extraction rates based on land use (irrigated pasture, unimproved pasture and two forestry cases), and rainfall scenarios (historic and a drier climate). Monte Carlo Simulation has been used to determine the rebound probabilities for different initial deficits and different periods of recovery. For most cases considered, rebound of the watertable is unlikely, as the rate of extraction is greater than the rate of recharge. The only scenario that was found to have a high probability of rebound of the watertable was for unimproved pasture with a high recharge rate. However, groundwater processes other than recharge that would be expected to increase the groundwater table have not been considered in this analysis, most notably lateral flow. Therefore, further groundwater numerical modelling is recommended to include these processes.

Based on the results presented in this report, further groundwater modelling is also recommended to assess two key potential implications:

1. What is the impact of the reduction in water level, and the likely reduction in recharge, in the aquifer recharge zone on lateral regional groundwater flows and winter surface flows?
2. What is the expected cone of depression associated with the drawdown observed at forestry sites, and does it extend to negatively impact on nearby agriculture and groundwater dependent ecosystems?

3.2 INTRODUCTION

The South East of South Australia has some of the most productive land in the state, with 3/4 of the state's forests and 1/3 of its improved pastures (Paydar et al. 2009). The economy, environment and community are linked to its water resources with groundwater being the main source of water (Paydar et al. 2009). Recharge to the groundwater system is therefore a fundamental component of the water balance for resource allocation in the South East (Brown et al. 2006). A detailed description of the region, including the topography and landscape, soils and geology, groundwater, confined and unconfined aquifers, drainage, and irrigation in the region is provided by Paydar et al. (2009).

Brown et al. (2006) estimated the mean annual recharge rates to almost all (total of 73) groundwater management zones in the Lower South East, Padthaway and Tatiara. However, the annual recharge rate would be expected to be dependent on the rainfall that fell over the year. In general, if a dry year is experienced there is likely to be little to no recharge, and, conversely in wet years there will be much more recharge to the watertable. In order to incorporate fluctuations in the rainfall climate on recharge to groundwater it is desirable to quantify the relationship between rainfall and recharge. This study will extend the results of Brown et al. (2006) to estimate recharge at a number of wells on an annual basis, to allow the recharge rates to be considered along with the corresponding annual rainfall. The relationships will not only allow the relationship between rainfall and recharge to be quantified, but also demonstrate how the relationship varies across the study region of the South East.

Groundwater observation wells have indicated that the watertable is declining at a number of locations in the South East, especially over the past 10 years. Of particular interest, the management areas of Coles and Short have demonstrated this declining trend. A number of years over this period have experienced below average rainfall, which is a potential driver for the decrease in the watertable, given the link between rainfall and recharge. The decline in the watertable also corresponds with a significant land use change in the region, with plantation forestry becoming established. It is difficult to conclude the likely cause of the declining watertable considering watertable observations alone. However, by investigating the historical trend between rainfall and recharge, it may be possible to determine if the recent groundwater observations can be attributed to rainfall alone, and if not it is likely that the land use change is a contributing factor. Along with the regional variation in recharge rates, this study will consider change in the long-term trend in the management areas of Coles and Short.

Given the decline in the watertable observed at a number of locations, it is also of interest to investigate the likelihood of the watertable returning to long-term average levels. As part of the South East Science Review, Thyer (2009) investigated the historic trend of rainfall at Penola, to produce probability distribution of annual rainfall for the region. Based on CSIRO projections, a drier climate scenario was also considered. Based on the results of Thyer (2009), and a relationship between rainfall and recharge, the probability of the groundwater table returning from a certain deficit to long-term average levels can be determined for different land use extraction.

It is difficult to tease apart the many factors affecting the observed groundwater levels in the Lower Limestone Coast region. The aim of this report is to undertake a number of analyses based on observed data to quantify the different relationships and effects of the main recent changes, namely lower than average rainfall and significant land use changes. The outcomes produced may be considered for future water allocation planning to assist in the development of appropriate policy settings.

3.3 AIM AND OBJECTIVES

The overall aim of this study is to investigate the impact of rainfall and on changes in the observed groundwater table in the Lower Limestone Coast region. By considering wells associated with different land use characteristics, it may be possible to quantify the influence of both rainfall and land use. This aim encompasses the relationship at both the regional scale, and also more specifically the Coles and Short management areas.

In order to meet these aims, the specific objectives of this study are:

1. Extend previous study by Brown et al. (2006), which estimated average annual recharge, to consider the relationship between annual rainfall and observed recharge.
2. Quantify the spatial variation in the rainfall – recharge relationship over the region of the Lower Limestone Coast.
3. Consider the rainfall – recharge relationship in the management areas of Coles and Short on recharge, to determine if there has been a significant change in the past 10 years.
4. Investigate the declining trend in the watertable in the management areas of Coles and Short, to determine if the changes can be attributed to regional impacts, such as reduced rainfall, or local impacts, such as a change in land use.
5. Quantify the probability of the groundwater table rebounding to long-term average levels, based on different land uses and the probability of annual rainfall occurring.

The following section outlines the methods used to complete these objectives.

3.4 METHODOLOGY

This study has investigated trends in historical rainfall and groundwater level records in the South East of South Australia. The data and methods used to interpret the data are outlined in this section.

3.4.1 DATA SELECTION

The groundwater observation wells used by Brown et al. (2006) to estimate recharge have been adopted for this study. A total of 41 wells have been considered, the location of which can be seen in Figure 3.1. The data is freely available on the OBSWELL website, provided by DWLBC. Across the wells, the maximum depth to watertable is approximately 10 m, but typically in the 2 – 5 m range. The Bureau of Meteorology rainfall site closest to each well has been used as the source for rainfall data. The closest gauge that has been open since 1970 and is still current has been identified. The exception to this was site 26054, which was closed in April 2005, and was replaced by site 26110. Missing data has been in-filled with the monthly average recorded at 26025 to compute annual rainfall at each site. This is a high quality rainfall station, and is expected to be reliable. The location of the rainfall stations used in this study can be seen in Figure 3.1.

Figure 3.1 Location of groundwater observation wells and rainfall stations used in the study.

3.4.2 RECHARGE ESTIMATION

Brown et al. (2006) provided a review of methods available to estimate recharge, including the residual water balance, watertable fluctuation, lysimeters and environmental tracers. The authors made use of the Water Table Fluctuation (WTF) method to estimate the average annual recharge rate for a number of management areas in the South East. Paydar et al. (2009) compared the results of Brown et al. (2006) to a 1 – Dimensional SWAGMAN-Destiny soil profile model. The study concluded that the 1D model overestimated recharge, and that the recharge estimated derived by Brown et al. (2006), using the WTF method, were likely to be more accurate.

The WTF method assumes that a rise in the watertable as measured in a piezometer or observation well is due to rainfall recharge. The measured seasonal rise in watertable elevation is then multiplied by the specific yield of the aquifer to obtain an annual recharge rate (Brown et al. 2006). It is an indirect approach for determining recharge, but is related to a physical measurement of the aquifer. The WTF method is particularly effective in areas with high winter rainfall and shallow watertables (Armstrong and Narayan 1998), and is therefore an ideal method for determining recharge rates in the South East (Brown et al. 2006). A review of recharge techniques across Australia has also concluded that the WTF method is possibly the most robust approach, particularly where long-term observation data exists (Petheram et al, 2000). On the basis of this, Brown et al. (2006) concluded that the WTF method is the most suitable method for estimating recharge at wells in the South East with a shallow watertable, given the current observation well database.

The WTF approach can be limited by the monitoring frequency. If records are not taken frequently, there is potential for missing seasonal peaks and troughs of the watertable fluctuation. However, DWLBC has adjusted the monitoring times to measure the watertable at the peaks and troughs in order to minimise the likelihood of this occurring (Brown et al. 2006). Longer durations between watertable measurements can also mask usage of the groundwater, as over a period of a number of months there may be a short period of recharge followed by a sustained period of drawdown. Hence, in areas where there is significant groundwater use over the winter months, when recharge is likely to occur, the WTF method is likely to underestimate recharge rates.

The approach requires an accurate estimate of specific yield at the observation well that is seldom available and difficult to determine. Brown et al. (2006) used a specific yield of $S_y = 0.1$ for all management areas and this value has also been adopted for the study.

This component of the study will extend the results of Brown et al. (2006) to compare the annual WTF to the observed rainfall for that year to investigate the relationship between recharge and rainfall.

3.4.3 GROUNDWATER TABLE TREND ANALYSIS

Recharge estimates provide an indication of the annual increase in watertable level. This component of the study will consider all changes in the groundwater table. The investigation will focus specifically on the Coles and Short management areas, where there have been significant land use changes in the past 10 years. By developing relationships between the groundwater level and annual rainfall at wells that both are, and are not, expected to be influenced by the land use change, it will be investigated if the recent decline in the watertable can be attributed to either local or regional effects.

3.4.4 STATISTICAL RELATIONSHIPS

An initial investigation into the relationship between rainfall and recharge, as well as rainfall and total watertable changes, indicated that there is significant variation in the data. For example, similar annual rainfall can correspond to a wide range of recharge. This variation may be due to a number of causes, most notably different antecedent conditions and unknown variations in the watertable between measurements (between one and three months at most wells).

Due to this significant variation in the data, linear regression has been used to attempt to relate the dependent to the independent variables as the data does not support more sophisticated methods. Other forms of the relationship, such as power law and hyperbolic tangent equations, were initially considered, as they also have only two parameters, but did not provide a consistent improvement over linear relationships. The method of least squares has been used to determine the regression parameters.

In order to provide an indication of the accuracy of the relationships identified, the standard coefficient of determination (R^2) has been computed. The significance of the R^2 can be determined using the t distribution for a small number of samples (generally less than 30). For large sample sizes the t distribution tends toward the standard normal distribution. The following equation has been used to compute the critical t value:

where n is the number of samples, R is the square root of the coefficient of determination. The t value can then be converted to a probability using the Students t distribution. The resulting probability can be considered the probability that the R^2 value of the fit of the linear regression equation occurred due to chance alone, hence low values for the probability indicates a statistically significant result.

Confidence intervals for the linear regression relationships have also been computed. Assuming normally distributed errors, the confidence interval (CI) can be computed based on the variance in the prediction errors as follows:

where y_i is the observed value, $y_i^{'}$ is the predicted value, and z is the critical value from the standard normal distribution. For a two sided 95% confidence interval, z = 1.96, a one-sided 95% confidence interval, z = 1.645, and for a one-sided 90% confidence interval, z = 1.208.

3.4.5 PROBABILITY OF WATERTABLE REBOUND

Given an initial deficit from the long-term average watertable level, the probability of the level returning to that long-term average is estimated. The rainfall – recharge relationships developed will be used to convert the probability of a certain annual rainfall occurring to the corresponding recharge. The recharge rate is used to represent the annual increase in the watertable, and a corresponding annual extraction from the unconfined aquifer will be assumed based on different land uses. Hence, the resulting change in the groundwater level was determined the calculating the difference between the annual increase in the watertable and the annual decrease. Again, a specific yield of S_y = 0.1 has been adopted to convert depths of recharge and extraction to changes in the observed groundwater level.

