Faculty of Health, Engineering and Science

GROUNDWATER RECHARGE PREDICTION

FOR BROAD SCALE IRRIGATION MODELLING:

A CASE STUDY IN THE M.I.A-MAIN CANAL IRRIGATED AREAS

A dissertation submitted by

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ABSTRACT

Determining the water balance is a vital element in water resource management. This is particularly important for arid and semi-arid regions in Australia where surface water resources such as rivers and rainfall are less available. Consumption of water is the highest for agricultural purposes in Australia. Due to the importance of conserving water resources in the background of agriculture and climate it is necessary to quantify the water incoming to the system and water outgoing from the system. For this reason, it is required to estimate the amount of groundwater recharge. The project deals with recharge within irrigated areas. The study area chosen is a group of irrigation districts, geographically located within the Murrumbidgee Irrigation Areas (MIA). The MIA is situated in southern-central New South Wales. The study area and the MIA come under semi-arid environment. Agriculture is prevalent in the MIA. The irrigation districts under the study area receive irrigation water diversions from the Main Canal which inturn is diverted from the Murrumbidgee River.

This report describes the application of a newly developed recharge optimisation method for arriving at prediction parameters specific to the study area for estimating groundwater recharge from an irrigated area. The method is developed leading from AWRA-R irrigation model which is developed by Commonwealth Scientific and Industrial Research Organisation (CSIRO). The irrigation model has two components in it: Diversions modelling module and Recharge estimation module. The diversions module is built inorder to estimate irrigation diversions to agricultural farms at a river basin scale. It is simple, can be calibrated and run for long-term simulations quickly. It is designed to generate estimations of diversions even under circumstances of parsimonious data availability. Recharge module, the other component, is a modified form of Overbank flood recharge (OFR) method to estimate groundwater recharge for a given district.

The AWRA-R irrigation model is applied to the study area and the simulated results for groundwater recharge are obtained. These results are further optimised based on factors that influence recharge dominantly in the study area. Simulations are run by varying the input parameters to the irrigation model thus obtaining 840 trial recharge estimations. These recharge values are fitted against a set of collated recharge estimates from previous studies and researches done within the MIA and the lower Murrumbidgee by means of root-mean-square error analysis. The simulation recharge outputs that give the closest fit to the collated data are accepted to be the recharge estimates specific to the study area. The input parameters, Kc and soilCap, applied for that simulation are determined to be prediction parameters, the values of which are 7.78E-07m/sec and 0.105m respectively. The prediction parameters, thus deduced, have been used to estimate recharge for years 1970-2012. From the results of simulated recharge, it is observed that there are several years with no recharge while the maximum recharge is 79.49mm in the year of 1991.

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ENG4111 Research Project Part 1 &

ENG4112 Research Project Part 2

LIMITATIONS OF USE

CERTIFICATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course of institution, except where specifically stated.

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GLOSSARY OF TERMS

The following list contains only the principal abbreviations and symbols used in the paper. Other symbols used within this paper not mentioned in this list are less common and defined in their relevant sections.

AWRA	Australian Water Resources Assessment
AWRA-L	AWRA-Landscape
AWRA-R	AWRA-Rivers
AWRA-G	AWRA-Groundwater
BoM	Bureau of Meteorology
CSIRO	Commonwealth Scientific and Industrial Research Organisation
d_{gw}	Depth to Groundwater (m)
DPI	NSW Department of Primary Industries
ET	Evapotranspiration
ET_o	Reference ET
ET_c	Crop ET under standard conditions
$ET_{c\ adj}$	Crop ET under non-standard conditions
K_c	Hydraulic Conductivity (m/sec)
K_o	Crop Coefficient
MIA	Murrumbidgee Irrigation Area
MIL	Murrumbidgee Irrigation Limited
ML/d	Megalitres per day
ML/yr	Megalitres per year
NoW	NSW Office of Water
NSW	New South Wales

OFR	Overbank Flood Recharge
PEST	Parameter Estimation software
Q	Catchment surface Runoff
R	Recharge
ΔS	Change in catchment Storage
soilCap	User defined maximum top soil thickness
Sy	Aquifer Specific Yield (m/m)
Δt	Change in time
WIRADA	Water Information Research and Development Alliance

1. INTRODUCTION

1.1 Background

Australia is a vast and diverse continent with varying temperature zones and climate patterns across the country. Surface water resources such as rivers and lakes are more available in coastal areas due to abundance of rainfall they receive. Large parts of inner Australia are either desert or semi-arid regions; rainfall received is moderate and evaporation losses are much higher than that. Groundwater is treated as a dominant water resource in inner Australia and is used to support significant urban and rural communities. A wide variety of agricultural enterprises and many non-agricultural industries also use vast amounts of groundwater. Habermehl (2007) indicates that groundwater accounts for 20 percent of all water used in Australia. For many regional areas, particularly in arid and semi-arid Australia, it is often the only reliable source of water supporting communities and economic activity.

The replenishment of groundwater occurs through diffuse recharge from rainfall and irrigation water, and localised recharge from surface water seepage in streams. Recharge occurs when surface water, either from direct precipitation or from rivers and lakes, percolates downwards through the microscopic spaces in the soil and rock profile. Eventually, the infiltrated water may make its way into an underground water-bearing rock formation, known as an aquifer. Recharge mainly occurs in areas where parts of the aquifer are exposed at or close to the surface.

Groundwater recharge under irrigated agriculture occurs due to application of water to meet the water requirement of crops/horticulture. Quantification of recharge under irrigated agriculture is one of the most important but least understood components in groundwater studies (Ali 2013). It is least understood because of its large variability in space and time and its difficulty to measure directly. Better management of groundwater resources is only possible if the fluxes into and out of a groundwater system can be accurately estimated. Reducing the uncertainty remains one of the major challenges facing irrigated agriculture and is a major impediment to reliable quantification of groundwater resources (Ali 2013). This in turn affects assessments of sustainable yield of groundwater and its allocation to the irrigation industry. Reducing uncertainty in the rate of groundwater recharge under irrigated agriculture is a pre-requisite for effective, efficient and sustainable groundwater resource management especially in dry areas where groundwater resources are often the key to economic development (Sophocleous 2005). An accurate quantification of groundwater recharge in irrigated systems is crucial because of its potential impacts on the soil profile and groundwater quality (Ali 2013). This project aims to reduce uncertainty in groundwater recharge under irrigated agriculture.

1.2 Developing a Recharge optimisation method

The project focuses on estimating groundwater recharge over broadscale irrigated areas. Recharge for a particular region is usually calculated as part of a bigger groundwater model. There exist groundwater or surfacewater models that estimate recharge using techniques such as water balancing or watertable hydrographs. They are, however, data intensive and take longer simulation time and not suitable for calibration. Considering these limitations CSIRO has developed an irrigation diversion model (Hughes et al. 2013 & 2014) which also estimates groundwater recharge in a particular irrigation district. It uses a recently developed recharge calculation technique based on Richard's equation (Doble et al 2012) termed as modified overbank flood recharge method. Recharge can be determined for past years depending on availability of historic diversion data. The integrated diversion and recharge model, termed as AWRA-R irrigation model, can be calibrated which makes it adaptable for any given district.

The study area for current project is located within the irrigation districts of the MIA. The MIA is located in southern-central New South Wales in south-east Australia and includes the towns of Narrandera, Yanco, Leeton, Griffith and Carrathool. It is about 600km west of Sydney. The study area includes irrigation districts of Yanco, Mirrool, Tabbita and Wah Wah.

Recharge optimisation method is developed for the study area based on the AWRA-R irrigation model. The project describes the process of obtaining prediction parameters specific to the study area. These parameters would be useful in accurate estimating of groundwater recharge in the study area for any required period in the past or future years.

1.3 Objectives of Research

1. To collect groundwater table data, irrigation diversions and allocation data for the MIA and process them in the format ready for incorporation in AWRA-R irrigation Model.

2. To collect groundwater recharge estimates (observed data) made within the MIA from previous studies.

3. To deploy the AWRA-R irrigation model developed by CSIRO for the purpose of estimating groundwater recharge.

4. To extract simulation outputs from the AWRA-R irrigation model for various combinations of calibration parameters and develop recharge simulations of best fit against observed data.

5. To arrive at prediction parameters for the purpose of estimating groundwater recharge for future years.

1.4 Scope of Research

Salinity is a widespread phenomenon that is associated with the problems faced by irrigation in Australia. It is, however, not covered by current project owing to the level of complexity associated with including salinity element.

Tile drainage is in use under irrigated land to control the levels of groundwater in the MIA. Current project does not cover the aspect.

Groundwater accessions and on-farm storage with regards to water resources are accommodated for in the irrigation model. However, they are not included in the current project. It is because those water resources are not tapped into in the MIA.

The hydraulic conductivity and specific aquifer yield values utilised in the project are obtained from other literary sources rather than by direct measurements.

1.5 Report Structure

Chapter 2 makes a review of literature available on groundwater, groundwater recharge, factors governing recharge and suitable recharge estimation techniques in the context of agriculture areas in Australia. Literature review identifies results, observations and deductions made by authors internationally regarding the subject.

Chapter 3 provides an overview of the study area interms of geography, location, climate, land use and hydrogeology. It provides brief description of major soil types and aquifers underlying the region to signify the purpose of the project which is estimating groundwater recharge in irrigated areas. The chapter also presents a study area specific literature review. It provides synopsis of various groundwater models developed for the MIA and the lower Murrumbidgee and their respective recharge estimation models. Recharge estimates from such models and other reports are collated and presented in table format.

Chapter 4 presents brief description about background information leading to the development of Irrigation model. It details the mechanism of recharge module and its integration with diversion module. It also enumerates the various inputs required to run the AWRA-R irrigation model. Finally, it describes the process of arriving at prediction parameters by developing a recharge optimisation method. Chapter 5 discusses the results from calibration of input parameters in the form of analysis. Chapter 6 presents conclusions from the project and makes recommendations for future work.

2. LITERATURE REVIEW

2.1 Groundwater

The term groundwater is usually reserved for the subsurface water that occurs beneath the water table in soils and geologic formations that are fully saturated.

The endless circulation of water between ocean, atmosphere, and land is called the hydrologic cycle. Inflow to the hydrologic system arrives as precipitation, in the form of rainfall or snowmelt. Outflow takes place as streamflow (or runoff) and as evapotranspiration, a combination of evaporation from open bodies of water, evaporation from soil surfaces, and transpiration from the soil by plants (Freeze & Cherry 1979).

As precipitation occurs, it is partially intercepted by vegetation and the rest infiltrates into the ground. This, besides infiltration of surface water from runoffs and streams, is the source of groundwater. Figure 2.1 depicts the inflow and outflow of water in a hydrologic cycle and the process of groundwater recharge and storage.

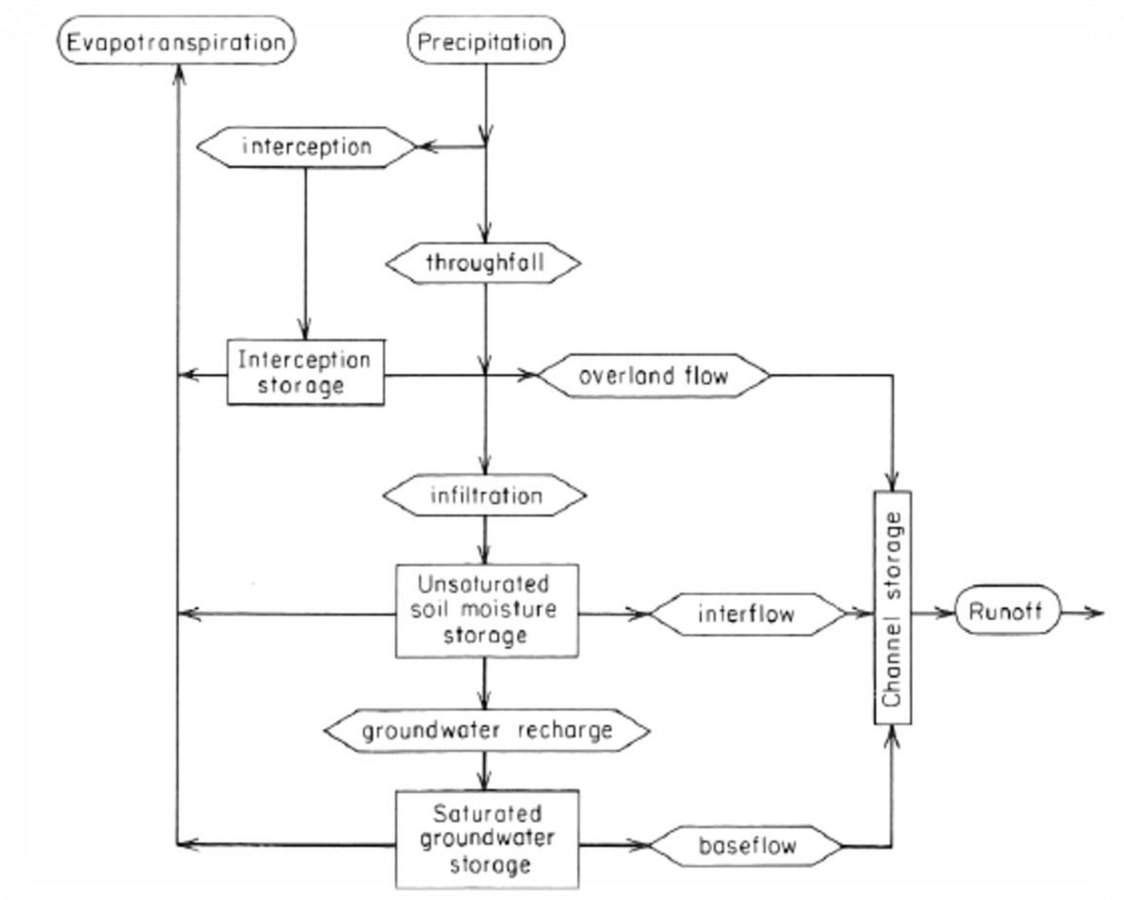

Figure 2.1 Systems representation of the hydrologic cycle (Freeze & Cherry 1979)

As water seeps into the ground, gravity pulls it downward through two zones of soil and rock called vadose zone and phreatic zone. In vadose, the upper zone, the pore spaces in the rocks are only partly filled with water and the water forms thin films, clinging to grains by surface tension. This leads to slow downward percolation of the water forming partially saturated flow systems. The vadose zone or the zone of aeration is of primary concern to agricultural engineers (Kashef 1986).