A number of assumptions must be made to allow this simplistic approach to be taken:

- The WTF method is appropriate to compute the expected recharge rate;
- The watertable is not shallow enough for evapotranspiration to contribute to the reduction in the watertable each year; and
- The net change in the watertable due to processes other than recharge and extraction (either active or natural) is zero, for example lateral inflow is equal to lateral outflow.

A number of different scenarios will be considered, including different recharge relationships, rainfall probabilities (historic and drier climate scenarios) and extraction rates based on different land uses. Hence, the results produced by this analysis are not specific to a certain region, but the different scenarios are considered to allow a range of conditions to be evaluated.

Due to the distribution of the annual rainfall probabilities, and distributions used for annual extraction rates, it is difficult to undertake the convolution required to compute the probability of the change in the watertable expected in sequential years analytically. Therefore, Monte Carlo Simulation (MCS) has been used to estimate the rebound probabilities, by tracking the annual change in watertable for ongoing periods. One million simulations have been adopted to ensure convergence of the MCS results.

3.5 RESULTS

3.5.1 REGIONAL RAINFALL RECHARGE RELATIONSHIPS

Using the WTF method, the annual recharge at each of the 41 wells has been estimated. The resulting recharge rates are provided in Appendix B. Total recharge based on one observed event totalling less than 0.02 m/yr has been ignored, and only subsequent groundwater level observations occurring within 4 months considered, as there is large uncertainty in these values.

Both annual precipitation (mm) and winter precipitation (mm), defined as the precipitation recorded between April and September when rainfall is expected to exceed evapotranspiration, have been used to predict the estimated recharge at each well (*pers. comm. DWLBC 2010*). Linear regression has been used to predict the recharge, of the form:

where R is the annual recharge rate (mm/yr), P is either the annual or winter precipitation (mm), and m and c are calibration coefficients. The results derived based on annual precipitation are presented in Table 3.1, and results based on winter precipitation are presented in Table 3.2. Along with the calibrated m and c coefficient values, number of values used to develop the relationship, the number of outliers that were removed prior to calibrating the relationship (due to long periods between recharge events), the coefficient of determination (R^2) and t distribution probability (t) are presented. All wells with an R^2 value significant at the 95% confidence level, as indicated by a t probability less than or equal to 0.05, have been highlighted in Tables 3.1 and 3.2.

The most accurate result based on the annual rainfall variable can be seen in Figure 3.2 at well MAY002 with R^2 = 0.63. The average R^2 value across all 41 wells for the annual rainfall results was found to be R^2 = 0.26. The results for well DUF002 with R^2 = 0.28 can also be seen in Figure 3.2 to indicate a typical result. While this R^2 is relatively low, the positive relationship between rainfall and recharge can be seen in Figure 3.2Figure 3.2, and the relationship is significant at the 99% confidence level (as indicated by the t probability in Table 3.1).

Similar outcomes are presented in Figure 3.3 for the results based on winter rainfall, where the best relationship was found for well RID012 with R^2 = 0.72. The average R^2 value across all winter rainfall results was R^2 = 0.37. The results for well SHT011 are presented in Figure 3.3 to represent the typical result, with R^2 = 0.40.

Overall, the results presented suggest that there is a strong dependence between rainfall and observed recharge, which would be expected. Statistically significant linear relationships between recharge and annual rainfall were identified for 25 of the 41 wells considered, and this increased to 31 wells for the relationships based on winter rainfall. Also, 36 of the 41 wells have a higher R^2 value for the relationship based on winter rainfall compared to that based on annual rainfall. It is expected that most recharge will occur over the winter months, so again this result is to be expected. Due to the more accurate results observed, winter rainfall will be considered as the rainfall input for the remainder of this study.

Table 3.1 Linear regression results for predicting estimated recharge based on annual rainfall.

Management Area	Well	Values	Outliers	m	c	R^2	t
Bool	ROB006	33	1	0.26	-26.58	0.37	0.00
Bowaka	BOW004	23	0	0.04	47.90	0.07	0.24
Bray	BRA020	24	0	0.09	48.21	0.17	0.04
Coles	CLS004	22	0	0.26	-67.10	0.24	0.02
Coles	CLS006	27	0	0.27	-26.87	0.08	0.14
Coles	CLS009	22	2	0.19	11.89	0.10	0.16
Conmurra	CNM016	21	0	0.15	2.11	0.42	0.00
Duffield	DUF002	22	0	0.07	-6.31	0.28	0.01
Duffield	DUF004	17	0	0.15	-24.65	0.18	0.09
Fox	FOX004	24	0	0.09	56.53	0.12	0.09
Grey	GRY001	26	3	0.16	37.86	0.05	0.25
Hynam West	HYN015	28	0	0.19	-10.20	0.22	0.01
Joyce	JOY007	30	1	0.28	-73.97	0.43	0.00
Kennion	KEN005	28	0	0.28	-70.05	0.43	0.00
Kennion	KEN016	23	0	0.48	-138.48	0.29	0.01
Killanoola	KLN005	23	0	0.16	44.45	0.05	0.29
Landseer	LAN019	26	0	0.15	-44.85	0.57	0.00
Lochaber	LOC008	28	0	0.38	-96.70	0.55	0.00
Marcollat	MAR020	32	0	0.07	43.05	0.06	0.19
Marcollat	MAR076	11	0	0.09	8.17	0.06	0.46
Mayurra	MAY002	28	0	0.38	-155.15	0.63	0.00
Minecrow	MNC012	23	0	0.16	6.48	0.22	0.02
Monbulla	MON016	19	0	0.05	103.56	0.00	0.80
Moyhall	ROB004	29	0	0.33	-102.39	0.58	0.00
Mt Benson	MTB009	23	0	0.08	9.85	0.17	0.05
Mt Muirhead	MTM018	25	0	0.14	22.07	0.08	0.18
Murrabinna	MRB003	23	0	0.24	-66.38	0.25	0.02
Peacock	PEC064	14	0	0.05	27.95	0.02	0.66
Peacock	PEC065	16	0	0.18	-22.11	0.26	0.05
Riddoch	RID012	25	1	0.53	-161.11	0.63	0.00
Rivoli Bay	RIV012	23	0	0.24	-77.07	0.52	0.00
Ross	ROS009	22	2	0.13	51.99	0.20	0.04
Short	SHT011	22	0	0.36	-86.40	0.15	0.07
Short	SHT012	22	0	0.27	-49.97	0.15	0.08
Short	SHT014	21	0	0.22	-20.63	0.14	0.09
Smith	SMT005	30	0	0.24	-47.81	0.43	0.00
Spence	SPE004	22	0	0.17	-18.99	0.31	0.01
Stewarts	NAR002	31	0	0.16	6.90	0.16	0.02
Symon	SYM004	29	0	0.30	-84.88	0.41	0.00
Waterhouse	WAT007	15	1	0.17	-3.55	0.40	0.01
Woolumbool	WLM010	30	0	0.01	55.24	0.00	0.89

Table 3.2 Linear regression results for predicting estimated recharge based on winter rainfall.

Management Area	Well	Values	Outliers	m	c	R^2	t
Bool	ROB006	33	1	0.36	-22.32	0.43	0.00
Bowaka	BOW004	23	0	0.04	56.02	0.04	0.35
Bray	BRA020	24	0	0.11	56.90	0.18	0.04
Coles	CLS004	22	0	0.49	-111.82	0.46	0.00
Coles	CLS006	27	0	0.35	-4.89	0.09	0.14
Coles	CLS009	22	2	0.49	-72.95	0.42	0.00
Conmurra	CNM016	21	0	0.19	11.06	0.52	0.00
Duffield	DUF002	22	0	0.09	-1.99	0.50	0.00
Duffield	DUF004	17	0	0.18	-10.91	0.42	0.00
Fox	FOX004	24	0	0.14	56.25	0.14	0.07
Grey	GRY001	26	3	0.34	-14.33	0.17	0.04
Hynam West	HYN015	28	0	0.27	-4.96	0.27	0.00
Joyce	JOY007	30	1	0.42	-82.62	0.56	0.00
Kennion	KEN005	28	0	0.41	-73.59	0.61	0.00
Kennion	KEN016	23	0	0.76	-161.11	0.45	0.00
Killanoola	KLN005	23	0	0.27	27.39	0.10	0.15
Landseer	LAN019	26	0	0.17	-26.73	0.50	0.00
Lochaber	LOC008	28	0	0.52	-80.57	0.57	0.00
Marcollat	MAR020	32	0	0.09	47.50	0.05	0.21
Marcollat	MAR076	11	0	0.10	15.28	0.14	0.26
Mayurra	MAY002	28	0	0.53	-153.47	0.72	0.00
Minecrow	MNC012	23	0	0.27	-10.84	0.40	0.00
Monbulla	MON016	19	0	0.25	27.58	0.06	0.32
Moyhall	ROB004	29	0	0.46	-94.35	0.71	0.00
Mt Benson	MTB009	23	0	0.11	9.56	0.23	0.02
Mt Muirhead	MTM018	25	0	0.16	45.47	0.06	0.24
Murrabinna	MRB003	23	0	0.34	-66.27	0.55	0.00
Peacock	PEC064	14	0	0.03	39.70	0.01	0.70
Peacock	PEC065	16	0	0.20	-1.82	0.41	0.01
Riddoch	RID012	25	1	0.64	-104.84	0.72	0.00
Rivoli Bay	RIV012	23	0	0.33	-76.77	0.60	0.00
Ross	ROS009	22	2	0.18	52.40	0.35	0.00
Short	SHT011	22	0	0.74	-170.65	0.40	0.00
Short	SHT012	22	0	0.50	-94.76	0.32	0.01
Short	SHT014	21	0	0.52	-99.67	0.44	0.00
Smith	SMT005	30	0	0.32	-32.80	0.48	0.00
Spence	SPE004	22	0	0.28	-35.14	0.60	0.00
Stewarts	NAR002	31	0	0.29	-13.11	0.34	0.00
Symon	SYM004	29	0	0.44	-86.45	0.48	0.00
Waterhouse	WAT007	15	1	0.30	-27.41	0.72	0.00
Woolumbool	WLM010	30	0	0.01	53.88	0.00	0.82

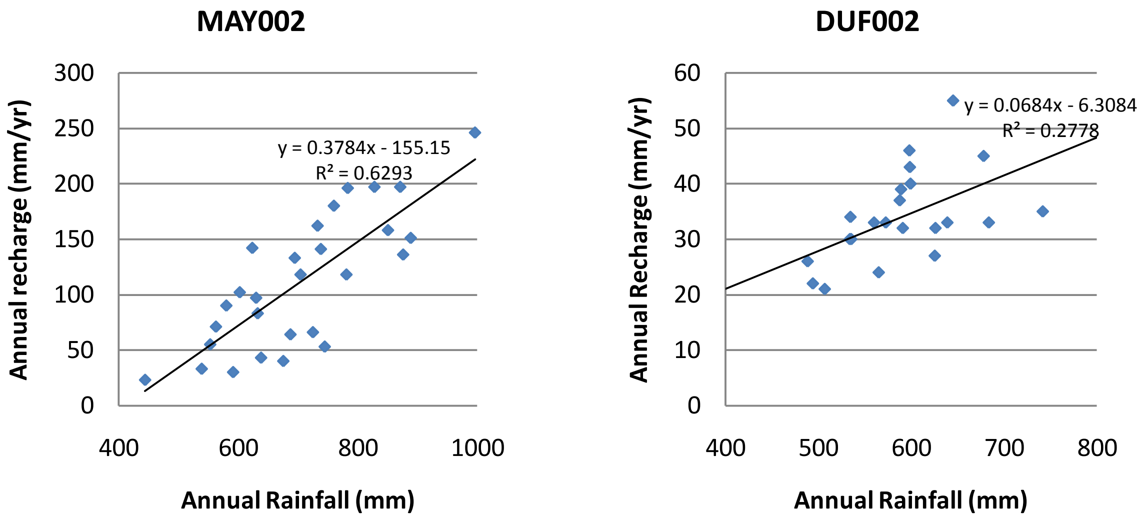

Figure 3.2 Best relationship (MAY002) and typical relationship (DUF002) found between recharge and annual rainfall.