The phreatic zone lies below the vadose zone. It is also called the zone of saturation because all of the openings in the rock are completely filled with water. The continuous process of infiltration from the vadose zone leads to an accretion to phreatic zone. The water table, which is the upper surface of the phreatic zone, is an important element in the groundwater system. It may be only a meter or so deep in humid regions, but it might be hundreds or even thousands of meters below the surface in deserts (Kashef 1986).

Groundwater occurs in soils in different modes. Hygroscopic moisture is the moisture absorbed by the dry soil from the atmosphere near the ground surface. When water infiltrates through the soil, it forms isolated moist patches as a result of the molecular attraction of soil grains for water. Such water cannot be separated by gravitational movement. It occupies the upper part of the vadose zone. Immediately above the watertable, a capillary fringe develops as a result of the upward movement of water under the action of capillarity. Generally, such water movement in the vadose zone is due to both capillary action and evaporation. Downward movement is due to infiltration of rain and surface water. Vadose water is mainly the unsaturated zone when the watertable is close to the ground surface, and it may be very deep in arid zones (Kashef 1986).

Below the watertable, completely saturated soil is encountered. It may be realized that immediately above the watertable, within the lower part of the capillary zone, the soil is also completely saturated even though the pore-water pressure is negative. Hence, the watertable may be thought of as the surface along which the pore-water pressures are atmospheric rather than as the upper level of saturation (Kashef 1986).

2.2 Groundwater Recharge

Healy (2010) defined groundwater recharge as the downward flow of water reaching the water table, adding to the ground water storage. This definition does not include water flow to an aquifer from an adjoining groundwater system.

Recharge is usually expressed as a volumetric flow, in terms of volume per unit time [L^3/T], such as m^3/d, or as a flux per unit surface area per unit time (L/T], such as mm/yr.

Groundwater recharge occurs from a variety of both natural and artificial sources. Natural phenomenon such as precipitation, rivers, canals and lakes and man-induced circumstances via such activities as irrigation and urbanisation lead to recharge. Jones et al. (1981), Lloyd (1986) and Lerner, Issar and Simmers (1990) categorise recharge principally as two types, direct and indirect.

Direct recharge pertains to the water added to aquifers by direct vertical percolation of surface water through the vadose zone. Surface water reaches the ground either through rainfall or irrigation activities. The water infiltrates through the top layer of ground controlled by its porosity and permeability. In urban settings, where the surface is likely to be non-permeable, the surface water escapes as runoff with little infiltration. In undeveloped areas and agricultural fields, infiltration occurs depending on the characteristics of soil and slope of land. The infiltrated water, in excess of soil-moisture deficits and evapotranspiration, eventually becomes recharge.

Indirect recharge deals with water added to groundwater table by percolation from surface water bodies such as rivers, streams, unlined irrigation channels, lakes and ponds, or beds of surface watercourses or in joints (Lerner, Issar & Simmers 1990). In addition to the above, runoff collected in low-lying areas or depressions also contribute to the recharge. This leads to categorise indirect recharge in two types; one that is associated directly with surface watercourses, and a second, localised recharge resulting from accumulation in surface water bodies that are not located in the course of well-defined channels or drainage lines (Lerner, Issar & Simmers 1990).

Groundwater recharge has its importance in the management of both surface water and groundwater. The amount of recharge occurring in an area directly impacts the physical characteristics and behaviour of groundwater. Lerner, Issar and Simmers (1990) indicate that identifying the probable flow mechanisms and important factors influencing the recharge process within a given area is the key to successful groundwater recharge estimation.

2.3 Factors affecting recharge process

A number of factors influence groundwater recharge process. Groundwater recharge in any area is impacted by interactions between climate, geology, morphology, soil condition and land cover. Generally it is much more susceptible to near-surface conditions in semi-arid and arid regions than in humid regions (de Vries and Simmers 2002). The evapotranspiration is higher than rainfall in arid and semi-arid regions due to which recharge mainly depends on rainfall events and irrigation application of water. The project aims at calculating direct recharge within agricultural regions. Hence, only the factors affecting groundwater recharge within the sphere of agriculture have been discussed. Several of many factors affecting recharge have been identified (Allen et al. 1998, Rushton 1988 and Ali 2013) and are illustrated through figure 2.2. Factors which control the recharge process both directly and indirectly are discussed as follows:

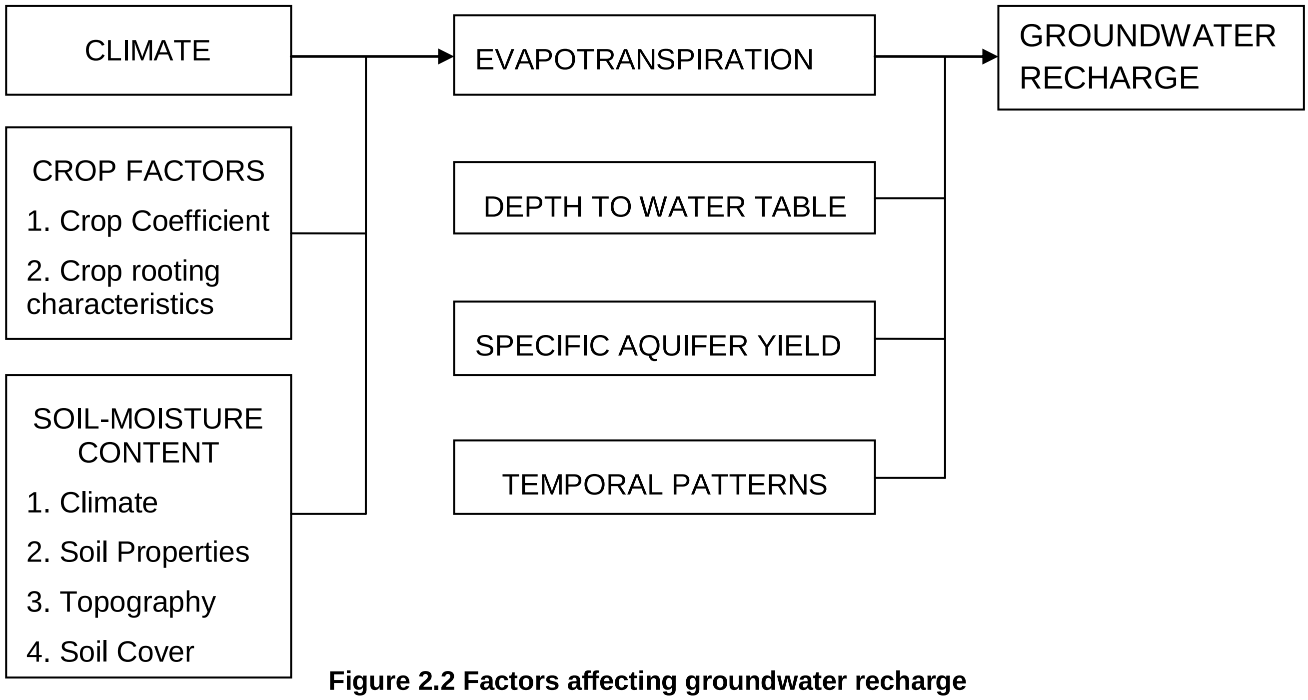

Figure 2.2 Factors affecting groundwater recharge

Climate: Climatic factors have direct influence over evapotranspiration (ET) which inturn affect the rate of recharge. Changes in weather parameters like radiation, air temperature, humidity, wind speed and rainfall over longer periods of time are considered for measuring their affect on ET (Allen et al. 1998). Owing to its size, Australia has 6 climatic zones and several sub-zones in each zone (BoM 2006). Similarly, there are 8 major air mass types influencing Australian weather (Carberry, George & Buckley 2007). The variations in climate determine the type of irrigation management principles adopted and the types of crops cultivated across Australia (Brouwer et al. 1986). Table 2.1 summarises the effect of climatic factors on crop water needs. The climate data is obtained from weather stations spread across Australia.

Table 2.1 Effect of climate on crop water needs (Brouwer, Heibloem 1986)

CLIMATIC FACTOR	**CROP WATER NEEDS**	
	HIGH	**LOW**
Sunshine	Sunny(no clouds)	Cloudy (no sun)
Temperature	Hot	Cool
Humidity	Low (dry)	High (humid)
Wind speed	Windy	Little windy

Crop Coefficient: Crop coefficient (K_c) is a property of crop that is used to estimate specific crop evapotranspiration rates. It is influenced by crop type and crop growth stages and environmental factors like climate and soil evaporation (Allen et al. 1998). Crop types differ by their albedo, crop height, aerodynamic properties, and leaf and stomata properties. Each crop type is also subjected to changes due to its growth stages. As crop develops, the ground cover, the leaf area and the crop height change. The growth period can be divided into four stages: initial, crop-development, mid-season and late season. The crop reaches its maximum Ko during mid-season. Figure 2.3 shows the factors affecting Ko in the 4 growth stages.

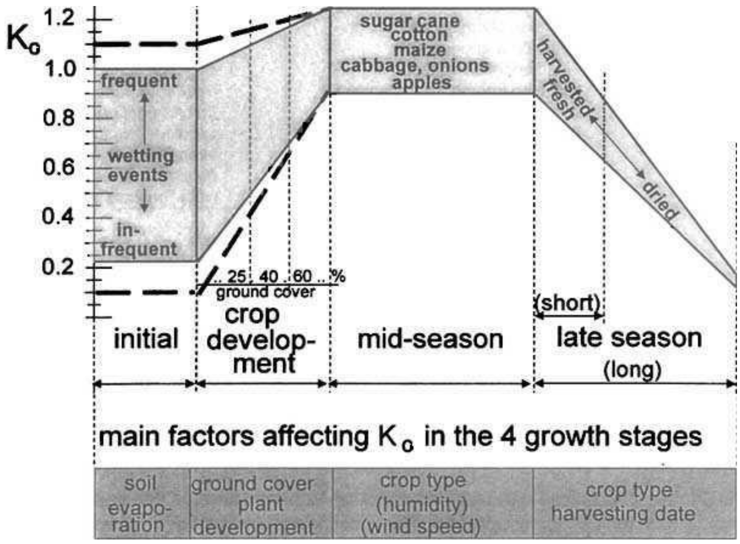

Figure 2.3 Factors affecting Ko (Allen et al. 1998)

Climate conditions affect Ko depending on the height of crop. The ranges of Ko are smaller for short crops compared to tall crops. Figure 2.4 illustrates the impact of climate on Ko for full grown crops. The effect of soil evaporation is noticeable after a rain event or irrigation when the crop is small with lesser canopy. Ko values may exceed 1 under such conditions. As canopy size increases transpiration takes over evaporation and Ko may fall as low as 0.1(Allen et al. 1998).

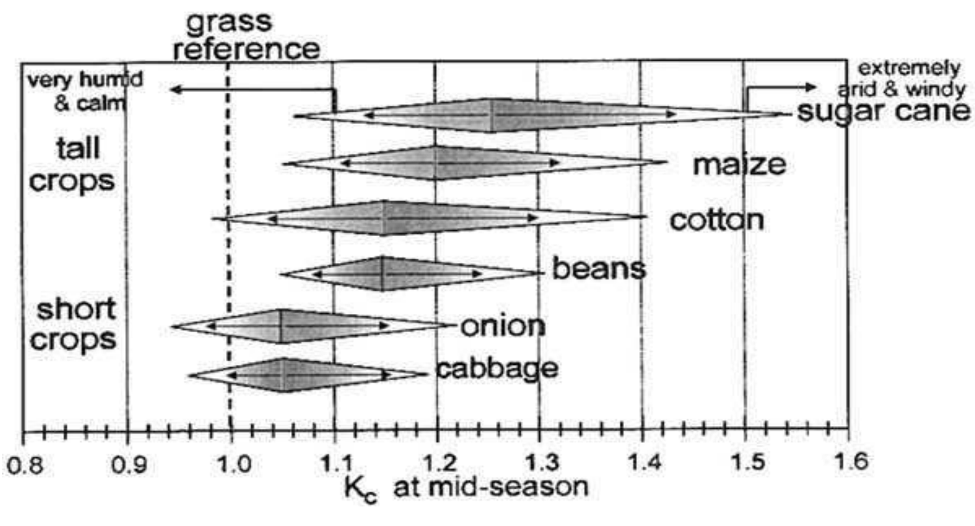

Figure 2.4 Impact of climate on Ko for full grown crops (Allen et al. 1998)

Crop Rooting Characteristics: Plant rooting depth determines the amount of plant water uptake by roots. A deep rooted crop has more access to soil-moisture compared to a shallow rooted crop. Hence, it can sustain longer intervals between irrigation. Rooting depth also influences the depth of irrigation of soil profile. For example, varieties of major pasture have typical rooting depths of only upto 0.6m (Blaike, 1986; Mehanni & Repsys1986) such as ryegrass and white clover. Any applied irrigation water which passes below this rooting depth will not be used by the plant roots and may recharge groundwater. The type of land cover determines the amount of recharge both under irrigated agriculture and dryland. Recharge is high under irrigated crops that have relatively longer growing sessions (Ali, 2013). Recharge is minimal under deep rooted native vegetation in semi-arid regions of Australia (Timms, Young & Huth 2012; Tolmie, Silburn & Biggs 2011).