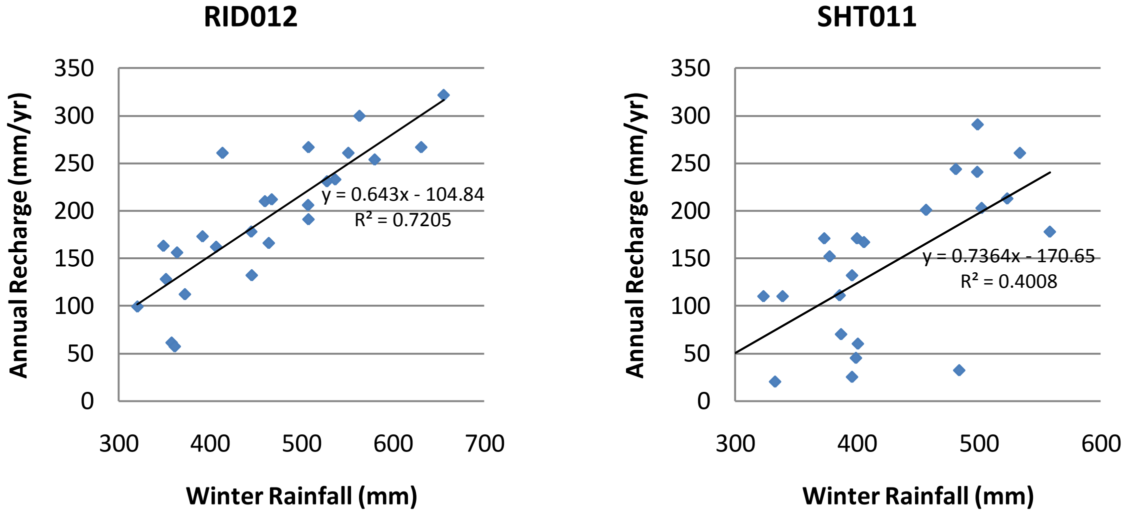

Figure 3.3 Best relationship (RID012) and typical relationship (SHT011) found between recharge and winter rainfall.

Further investigation is required to determine reasons for the lack of significant relationships at some of the wells, as there are a number of possibilities. For example, variations in the water use or antecedent conditions, infrequent water level observations, highly variable vegetation densities, non wetting soils or geological influences such as shallow calcrete layers preventing recharge to the unconfined aquifer are all possible explanations.

The distribution of the slope value (m) of the relationship between estimated recharge and winter rainfall over the study region can be seen in Figure 3.4. Spherical Kriging has been used to produce the results, based on the statistically significant relationships found in Table 3.2 (highlighted in blue). High values indicate a strong relationship between rainfall and recharge, where an increase in rainfall is expected to produce an increase in recharge, and vice versa. Conversely, low values of slope indicate that the observed recharge rate was less influenced by the winter rainfall.

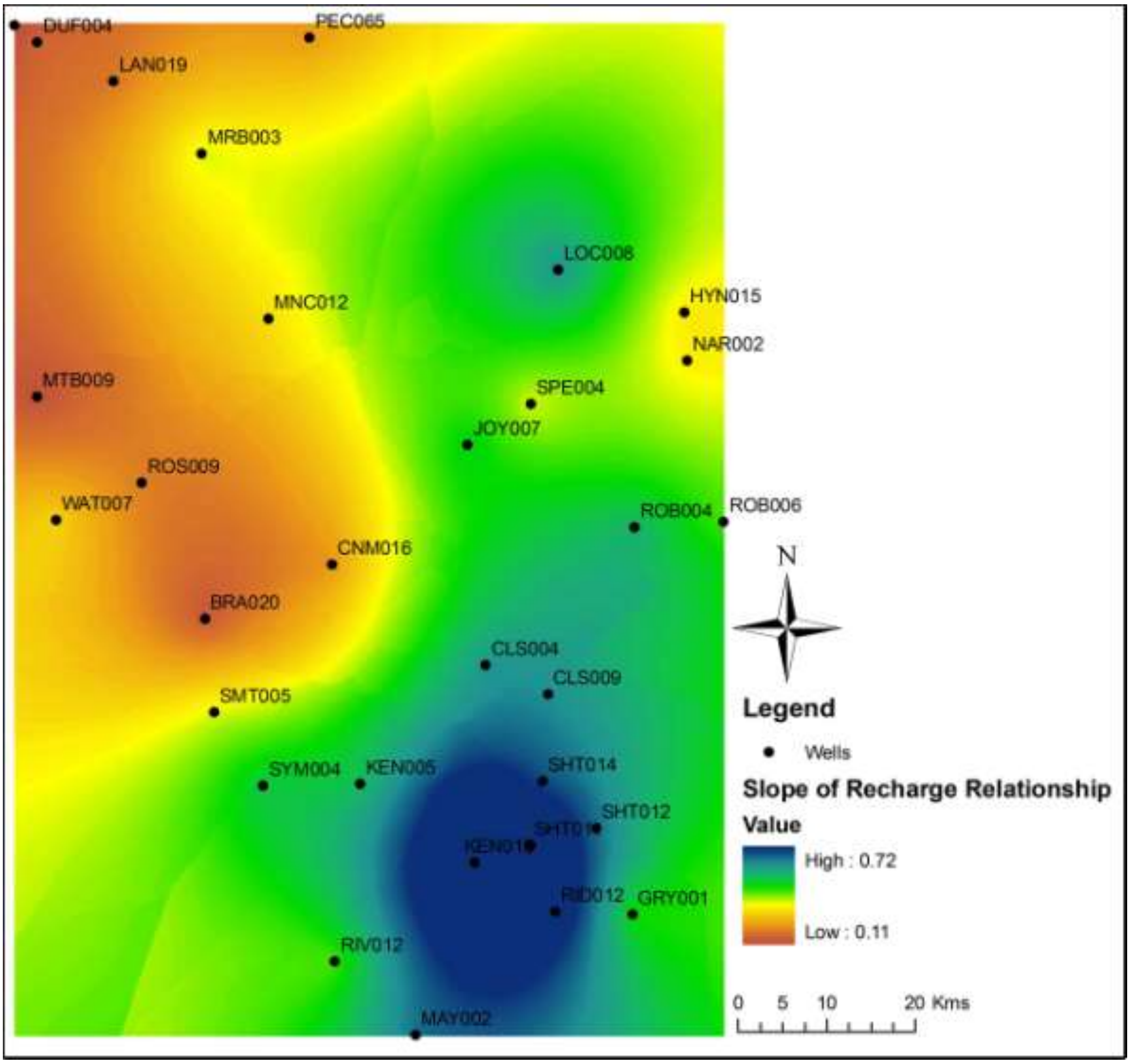

Figure 3.4 Slope of the relationship between winter rainfall and recharge. High values represent a strong relationship between the two, low values indicate recharge is less dependent on rainfall.

The results suggest that the region encompassing the management areas of Short, Kennion and Riddoch, and to a lesser extent the surrounding management areas, is a region of high rainfall dependent recharge. Most likely, this is due to the historically shallow watertable and permeable soils in the area. Conversely, at management areas near the coast to the north west of the study region, such as Duffield and Mt Benson, the recharge rate is less dependent on the winter rainfall.

3.5.2 IMPACT OF LAND USE CHANGES

The management areas of Coles and Short are of particular interest to the Lower Limestone Coast Task Force. Groundwater observation wells associated with different land uses in the region have been investigated in more detail in an attempt to determine the likely cause of the decline in the watertable in the region over the past 10 years. The hypothesis used is if a similar trend is observed at all wells regardless of land use then the decline is most likely due to a regional reduction in rainfall. Conversely, if the declining trend is observed at only wells associated with the change in land use, then it is likely the trend is caused by the increase in vegetation density at the forestry sites.

The wells considered for this component of the study can be seen in Figure 3.5. Wells marked by a green triangle, CLS004, CLS009, SHT012 and SHT014, are located near or at forested sites that have been planted since 2000. The wells marked by yellow circles, CNM016, FOX004, KEN016 and RID012, are nearby wells that are associated with a pasture land use. Firstly the recharge rates considered in Section 3.5.1 will be investigated, before the total trend in groundwater levels is investigated in Section 3.5.2.2.

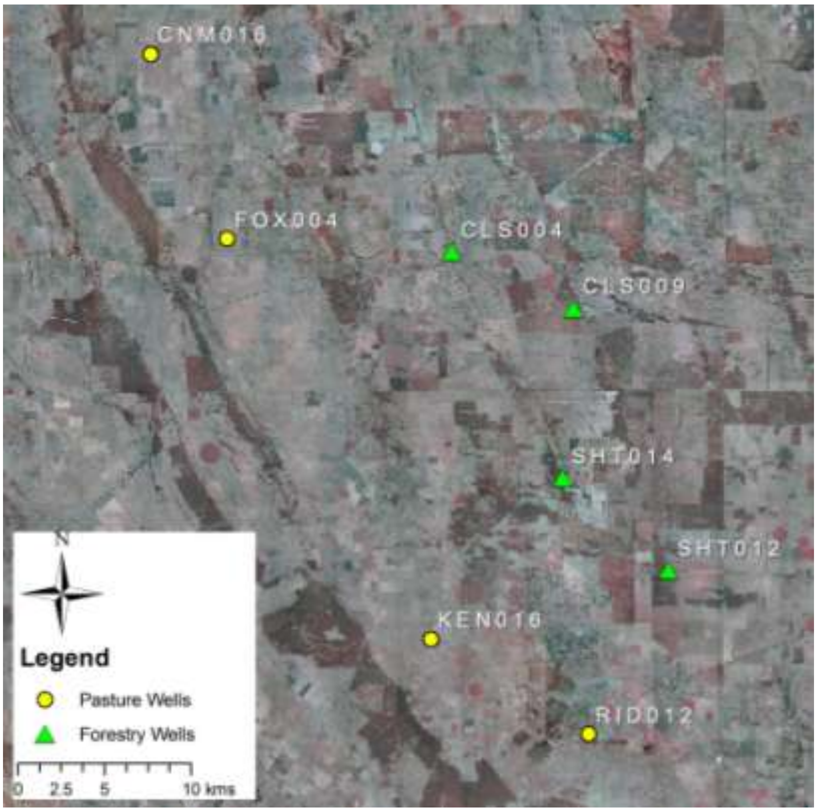

Figure 3.5 Wells considered for Coles and Short study.

3.5.2.1 Recharge Rates

Figure 3.6 presents pre (before 2000) and post (after 2000) forestry rainfall recharge relationships at the wells associated with the forestry land use. There is no evidence to suggest that the rainfall recharge relationship has change in the period since the introduction of forestry to the Coles and Short management areas in 2000 up to 2006. 2007 to 2009 recharge rates are plotted as a separate series in Figure 3.6, and the recharge rates can be seen to be much lower than the long-term trend for this period, suggesting that the rainfall recharge relationship has decreased significantly in the past three years.

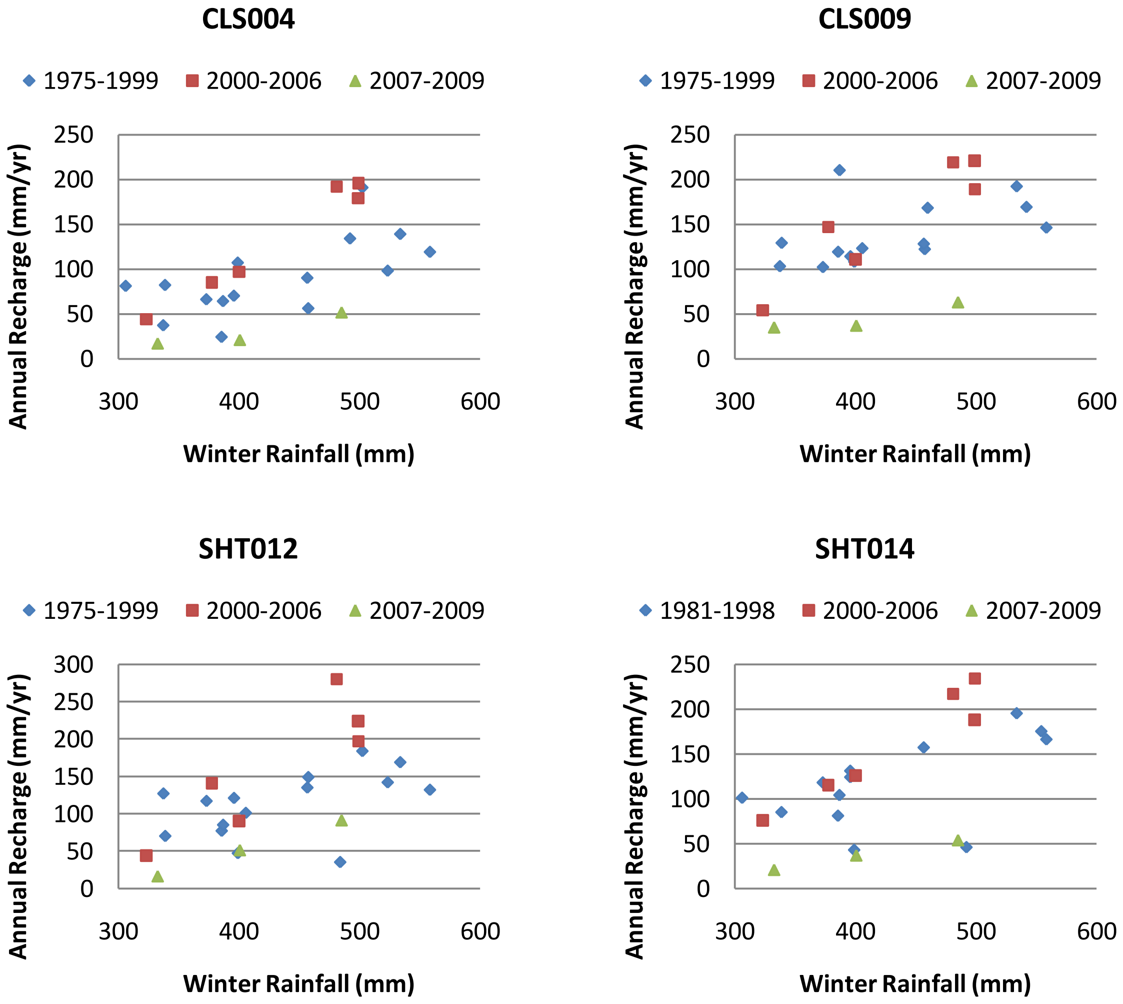

Figure 3.6 Rainfall Recharge Relationships, pre and post forestry, at relevant wells

By making use of the linear regression relationships presented in Table 3.2, the results presented in Table 3.3 indicate that the recharge rates observed in the period 2007-2009 are approximately 60% below the recharge rates predicted at each well based on the long-term linear relationship with winter rainfall. This can be compared with the results for pasture sites nearby (Table 3.4), where this consistent reduction in observed recharge is not present. While there is significant scatter in the difference between observed and simulated recharge, 9 of the 12 recharge rates are under-predicted, as opposed to over-predicted for the forested sites, with the average difference being an under-prediction of 10%.

Table 3.3 **Observed recharge rate (mm/yr) for year, compared to the simulated recharged rate for each year, based on the linear relationship with winter rainfall (mm) at well expected to be influenced by forestry.**

	Winter	CLS004			CLS009			SHT012			SHT014		
Year	Rainfall	Obs.	Sim.	%	Obs.	Sim.	%	Obs.	Sim.	%	Obs.	Sim.	%
2007	401	21	83	-75	37	122	-70	51	104	-51	37	109	-66
2008	333	17	48	-64	35	89	-61	16	66	-76	21	74	-72
2009	485	52	126	-59	63	163	-61	91	150	-39	54	153	-65

Table 3.4 **Observed recharge rate (mm/yr) for year, compared to the simulated recharged rate for each year, based on the linear relationship with winter rainfall (mm) at pasture wells.**

	Winter	CMN016			FOX004			KEN016			RID012		
Year	Rainfall	Obs.	Sim.	%	Obs.	Sim.	%	Obs.	Sim.	%	Obs.	Sim.	%
2007	401	78	72	9	107	112	-4	89	140	-36	163	120	36
2008	333	67	67	1	137	102	34	19	84	-77	156	129	21
2009	485	128	99	29	202	123	64	273	209	31	255	213	19

To quantify the uncertainty in the results presented in Tables 3.3 and 3.4, the same information has been plotted in Figure 3.7 for the pasture sites, and Figure 3.8 for the forestry sites. The dashed lines indicate one-sided confidence intervals, with the lowest dashed line representing the 95% confidence limit, or that there is a 95% chance that the recharge rate is above the dashed line. The remaining dashed lines represent 90%, 10% and 5% confidence intervals, respectively, where for the 5% confidence interval there is only a 5% chance that the recharge rate is above the top line. For the pasture sites, all but two of the predictions fall within the 10% and 90% confidence bounds. The two least accurate predictions significantly under predict the observed recharge in 2009 at wells FOX004 and CNM016.

For the forested sites, seen in Figure 3.8, the number of observations falling outside the 10 and 90% confidence limits is to six of the 12 observations. If the dry year of 2008 is ignored (as little recharge would be expected), all but two of the observed rates are below the predicted 90% confidence line, and the two that are above this interval are only slightly above. All of the observed recharge rates are below the rate predicted based on the long-term average, compared to the pasture sites where this constant reduction in the observed recharge rate is not present. This bias in the predicted recharge rates at the forested sites suggests there is a change in the rainfall recharge relationship in the past three years at these sites. However, due to the scatter in observed recharge, and subsequent wide confidence bounds, it is difficult to draw statistically significant conclusions.

There are a number of potential causes to explain the likely decrease in the recharge rate in the past three years. It could be an actual reduction in recharge, caused by canopy interception reducing the rainfall reaching the soil, and subsequently the groundwater table. Also, it is possible that the recharge rate is similar to the long-term average and is just masked by increased drawdown on the watertable between observations made monthly and quarterly. This is an inherent problem with using data recorded at this interval. Greater insight could be obtained from daily well records, where a more direct relationship between rainfall events and watertable response could be deduced. Further investigation is required to confirm the suspected reduction in recharge at the forested sites, and to deduce the cause of any reduction in observed recharge.

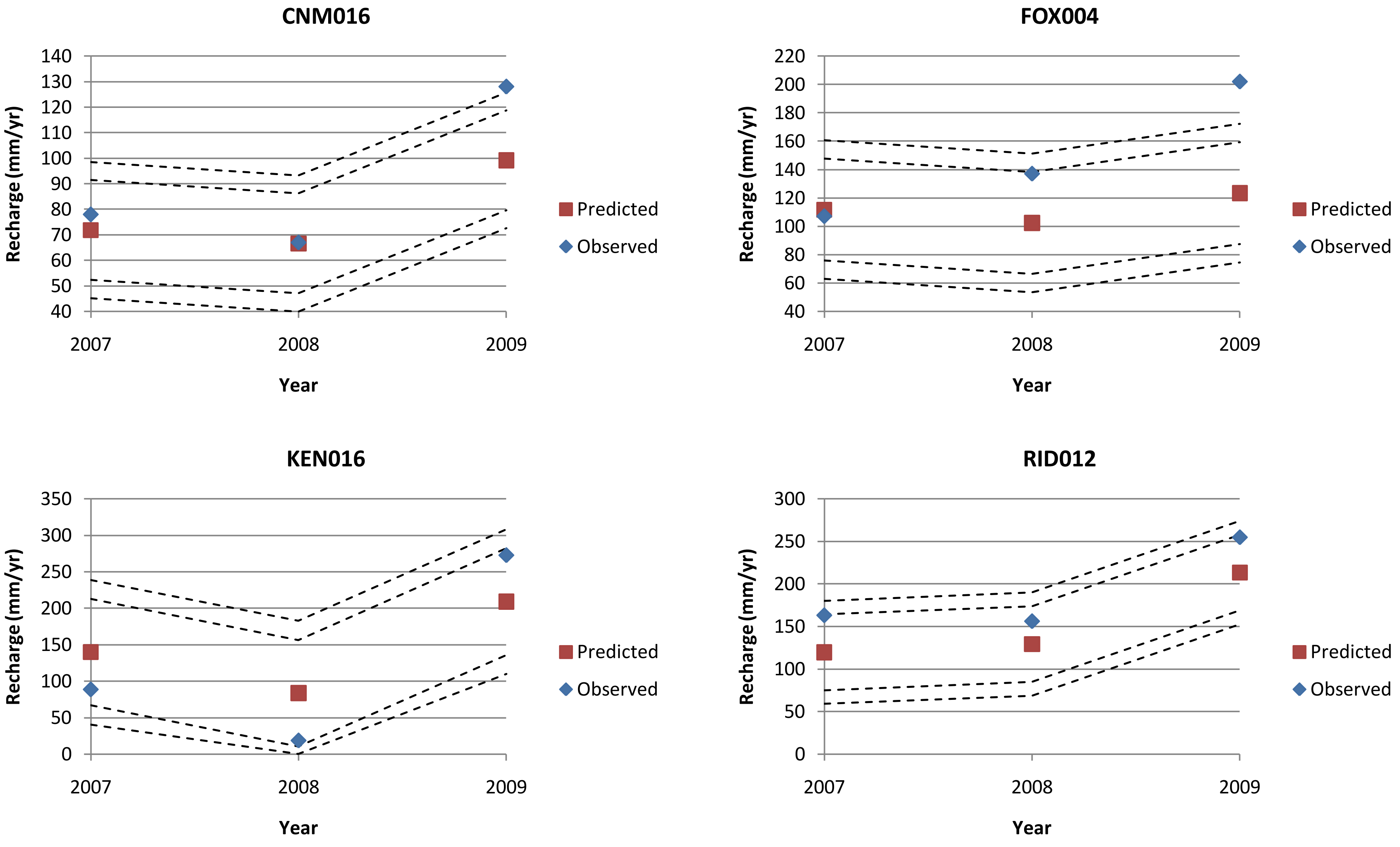

Figure 3.7 Predicted and observed recharge for 2007-2009 at pasture sites.