Soil Properties: Soil physical and textural properties have a significant affect on infiltration, water holding capacity, irrigation requirements and recharge. Light textured soils rich in sand and silt have a high hydraulic conductivity (Kc). These have a low water holding capacity. Hence, such homogenous soils encourage groundwater recharge. Conversely, heterogeneous soils and soils rich in clay content restrict recharge. Kc values of variety of soils found in Australia have been extracted from Atlas of Australian soils (McKenzie et al. 2000) and are shown in table 2.3 below.

Table 2.2 Hydraulic conductivities of soils in Australia (McKenzie et al. 2000)

CLASS	MEDIAN Kc (mm/hr)	Log10	DESCRIPTIVE NAME
1	0.03	-1.5	
2	0.1	-1.0	Very Slow
3	0.3	-0.5	
4	1.0	0	Slow
5	3.0	0.5	
6	10	1.0	Moderate
7	30	1.5	
8	100	2.0	High
9	300	2.5	
10	1000	3.0	Extreme
11	3000	3.5	

It has been found that clay content of the top 2m of soil profile and annual average rainfall are statistically significant predictors of recharge under dryland agriculture (Wohling, Leaney & Crosbie 2012). Clayey soils have high micropores hence, high water holding capacity and less infiltration rates unlike sandy or silty soils which have high macropores and low water holding capacity. Smith, Raine & Minkevich (2005) found that differences in water holding capacity between sandy soils and clayey soils can often result in higher deep percolation of water under sandy soils than under the clayey soils. From the soil texture triangle in figure 2.5, an approximation of water holding capacities of different soils can be made. It can be stated that groundwater recharge is directly proportional to rainfall and irrigation and inversely proportional to available water capacity (Tolmie, Silburn & Biggs 2011).

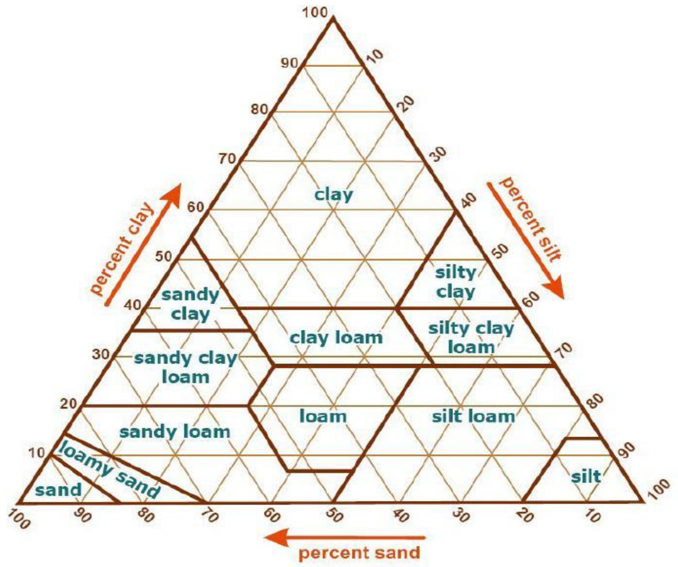

Figure 2.5 Soil texture triangle (Brady 1990)

Topography: The affect of topography on soil moisture content is directly related to the slope of terrain. During rainfall, a steeper terrain generates a higher runoff than a flatter landscape. A higher proportion of runoff leads to lesser proportion of rainfall that translates to soil-moisture and groundwater recharge. (Allen et al. 1998). Topography also affects the physical and chemical properties of soil by erosion and deposition processes (Delin et al. 2000; Norton & Smith 1930; Ebeid et al. 1995; and Agbenin & Tiessen 1995). Famiglietti, Rudnicki & Rodell (1998) found that topography and clay content influence the soil-moisture retention capacity of the soil during dry conditions that follow after rain events. During a wet season variability in surface moisture content is most strongly influenced by porosity and hydraulic conductivity.

Soil Cover: This is important for irrigation management in agricultural farms. During the early stage of plant growth the canopy is small exposing the moisture in top soil to evaporation. Having a soil cover reduces the amount of evaporation losses from the top soil by acting as an insulating layer (Allen et al. 1998). Soil cover also reduces the impact of raindrops on the soil thus protecting the porosity of top soil. In the absence of soil cover, the surface soil particles disintegrate under the impact of rain drops and clog the soil layer. This leads to increased runoff. Thus soil cover detains runoff and improves soil-moisture held and subsequently infiltration rates (Allen et al. 1998). Soil cover can be provided by vegetative or non-vegetative mulches, cover crops or crop residue depending on the type of management (Allen et al. 1998).

Soil-Moisture Content: It signifies the amount of water present in the soil. During a rainfall event or irrigation application the infiltration rate through the top soil is high and it gradually reduces to zero as the soil becomes saturated. Soil is saturated when all the pores are filled with water. Any more water beyond this point is either runoff or converted into recharge. Soil continues to drain excess water downwards even after rainfall or irrigation application ceases until the soil only retains water that can be held against gravity. At this stage the soil is at field capacity (Dingman 1994). Drainage takes longer to occur in clayey soils than sandy soils (Shaxson & Barber 2003). This water at field capacity is available for evaporation or plant uptake as part of transpiration process. The evapotranspiration process generates surface tension as soil seeks to prevent the removal of water. This creates negative soil pressures compared to atmospheric pressure. As suction increases, the surface tension in the larger pores of soil is overcome thus withdrawing further water and air enters the emptied pores. With time this water reduces upon no additional supply and gradually the plant wilts. This is called permanent wilting point. The difference between the field capacity and permanent wilting point is called available water content (Dingman 1994). The available water is influenced by factors like soil cover and textural properties. Figure 2.6 shows relationship between soil-moisture content and water pressure in the pores for contrasting soils. It is understood that clayey soils have higher initial water content than sandy soils owing to a higher porosity, but with small or moderate surface tensions, the sandy soils release more water from larger pores than clayey soils (Shaw 1994).