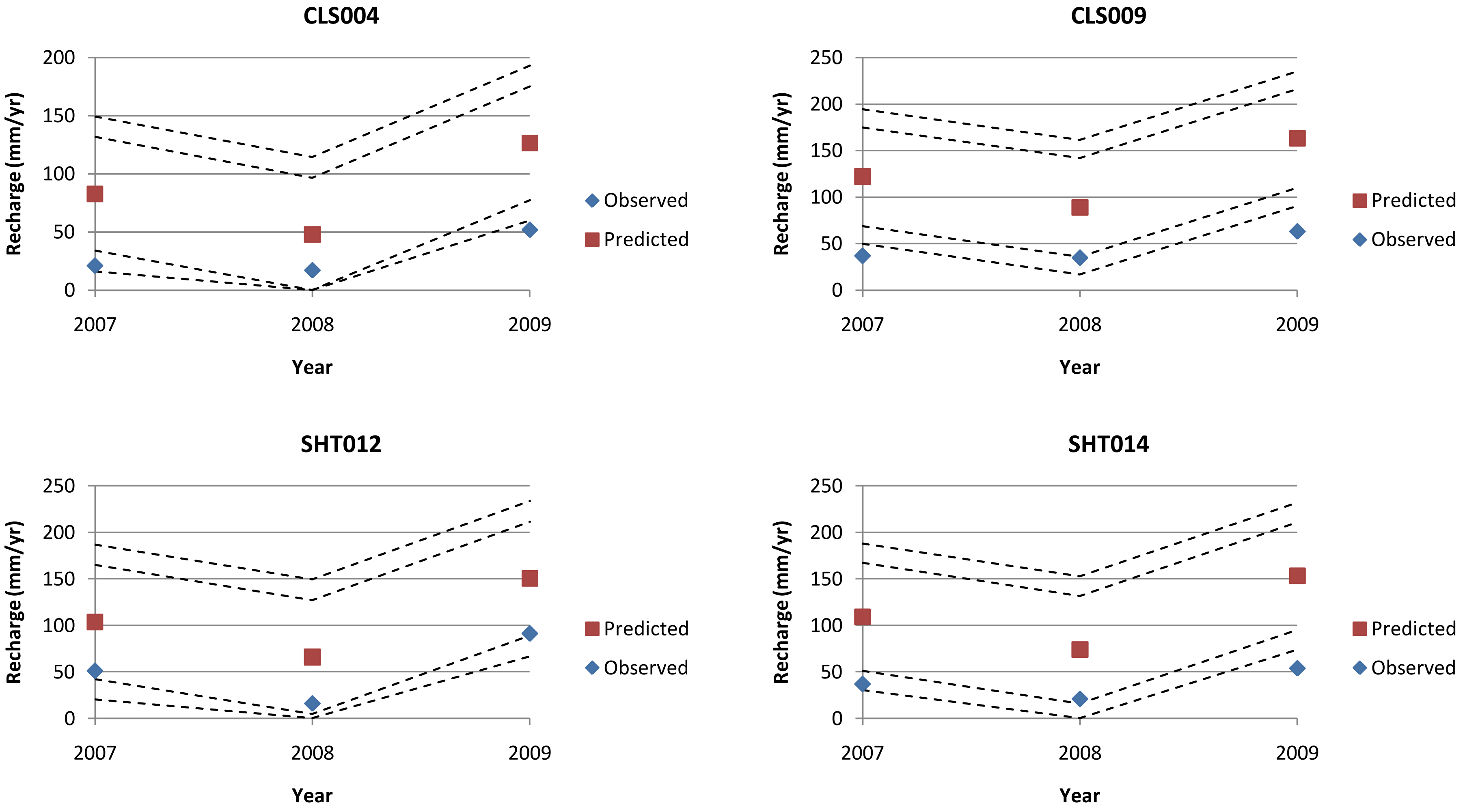

Figure 3.8 Predicted and observed recharge for 2007-2009 at forestry sites.

3.5.2.2 Total Groundwater Level

The previous analysis investigated changes in the recharge rate, which only considers the increases in the groundwater table. This component of the study has been undertaken to investigate all changes in the watertable, specifically in the management areas of Coles and Short. Brown et al. (2006) stated that many groundwater recharge studies have found a strong, linear relationship between rainfall amount and change in groundwater levels (e.g., Armstrong and Smith 1974; Stadter, 1989; Brown et al. 2001). The two latter studies were undertaken in the South East region. Therefore, as an initial analysis, the observed standing water level has been plotted against the annual winter rainfall for the pasture sites in Figure 3.9, and for the forestry sites in Figure 3.10.

The information presented in Figures 3.9 and 3.10 is all observed data; the only variation made was to adjust the winter rainfall scale on the secondary y-axis in an attempt to overlay the two time series. Over the compete record, it can be seen that the groundwater level is highly correlated to the winter rainfall where generally an increase in rainfall leads to an increase in the watertable, and vice versa. An exception to this trend can be seen over the past decade in Figure 3.10, where the groundwater table deviates from the rainfall time series. The timing of this deviation corresponds with the change in land use that occurred at the forestry sites, suggesting that this land use change has caused the rapid change in the ground water trend. The fact that this trend is not observed 10 – 20 km away at the sites presented in Figure 3.9 strongly suggests that the drawdown observed at the forested sites is not caused by any wider climatic or regional effects. The results presented in Figure 3.9 also imply that the pasture sites have been unaffected by forestry thus far.

The data presented in Figures 3.9 and 3.10 suggests that there is a strong relationship between winter rainfall and the groundwater level at the wells considered. Also, the depth to the groundwater table would be expected to be dependent on the depth the previous year. In order to further investigate the relationship between rainfall and groundwater level, Multiple Linear Regression (MLR) has been used to develop simple relationships. As was the case for the recharge rate relationships, the variation in the data does not support the use of more sophisticated modelling approaches. The following form has been adopted for the MLR equation:

Where SWL_Y is the average Standing Water Level (m) in year Y, $P_{w,Y}$ is the winter precipitation in year Y (mm), SWL_{Y-1} is the average Standing Water Level predicted for the previous year, and *a, b* and *c* are calibration coefficients. For the initial prediction, the observed SWL has been used as the value for SWL_{Y-1}. The first 20 years of consecutive groundwater observations have been used for calibration of the *a, b* and *c* coefficients, and the remainder of the data has been used for validation of the relationship.

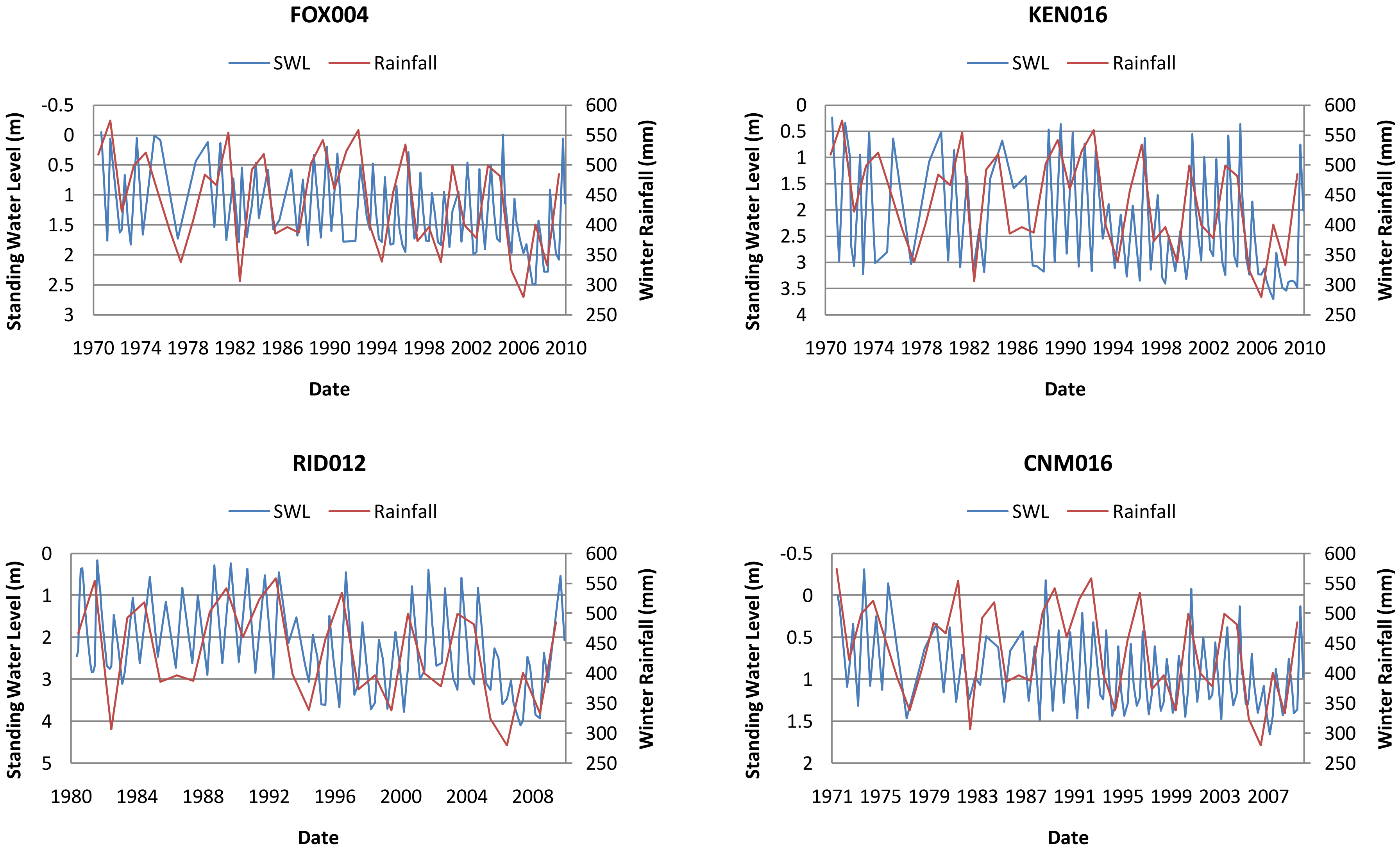

Figure 3.9 Winter Rainfall and groundwater level trends at pasture sites.