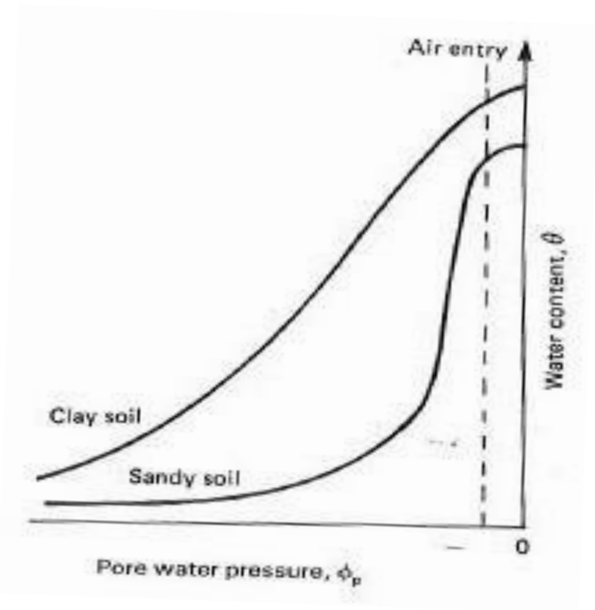

Figure 2.6 Soil-Moisture retention curves for different soils (Hillel 1980)

Evapotranspiration (ET): It is a combined process of evaporation from soil and plant surfaces and transpiration from plant surfaces (Burman & Pochop 1994) occurring simultaneously. When the crop is small its canopy occupies less area of surface and water from soil is lost through evaporation predominantly. This in turn is mainly determined by fraction of solar radiation reaching soil surface. As the crop develops the fraction of radiation decreases and transpiration becomes the main process (Allen et al. 1998). ET is affected by factors like climate, soil characteristics and soil-moisture content. Accounting for ET in perspective of agriculture is important for two reasons: 1. to calculate the crop water requirement, which is identical to ET, to compensate for the loss of moisture from the cropped field and 2. To calculate the amount of water that eventually becomes recharge.

Inorder to calculate crop water requirements, terms ETo, ETc and ETc adj have been defined in Monteith (1965 & 1981). ETo, which represents evapotranspiration for a reference crop (Monteith 1965 &1981), is adopted as a standard to estimate ETc or ETc adj. Ko is multiplied with the crop ETc to arrive at the crop requirement or actual Evapotranspiration.

The groundwater recharge is calculated using a water balance equation of hydrological cycle. Recharge = Precipitation - Runoff - Actual Evapotranspiration ±Storage change (Lerner, Issar & Simmers 1990)

Depth to Water table: Depth to watertable has a major impact on recharge. It controls the thickness of the unsaturated zone and the time for the subsurface flux to reach the watertable (Nachabe, Martysevich & Su 2012). Under irrigated fields the watertables may rise during rainfall events or irrigation application due to increased recharge. But, as the watertables rise closer to the soil surface the recharge often reduces due to the reach of the capillary fringe into the root zone (Ali 2013). The soil-moisture potential below the root zone is affected by the depth of watertable below the soil surface. This in turn provides a feedback on recharge (Hillel 1980).

Aquifer Specific Yield (Sy): (Prathapar & Sides 1993; and Freeze & Cherry 1979) defined aquifer specific yield as the depth of water that an unconfined aquifer releases from storage per unit decline in the watertable level. The converse holds true for recharge. Sy can be considered as the volume of water taken into storage in the column with each unit rise in the watertable (Price 1996). Its units are m/m. The amount of water that enters the aquifer is controlled by Sy both for confined aquifers and unconfined aquifers. Table 2.3 shows the mean, minimum and maximum values of Sy for Australia (McKenzie et al. 2000).

Table 2.3 Specific Aquifer Yield values for Australia (McKenzie et al. 2000)

MIN	MAX	MEAN
0.030	0.314	0.191

Temporal patterns in deep drainage: Temporal variations in groundwater recharge within the same irrigated field can be considerable due to changes in the physical and chemical characteristics of the soil, duration and timing of water application via rainfall or irrigation. Over extended periods of time, near saturated soil root zone can yield considerable amount of recharge despite low subsoil hydraulic conductivity (Bethume 2004). It has been observed by Dunabin, Hune & Ireson (1997) that prolonged ponding of a perennial ryegrass white clover pasture at Deniliquin, NSW increased infiltration. Changes in landuse and climate can also trigger a temporal variation in recharge (Bouraoui et al. 1999).There can be noticeable inter-annual variation in recharge due to seasons in a year (Degu, Wagner & Birk 2013). A review by Humphreys, Edraki and Bethune (2003) revealed the lack of comprehensive data for components of the water balance for a range of crops, soil types, climate conditions, site and seasonal conditions and management.

2.4 Groundwater Recharge Estimation Techniques

One of the objectives of the project is to quantify groundwater recharge within irrigated agricultural areas. Recharge estimation techniques vary according to the scale of area, climate and available tools for investigation. Current project focuses on estimating recharge on a broadscale in semi-arid regions of Australia. Hence, recharge models that suit the purpose of the project have been described in the following subsections. The models are built by taking into account the factors affecting recharge process discussed in the previous section to finally result in recharge.

2.4.1 Meteorological Water Balance

Water balance models operate on the law of conservation of mass. The hydrological cycle for a particular area can be accounted for by using a water balance model. The model balances the inputs to the system with outputs from the system. Water content of soil volume increases when additional water is added by infiltration or capillary rise, and decreases when water is withdrawn by evapotranspiration or recharge (Humphreys, Edraki & Bethune 2003).

The water balance method has four characteristic features (de Ridder & Boonstra 1994). They are:

1. A water balance can be assessed for any subsystem of the hydrologic cycle, for any size of area, and for any period of time;

2. A water balance can serve to check whether all flow and storage components involved have been considered quantitatively;

3. A water balance can serve to calculate the one unknown of the balance equation, provided that the other components are known with sufficient accuracy;

4. A water balance can be regarded as a model of the complete hydrologic process under study, which means it can be used to predict what effect the changes imposed on certain components will have on the other components of the system or subsystem.

The surface water balance equation may be expressed as:

$\Delta S = P - ET - Q - R$ (Humphreys, Edraki & Bethune 2003) 2.1

Where ΔS is the spatially averaged catchment storage, P is the spatially averaged precipitation, ET is the spatially averaged evapotranspiration, Q is the spatially averaged catchment surface runoff, and R is the spatially averaged catchment recharge.

The simplicity of the model lies in utilising available information such as climate data to calculate recharge. Although water balance model is very indirect, it has the advantage in that it can provide information on the temporal distribution of recharge.

Limitations of the model are:

1. Not suitable to measure groundwater recharge in semi-arid and arid regions because of longer periods of less than potential evaporation, when errors in ET are greatest and P and ET are nearly equal (Gee & Hillel 1988).

2. As the modelled area increases, the model becomes more complex and needs more data. The time required to process the model increases proportionately.

3. Input data is not always available. This problem becomes evident when the model is being built on a catchment or continental scale. More often, historical data is difficult to source and sometimes the only input data that is available might be the result of other approximate models.

4. Errors in the input data would translate into errors in the output.

Water balance methods have been widely used to estimate recharge in temperate climates (Howard & Lloyd, 1979; and Rushton & Ward 1979). They have not been routinely used in semi-arid areas, although Ferreira and Rodriques (1988) used a daily water balance to estimate recharge in semi-arid areas of Portugal, with good agreement with known hydrogeological conditions. As Gee and Hillel (1988) point out, in areas where recharge rates are low, very small errors in estimated actual evapotranspiration can lead to very large (as much as order of magnitude) errors in estimated recharge.