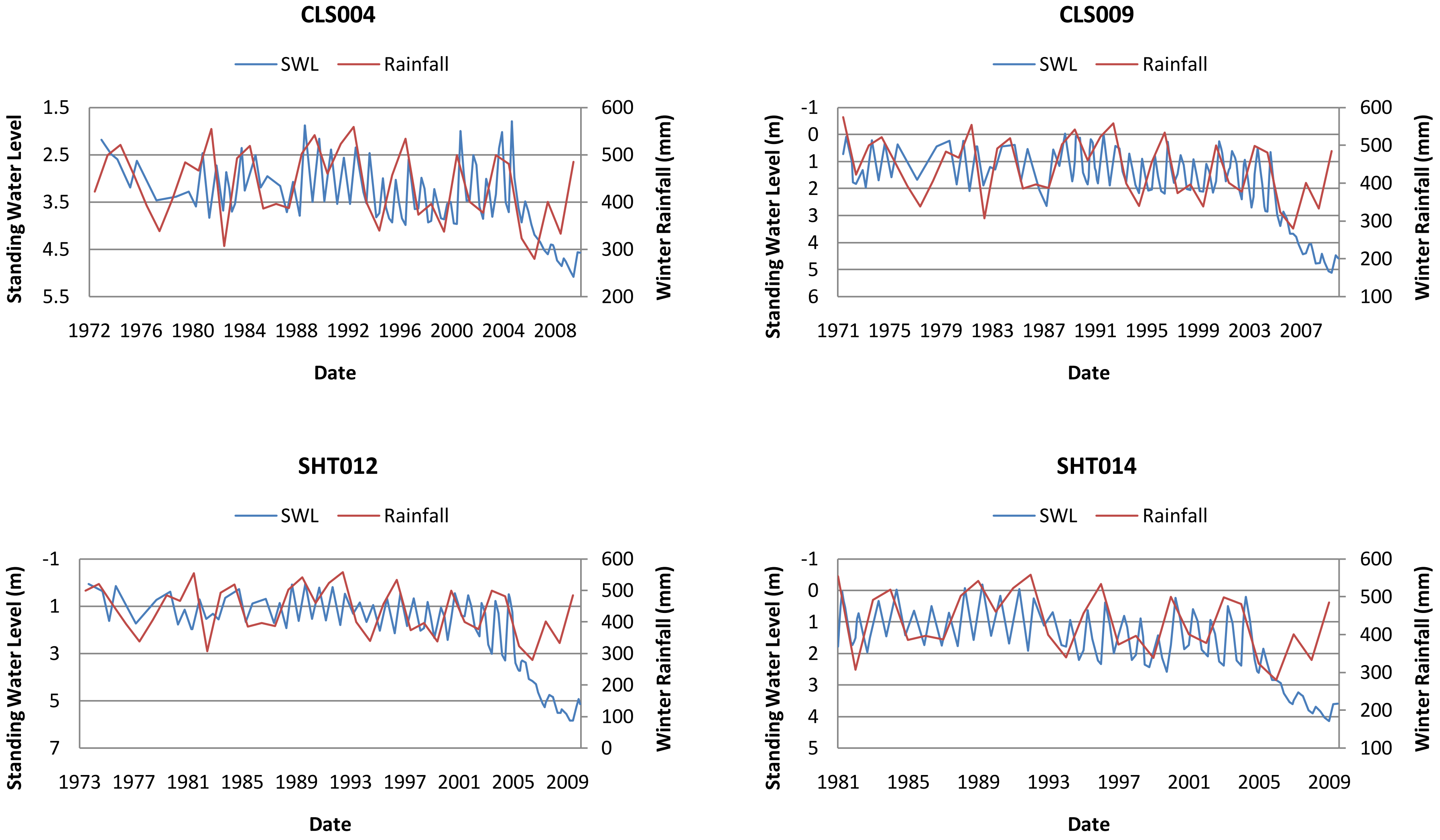

Figure 3.10 Winter Rainfall and groundwater level trends at forested sites.

For the eight wells considered, the calibrated MLR coefficients are presented in Table 3.5, along with the R^2 value of the relationship and the probability of the t distribution to indicate the statistical significance of the relationship. Highly significant relationships were only found at three of the wells (with $t \leq 0.05$), namely CLS004, CLS009 and RID012. For the remaining wells, the magnitude of the *a* and *b* coefficients is relatively small, indicating that the resulting relationship is based mainly on the long-term average groundwater level. For example, at site FOX004 in Figure 3.11, the SWL predicted by the MLR is effectively a constant value.

Table 3.5 Multiple Linear Regression Coefficients

Well	a	b	c	R^2	t
CLS004	-1.32E-03	0.493	2.208	0.472	0.001
CLS009	-2.69E-03	0.275	2.046	0.269	0.019
FOX004	-1.24E-04	0.125	1.013	0.018	0.571
KEN016	-3.16E-03	0.148	3.066	0.144	0.100
CNM016	-5.51E-04	0.100	1.042	0.035	0.428
RID012	-2.71E-03	0.587	2.093	0.655	0.000
SHT012	-1.07E-03	-0.006	1.557	0.054	0.326
SHT014	-7.85E-06	0.053	1.307	0.004	0.802

In order to account for the weak relationships developed, the results at each well have been plotted with two-sided 95% confidence bounds in Figure 3.11 for the pasture sites, and Figure 3.12 for the forested sites. The two-sided confidence bounds indicate that there is a 95% chance the observed groundwater table is within the two dashed lines, based on the long-term trend. The vertical line in Figures 3.11 and 3.12 represents the distinction between data used for model calibration and data used for model validation. The results on the left of the line are predicting values used in the calibration of the three MLR parameters, and on the right side of the vertical line the MLR equations have not been derived using any of this data, and can be considered a validation of the relationships.

For the pasture sites (Figure 3.11), the observed SWL can be seen to be within the 95% confidence bounds almost all of the time at all four wells. In fact, of the 126 values presented in Figure 3.11, almost exactly 5% of the values fall outside the 95% confidence bounds, as expected. These results confirm that the MLR equations calibrated to represent the relationship between rainfall and the groundwater level for the first 20 years of data can be used to predict the groundwater level for the remainder of the dataset for the four pasture sites.

The results for the forestry sites are presented in Figure 3.12. Similar results to those found in Figure 3.11 are obtained for the calibration period and the first 5 years of the validation period, where the observed groundwater level falls within the 95% confidence bounds. Starting around the year 2004, the observed groundwater level begins to significantly decline beyond the confidence bounds at all four wells. Given that the MLR equations provided good predictions before this period, and for the whole data record at the pasture sites, it is likely that the decline in the observed watertable from the long-term trend is not caused by a lack of rainfall, and most likely caused by the increased vegetation density at the forested sites.

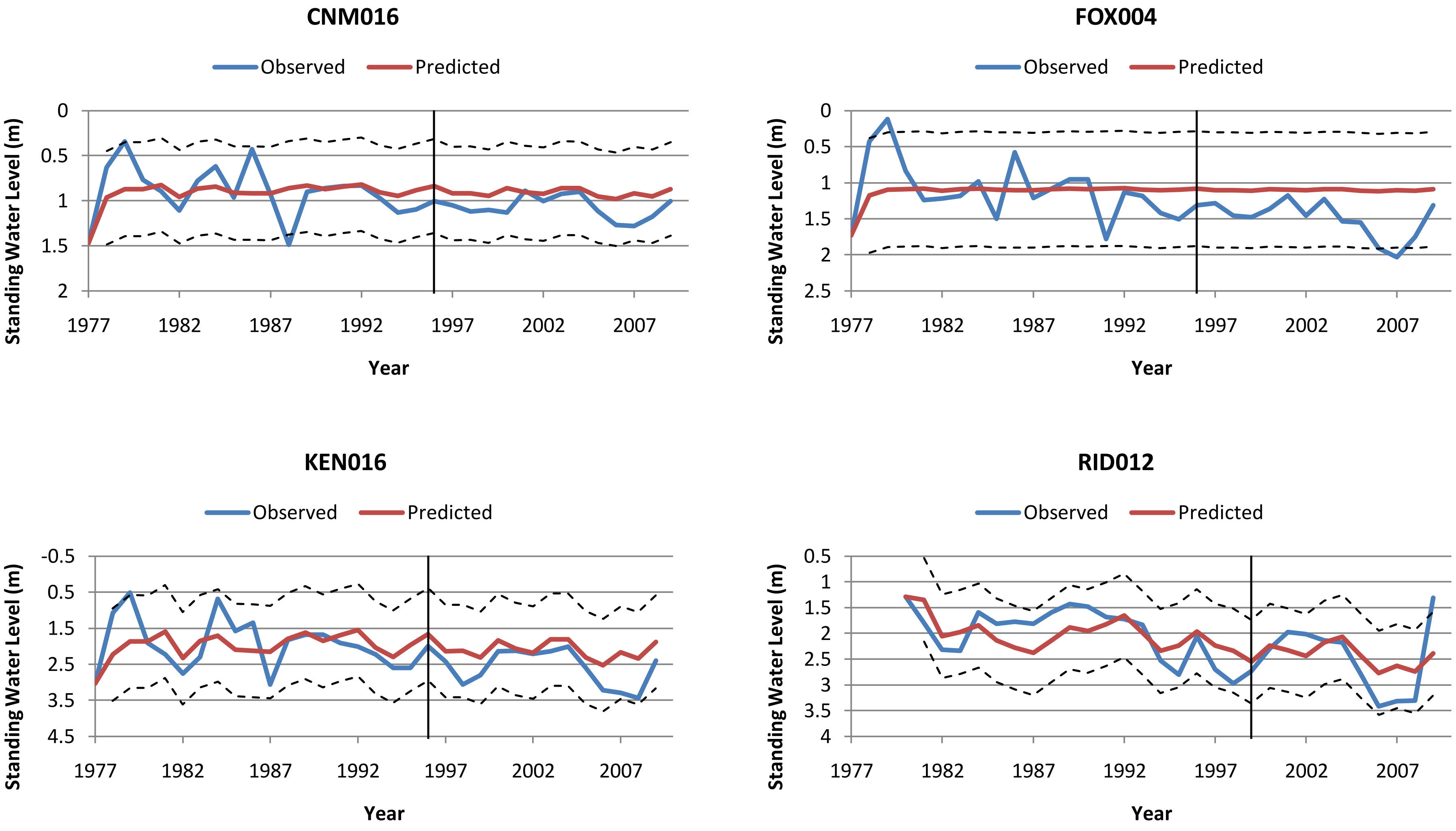

Figure 3.11 Standing Water Level predicted by Multiple Linear Regression at pasture sites, and corresponding 95% confidence bounds.

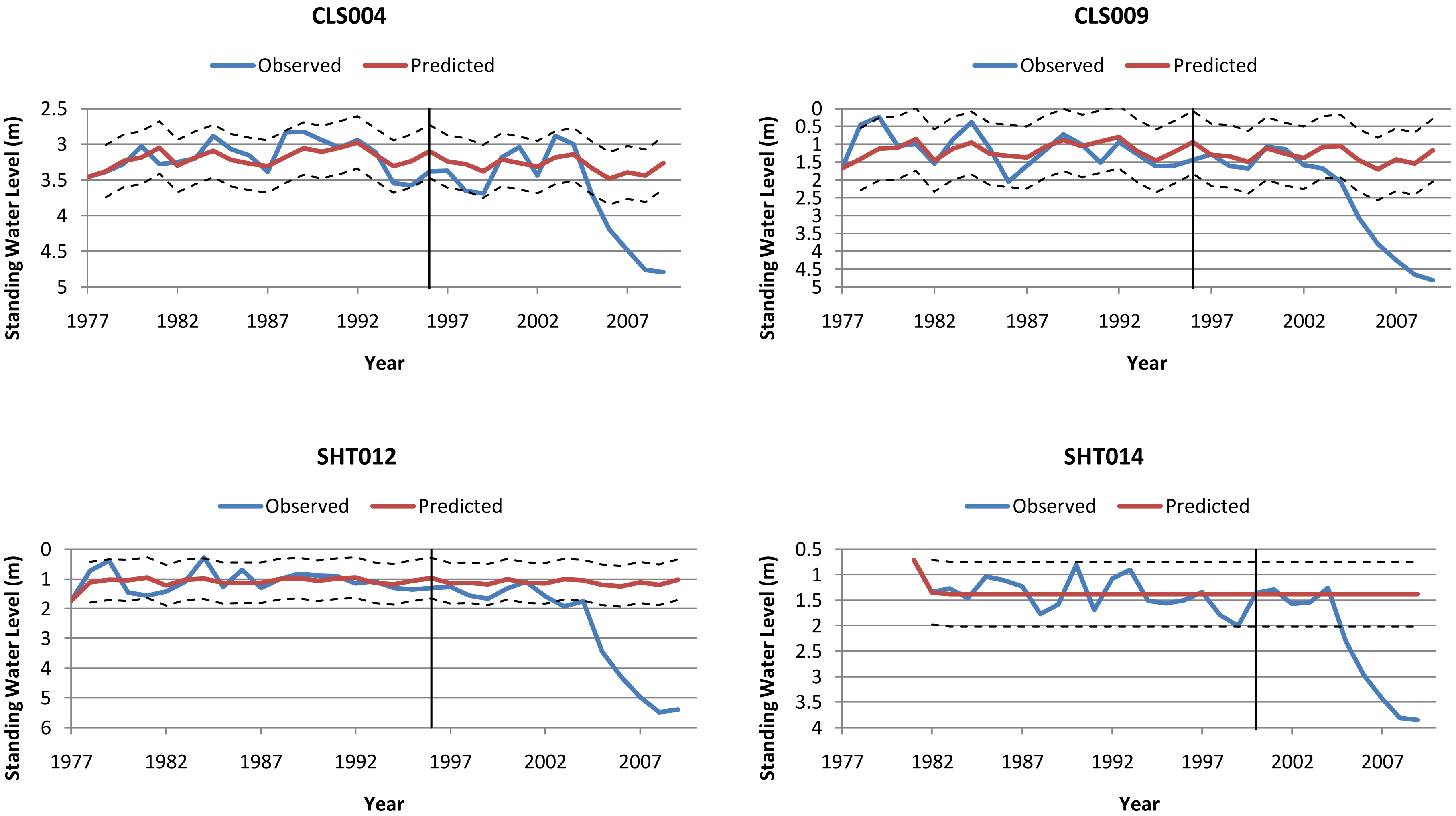

Figure 3.12 Standing Water Level predicted by Multiple Linear Regression at forestry sites, and corresponding 95% confidence bounds.

To quantify the rate of groundwater table decline, the average change in observed watertable over the period 2004 to 2009 has been calculated, simply as the SWL in 2004 minus the SWL in 2009, divided by the 5 year period to produce an average change per year. It should be highlighted that the average change in the watertable does not represent all changes in the watertable. For example, well RID012 in Figure 3.11 can be seen to both decrease and increase over the period considered.

The resulting average watertable changes can be seen in Table 3.6Table 3.6. The four pasture sites (FOX004, KEN016, CNM016 and RID012) show little overall change in the watertable over this period, with three of the wells changing less than 10 cm per year. A large rise in the watertable at well RID012 in 2009 is the main cause for the higher change at this site. Averaged over the four pasture sites, the annual change in the groundwater level between 2004 and 2009 has been an increase of only 0.03 m/yr.

In comparison, the average watertable change at the forestry sites (CLS004, CLS009, SHT012 and SHT014) can be seen to be much more considerable in Table 3.6, with a decrease in the watertable of 0.54 m/yr across the 4 wells. The data used to compute the values in Table 3.6 is based on the annual average observed standing water level, hence no modelling has been undertaken to produce these results. Again, as there is a significant difference between the observed values at the pasture sites and the forestry sites over the same period, it is likely that the land use change is the major cause for the difference in the observed groundwater table trend.

Table 3.6 Average change in watertable over period 2004-2009 (m/yr)

CLS004	CLS009	SHT012	SHT014	FOX004	KEN016	CNM016	RID012
-0.36	-0.55	-0.73	-0.52	0.04	-0.08	-0.02	0.17

3.5.3 PROBABILITY OF GROUNDWATER TABLE REBOUND

The final component of this study has investigated the probability of rebound of the watertable given a certain initial deficit. After making the assumptions outlined in Section 3, the annual change in the groundwater level, ΔG, can be computed as:

where R is the annual recharge (mm), E is the annual extraction (mm) and S_y is the specific yield. The 1000 value is used to convert units, so the final change in the groundwater level is calculated in metres.

3.5.3.1 Model Inputs

Annual recharge has been computed using the linear regression relationships with winter rainfall developed in Section 4.1. Three wells have been considered to represent the range of recharge relationships observed across the Lower Limestone Coast region. The three wells selected were RID012 to represent high recharge, ROB004 to represent average recharge and WAT007 to represent low recharge. The three wells selected as high R^2 values were observed with winter rainfall ($R^2 > 0.7$) and to represent the range in recharge rates (average recharge rates were 130, 105 and 80 mm/yr, respectively (Brown et al. 2006)).

In order to compute the annual recharge from the relationships presented in Table 3.2, the winter rainfall is required. The probability of occurrence for annual rainfall has been quantified by Thyer (2009), for both historic and drier climate (mean rainfall reduced by 10%) scenarios, with both being considered in this study. To convert from annual rainfall to winter rainfall, the variation in the ratio of winter to annual rainfall over the 149 year record at the Penola Post Office rainfall station has been investigated. As seen in Figure 3.13, the ratio is close to normally distributed, with a mean value of 0.67 and standard deviation of 0.076. The distribution of annual rainfall, and distribution of the ratio of winter to annual rainfall, has been used to compute values for winter rainfall. The probability distributions have been used in a MCS to represent the winter rainfall and hence the corresponding recharge.

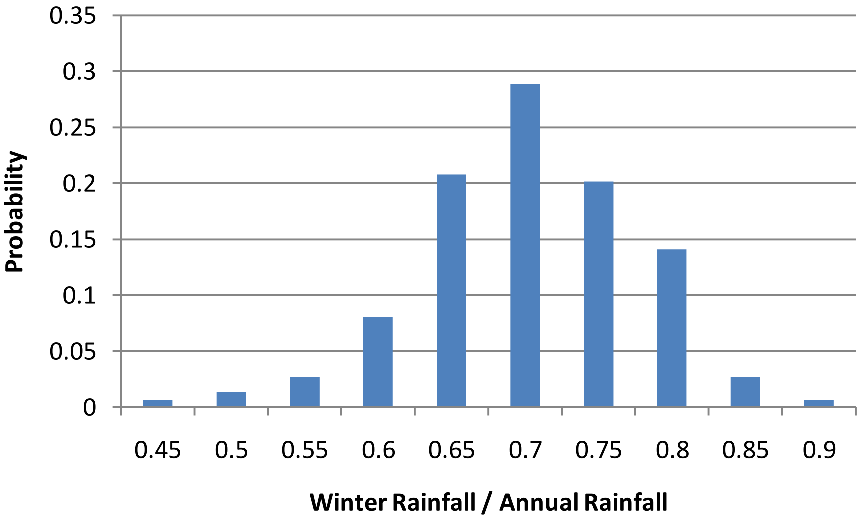

Figure 3.13 Ratio of Winter Rainfall to Annual Rainfall at Penola Post Office Rainfall Station

Water extraction values for different land uses have been adopted from a number of sources. For forestry, groundwater use of plantations was studied in research plots on sandy soils over watertables of low salinity in the South East on closed canopy plantations by Benyon and Doody (2004). For the eight study plots which used groundwater, the mean annual groundwater uptake was 435 mm/yr, with 90% confidence limits of 322 and 548 mm/yr and a range between the eight sites of 107 to 671 mm/yr. These measurements were all made in closed canopy plantations and therefore do not apply to the period before canopy closure when evapotranspiration will be lower (Benyon and Doody 2004). Brown et al. (2006), based on these results and some simplifying assumptions, estimated the mean annual extraction rates of hardwood (230 mm/yr) and softwood (260 mm/yr) plantations from shallow groundwater (< 7 metres depth) for the whole forest life cycle (Paydar et al. 2009).

Therefore, for forestry extraction, two scenarios were considered. The first is a constant extraction of 260 mm/yr. The second scenario has been used to attempt to incorporate the variability in the groundwater uptake observed by Benyon and Doody (2004). Assuming a normal distribution, a mean value of 435 mm/yr has been adopted, and a standard deviation of 68.7 mm/yr has been adopted to fit the 90% confidence bounds of 322 and 548 mm/yr.

The inverse of the WTF method has been used to estimate the groundwater extraction for pasture land use. Rather than looking for increases in the watertable, the annual decrease in the watertable has been identified. Averaged over the wells considered in Section 4.2, for the complete record for the pasture sites, and prior to 2000 for the forestry sites, the variation in the annual groundwater extraction has been identified. The resulting distribution can again be seen to be close to normal, hence to represent this variation a normal distribution with a mean of 136.7 mm/yr and standard deviation of 70.8 mm/yr has been adopted for the MCS.

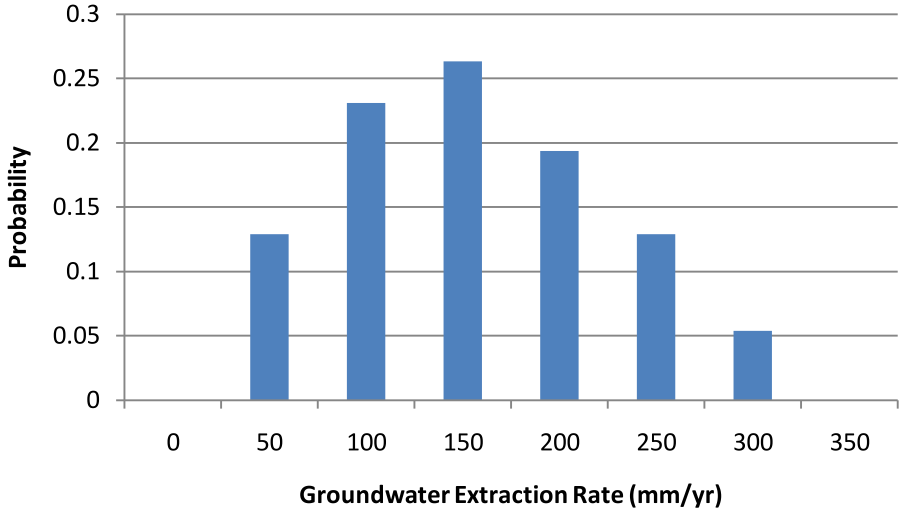

Figure 3.14 Variation in annual groundwater decline at wells to represent pasture extraction.