2.4.2 Watertable Fluctuation (WTF) Model

The watertable fluctuation method estimates groundwater recharge of the chosen catchment. This method is based on the principle that the rise in water table is due to the addition of recharge water to the unconfined aquifer. These variations in groundwater hydrographs can provide valuable information on the timing and amount of recharge (Healy and Cook 2002) for a comprehensive review).

$$R = Sy\ \frac{\Delta H}{\Delta t} \qquad \text{.......} \qquad 2.2$$

where R is recharge (m/day), Sy is the specific yield of the aquifer, ∆H (m) is the change in level of watertable over a period of time ∆t (day). Figure 2.5 shows ∆H graphically. ΔH_n (m) is the difference in head between the beginning and end of time interval.

The method assumes that a time lag occurs between arrival of recharge water and distribution of it to other components of hydrological cycle. The above equation, if applied during the time lags, can account for all the recharge (Healy 2010). Shorter time intervals such as hours or days are valid time lag. The application of ∆H in equation gives total or gross recharge while substituting ΔH_n for ∆H gives net recharge in saturated zone storage over any time interval. The difference between gross recharge and net recharge is equal to the sum of ET from groundwater, base flow, and net subsurface flow from the catchment area. This method actually estimates change in recharge over time of the hydrograph record. As the method represents an integration of recharge by porous media and by-pass flow it can integrate over large spatial scales (Herczeg & Love 2007).

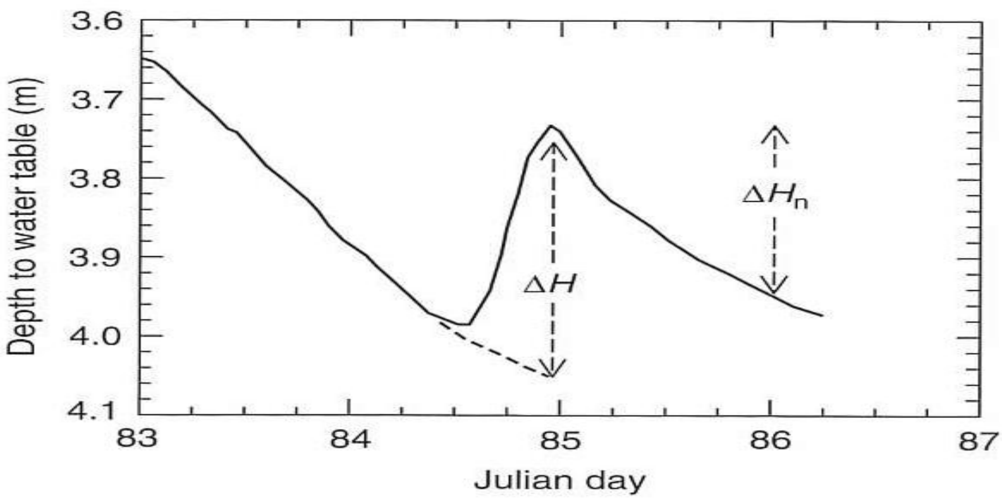

Figure 2.6 Hypothetical groundwater hydrograph (Healy 2010)

Advantages of using WTF method:

1. This method may be used as a preliminary mode of recharge estimation before applying a more sophisticated technology due to its simple approach and widespread availability of groundwater level data (Healy 2010).

2. This method is well suitable to shallow water tables that display sharp water level rises and declines (Herczeg & Love 2007).

Limitations of using WTF method:

1. Sy used in the method is difficult to measure and hence based on literature values (e.g Wood 2008) or a range of likely values (Cartwright, Hannam & Weaver 2007).

2. The method does not account for lateral flows (Herczeg & Love 2007).

3. The method is not suitable for measuring recharge or ET in areas of low water fluxes and deep watertables (Herczeg & Love 2007).

4. Frequency with which the watertable levels are measured may affect recharge estimates (Healy 2010). Delin et al. (2007) found that the frequency of measuring groundwater levels directly affected estimated recharge. For example, using this method for time intervals of years may underestimate recharge values because small recharge event peaks are ignored.

5. Recharge estimates may vary within a watershed due to variations in elevation, geology, landsurface slope, vegetation, and other factors (Lee, Yi & Hwang 2005).

6. If the rate of recharge to an aquifer is equal to the rate of drainage away from aquifer, the groundwater levels remain unchanged and WTF method would provide a zero recharge estimate.

The WTF method for estimating recharge has been used in many areas of Australia. Berhane (2001) used the watertable fluctuation method to estimate recharge in the lower Namoi. It was used to measure recharge in coastal climate by Crosbie et.al (2010). The watertable fluctuation method has been used at a variety of time scales from hourly (Crosbie et al. 2010) to annual (e.g. Cartwright, Hannam & Weaver 2007).

2.4.3 Overbank Flood Recharge (OFR) Method

Flooding of river plains occur when a river exceeds level over the bank height and fills up the low lying areas. Recharge of aquifers occurs during such episodic events. This component of groundwater balance is ignored in water accounting generally because of the variable nature of infiltration between catchments and the difficulty in quantifying it by physical experiments (Doble, Crosbie & Smerdon 2011). Doble et al. (2012) developed OFR method to calculate recharge from overbank flooding after an analysis of river-floodplain system using HydroGeoSphere.

HydroGeoSphere is a finite element model (Therrien et al. 2006) which fully integrates one subdomain three dimensional (3-D) variably saturated groundwater flow with another subdomain two dimensional (2-D) overland flow. HydroGeoSphere simulates the dynamic interaction between the subdomains at each timestep.

Continuity equation can be used to represent recharge from overbank flooding, where the change in storage (ΔS) is equal to inflow (I) minus outflow (Q). It may be stated that inflow is controlled by the total storage available and the maximum rate of outflow (Doble et al. 2012).

$\Delta S = I - Q$ 2.3

The maximum possible change in storage (i.e., filling the unsaturated zone) may be expressed as

$\Delta S = d_{gw}\, S_y\, x_w$ 2.4

The maximum potential infiltration volume is approximated from a vertical application of Darcy's law:

$I = K_c x_w \left(\frac{\mathrm{hw}}{\mathrm{dc}} + 1\right) t_w$ 2.5

and the maximum volume of water discharging laterally from the aquifer or transmissivity may be approximated as a horizontal application of Darcy's law:

$Q = K_{aq}\, d_{aq}\, t_w \frac{\mathrm{dgw}}{\mathrm{xw}/2}$ 2.6

where the depth to groundwater (d_{gw}) is taken at the centre of the flood wave extent, S_y is the aquifer specific yield, x_w is the lateral extent of the flooding (m), K_c is the saturated conductivity of the clogging layer, h_w is the height of the wave above the bankfull elevation (m), d_c is the thickness of the clogging layer (m), t_w is the duration of the flood wave (day), K_{aq} is the hydraulic conductivity of the aquifer, d_{aq} is the saturated thickness of the aquifer (m).

The actual infiltration or recharge to the system is represented by the minimum of the potential infiltration to the aquifer and the capacity of the aquifer to store and transmit the water, $\Delta S+Q$:

$I_{actual} = \min(I, \Delta S+Q)$ 2.7

The above equation reflects that there are three phases involved in the flood recharge process: the ability for the flood water to infiltrate the floodplain sediment, the amount of storage in the unsaturated zone and the ability for the aquifer to transmit water either toward or away from the river. Recharge is rejected where one of these factors limits the vertical recharge (Doble et al. 2012).