For irrigated pasture, the average extraction rate has been estimated from the total water extracted of 415 GL (Wood 2009), and the total area of irrigated activity of 78,118 Ha (Paydar et al. 2009). Converting this to a depth of extraction, the resulting extraction rate used in the simulation is 525 mm/yr. It is assumed that no water returns to the watertable after extracted for irrigation.

3.5.3.2 Probability Matrices

The results from the MCS applying the rebound equation for all scenarios are presented in Appendix C. A ‘no extraction’ situation is also presented, to represent the best case scenario for watertable rebound. The results can be interpreted as the initial groundwater deficit increasing down each table, and the probability of the watertable rebounding from that deficit to the long-term average groundwater level in the given number of years across each table. The probability for a deficit of 0 m can be interpreted as the probability of remaining at the stable watertable level. The conditions for recharge rates (Low, Average or High), extraction (as a function of land use), and rainfall scenario (historical or dry) are provided above each table. Scenarios that result in zero probability of rebound in all cases have not been presented.

The results indicate that for most scenarios considered, the groundwater table is not expected to rebound, and in fact is in decline. This is observed by the probability of rebound decreasing as the number of years to recovery increases. Effectively, this means that on average extraction is greater than recharge. For the high recharge scenarios, the average recharge rate is 160 mm/yr for the historical rainfall scenarios, and 140 mm/yr for the drier climate scenarios. Given that the extraction rates used for forestry and irrigated pasture are above these recharge rates, the groundwater table would not be expected to rebound within the rooting zone.

The watertable is expected to rebound for the case of high recharge under pasture, with both historical and drier climate rainfall. The rebound probability matrix for the scenario with historical rainfall can be seen in Table 3.7. For this case, the probabilities can be seen to increase as the number of years increases, indicating that recharge exceeds extraction on average. For a deficit of 0.5 m, there is a 43% chance that the watertable will recover that deficit in one year, and increasing up to 86% after 10 years. There is even a 19% chance of rebound from 6 m deficit after 10 years. For the drier climate scenario, with decreased rainfall and hence decreased recharge, the probability of groundwater table rebound is reduced. However, from Appendix C it can be seen that the probability of recharge is still increasing, indicating that recharge still exceeds extraction for this scenario, on average.

Table 3.7 Rebound probabilities for high recharge pasture site and historic rainfall distribution

Water Table Deficit (m)	Probability of recovering in Y number of Years									
	1	2	3	4	5	6	7	8	9	10
0	0.653	0.713	0.755	0.787	0.813	0.836	0.854	0.871	0.885	0.897
0.5	0.434	0.565	0.642	0.697	0.739	0.773	0.8	0.824	0.844	0.861
1	0.234	0.407	0.515	0.593	0.651	0.697	0.736	0.767	0.795	0.818
1.5	0.099	0.264	0.387	0.481	0.555	0.613	0.662	0.702	0.737	0.767
2	0.032	0.152	0.271	0.371	0.454	0.523	0.581	0.63	0.672	0.709
2.5	0.008	0.078	0.175	0.271	0.357	0.432	0.497	0.553	0.602	0.645
3	0.002	0.035	0.105	0.187	0.268	0.344	0.413	0.474	0.528	0.577
3.5	0	0.014	0.057	0.121	0.192	0.265	0.333	0.396	0.454	0.507
4	0	0.005	0.029	0.073	0.131	0.195	0.26	0.322	0.381	0.436
4.5	0	0.001	0.013	0.042	0.085	0.138	0.196	0.254	0.312	0.367
5	0	0	0.006	0.022	0.053	0.094	0.143	0.195	0.249	0.302
5.5	0	0	0.002	0.011	0.031	0.061	0.1	0.145	0.194	0.243
6	0	0	0.001	0.005	0.017	0.038	0.068	0.105	0.147	0.192

Previous studies have indicated (Brown et al. 2006) that the recharge rate under closed canopy forestry is significantly less than that observed for open pasture. Therefore, the recharge rate for the forestry scenarios may be more accurate with reduced recharge rates. However, given that the rebound probabilities are already close to zero, reducing the recharge rate further will not improve the probability of rebound.

The extraction used in this study was independent of the rainfall distribution. While there was no significant relationship detected between the annual drawdown of the watertable (Figure 3.14) and rainfall, this independence may be a simplification of the true case. However, the nature of any relationship is not immediately clear, as for reduced rainfall years the extraction rate may reduce, as excess water is not available to be extracted, or the rate may increase, as water availability from other sources (such as surface or soil moisture) is reduced.

Also, the rooting depth of each land use has not been considered. For irrigated pasture and forestry extraction at depths in the order of 5 – 6 m would be expected. However, for unimproved pasture, extraction at this depth is unlikely, and hence the decline in the watertable beyond 1 m due to extraction of pasture may not occur. For the scenarios where this is the case, the watertable would be expected to remain at the rooting depth, as opposed to continuing to decline.

With extraction exceeding recharge, the groundwater table would not be expected to rebound. However, the assumption that net lateral groundwater flow is zero may be conservative. As drawdown occurs and a difference in potential head develops, lateral flow would be expected to stabilise the watertable. If this is the case, the probabilities of rebound presented here may be underestimated. Numerical groundwater modelling could be undertaken to quantify the degree of lateral flow, and also incorporate mixed land uses where there are areas of high and low extraction. However, an investigation such as this is beyond the scope of this study.

3.6 DISCUSSION

This study presents the first time the relationship between rainfall and recharge has been quantified for the region of the South East of South Australia. Significant variation in the strength of the relationship between rainfall and recharge was observed, however, the recharge expected from average rainfall corresponds well with the values reported by Brown et al. (2006). By investigating the spatial variation in the slope of the rainfall recharge relationship, the region encompassing the management areas of Short, Kennion and Riddoch were identified as a high recharge zone for the region. The fact that plantation forestry has been established in this area is cause for concern, as recharge in this area may flow laterally to the wider unconfined aquifer, and the reduction of the groundwater table in this region is likely to reduce occurrence of surface flow from the Bakers Range north along the watercourse. However, numerical modelling of the groundwater response, and surface water – groundwater interactions, is required to investigate the implications of reduced recharge in this area.

The consistent overestimation bias in recharge predictions for 2007 to 2009 at the forestry sites suggests that the recharge rate has decreased over this period. However, due to the high variance in the observed recharge rates, it is difficult to conclude that the reduced observed recharge rates are different from the long-term trend with any statistical significance. Daily well observation data would allow recharge to be estimated more accurately from rainfall events, and would reduce assumptions involved in the WTF method, and therefore most likely the variation observed in the recharge rates.

The complete groundwater observation record for a number of wells in the management area of Coles and Short was considered for wells associated with both pasture and forestry land uses. Based on these records, the groundwater level was observed to decline to approximately 5 m at the forestry sites only, with the pasture sites remaining near the long-term average. This result alone suggests that the decline in the watertable observed in this area is due to the change in land use, and cannot be attributed to a reduction in rainfall alone. This conclusion was further supported using rainfall and the previous groundwater level to forecast the following year's groundwater level. In this case, the trends at pasture sites remaining within the 95% confidence bounds for 95% of the time, and a similar result was obtained at the forestry sites until 2004. After this time the groundwater level deviated from the 95% confidence bounds. For 2009, the difference from the long-term trend is significant at over 99.9% confidence limit. This result further reinforces the conclusion that the decline in the groundwater level at the forestry sites cannot be attributed to reduced rainfall alone. This is not a surprising conclusion, as since records began in the mid 1970s, the depth to the watertable in 2009 at site CLS009, SHT012 and SHT014 is over twice as deep as it ever was prior to the introduction of plantation forestry in the area.

Currently, the observed depth to watertable supports the widely held view that plantation forestry does not use groundwater beyond a depth of 5 – 6 m. However, the decline in the watertable of approximately 0.5 m/yr over the past 5 years has not stabilised, as yet. There is some evidence to suggest that this is starting to occur, with the standing water level increasing at SHT012 from 5.5 m below the surface in 2008 to 5.4 m in 2009. However, further evidence is required to determine if a new steady state is beginning to be achieved.

For most scenarios considered, the watertable was not expected to rebound, as the extraction rate exceeds the average recharge rate. For example, the average annual recharge rate for the high recharge scenario was 160 mm/yr, while the extraction rate used for forestry was 260 mm/yr. For the high recharge scenario considered, an annual rainfall of 842 mm is required to produce an equivalent recharge of 260 mm/yr. Based on the stochastic rainfall modelling of the historic rainfall record (Thyer 2010), the probability of experiencing over 842 mm annual rainfall is 6%. Hence, recharge is expected to exceed extraction under forestry only once every 16.7 years. Therefore, the groundwater table would not be expected to rebound to historic levels under this land use with extraction exceeding recharge 94% of the time. This result is reflected in the probability matrices (Appendix C). Similar situations were found for irrigated pasture and the second forestry land use cases considered, as the extraction rates were even higher for these scenarios.

3.7 CONCLUSIONS AND RECOMMENDATIONS

This study has investigated the relationship between rainfall and the watertable in the South East of South Australia. Statistically significant linear relationships between winter rainfall and recharge rate was identified at 31 of the 41 wells considered. These relationships may be useful for water allocation planning studies where both the average recharge and expected variation in the recharge rates can be quantified.

The recharge rates varied substantially over the region, with a high recharge zone in the management areas of Short, Kennion and Riddoch. The significance of recharge in this area to both ground and surface water resources should be further investigated to assess the consequence of a decline in the local watertable on the wider region.

There is evidence to suggest that forestry has reduced the recharge rate in the management areas of Coles and Short since 2007. However, due to the variation in the data it is difficult to draw statistically significant conclusions. Daily well observations or field studies would assist in quantifying the true recharge rates.

By considering all changes in the groundwater table (not just recharge), the recent drawdown in Coles and Short was observed to be a local phenomenon, and therefore cannot be attributed to regional effects, such as a lack of rainfall. There has been no change in the depth to the watertable since 2004 at the pasture sites considered (3 cm recharge per year on average), however, at the nearby sites associated with a forestry land use the watertable has been declining at approximately 0.5 metres per year. The most obvious explanation for the local effect is the change in land use that has occurred, with the introduction of plantation forestry around the year 2000. It is recommended that the depth to the watertable be monitored at the observation wells associated with forestry land use to determine if the watertable will continue to decline at this rate, or if it is beginning to reach a new steady state at approximately 5 metres below the surface level.

Based on the results presented in this report, further groundwater modelling is recommended to assess two key potential implications:

1. What is the impact of the reduction in water level, and the likely reduction in recharge, in the aquifer recharge zone on lateral regional groundwater flows and winter surface flows?
2. What is the expected cone of depression associated with the drawdown observed at forestry sites, and does it extend to negatively impact on nearby agriculture and groundwater dependent ecosystems?

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