Doble et al. (2012) found that the infiltration volume was directly proportionate to the conductance of the clogging layer, flood wave height, peak duration, and aquifer transmissivity and inversely proportionate to watertable gradient.

Advantages of using OFR method:

1. The results for groundwater recharge from this method are comparable to results from far more complex groundwater models accurately for similar input conditions. The amount of time consumed for computations is also less compared to other complex models (Doble et al. 2012). It is a simple and accurate model that calculates recharge without the requirement of intensive modelling. Hence it runs fast which makes it useful for iterative process of modelling.

2. An analytical equation is developed to estimate the infiltration volume for catchments where full numerical modelling is not warranted or applicable.

3. The method is robust to generate results with some parts of input data missing. This is useful when calculating recharge on a continental scale because it is difficult to source accurate historical data over a large area. It is also used where only parsimonious input data is available.

OFR method equations have been developed only in recent years, in 2011. The method has been tested for 66 unique scenarios The scenarios capture the effects of varying aquifer saturated hydraulic conductivity (K_{aq}), representing aquifer transmissivity, flooding depth, horizontal extent, and duration, as suggested by previous studies, and also include the presence of a clogging layer overlying the floodplain and river bed and different river-aquifer connections (Doble et al. 2012).

So far, the method has been applied on AWRA system (van Dijk et al. 2011) after modifying a relationship in the set of equations. It is also used in Irrigation Diversion Modelling (Hughes et al. 2013 & 2014). The equations are modified to calculate recharge from irrigated fields in place of flood plains.

2.5 Summary

Literature review discusses the background information regarding groundwater recharge and the factors responsible for it in the perspective of agricultural regions. The earlier sections of this chapter describe various factors in detail that directly and indirectly contribute to recharge. This generic discussion of the factors also contains results from other research studies done nationally and also internationally where information was available.

Section 2.4 of the chapter presents few groundwater recharge estimation techniques which are suitable for evaluating recharge on a broadscale in an agricultural background. The factors discussed in section 2.3 find their application in arriving at recharge using the above techniques.

3. STUDY AREA

3.1 Introduction

The study area is located within the MIA, situated in southern-central New South Wales in south-east Australia. The MIA includes the towns of Narrandera, Yanco, Leeton, Griffith and Carrathool. It is about 600km west of Sydney and 900km east of Adelaide. The Murrumbidgee River, the third largest river in Australia with a length of 1690 km, flows to the south of the MIA (Khan et al. 2004). Catchments along the Murrumbidgee River are classified into upper, mid and lower catchments. The MIA is included in the Lower Murrumbidgee catchment. Location of the MIA in the Murray-Darling basin and in the Murrumbidgee catchment is shown in figure 3.1.

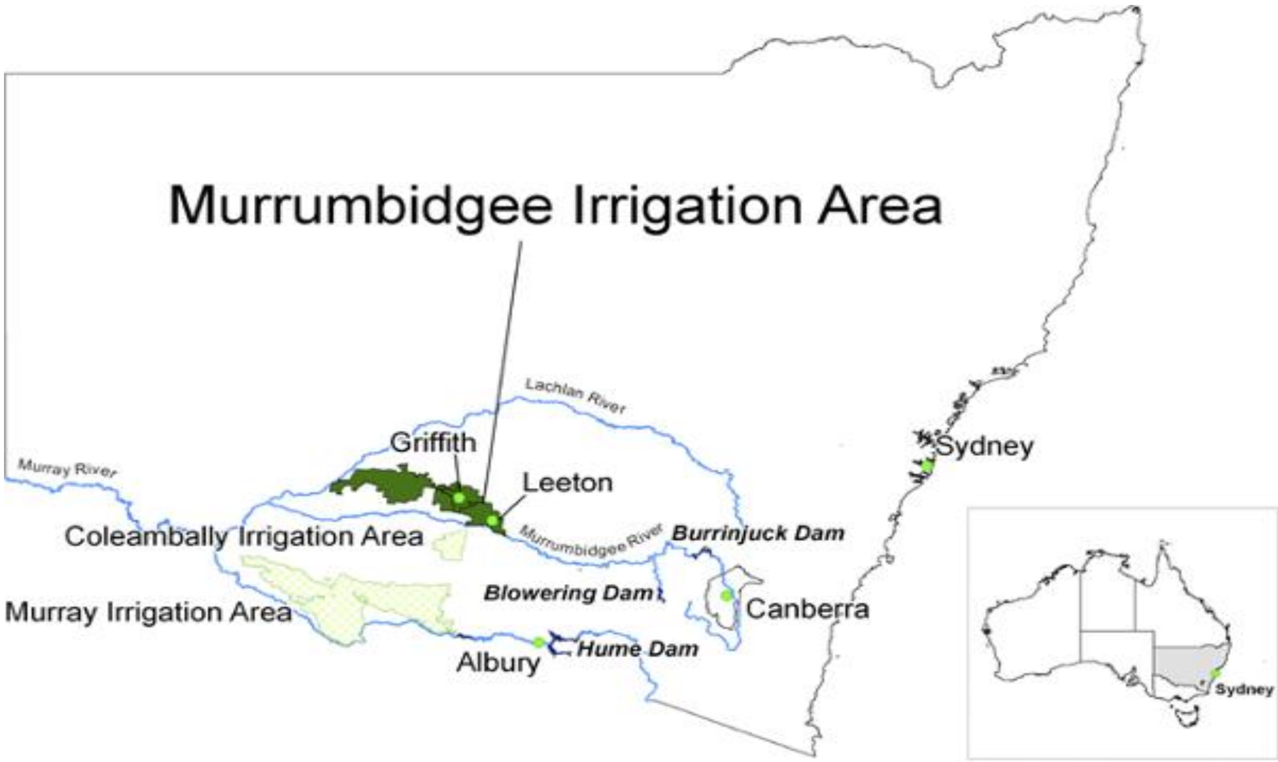

Figure 3.1 Murrumbidgee Irrigation Area (Mitchell, Curtis & Davidson 2012)

3.2 Geographical Location

Agricultural areas within the MIA are divided into a number of irrigation districts. The irrigation districts are fed by two canals, the Main Canal and the Sturt Canal, which in turn receive water diverted from the Murrumbidgee River. The Main Canal carries approximately 80 per cent of all water which is diverted for irrigation purposes in the MIA (Shields & Good 2002). It irrigates Mirrool irrigation district, part of Yanco irrigation district, Tabbita irrigation district and Wah Wah irrigation district. The study area comprises of irrigation districts that are irrigated by the Main Canal. The total area covered by these districts is approximately 519,000 ha (MIL 2014). Figure 3.2 shows the districts irrigated by the Main Canal and Sturt Canal. The blue network of channels and Wah Wah irrigation district represent the area covered by the Main Canal. The towns, Leeton, Yanco and Griffith and Carrathool in which the irrigation districts are located, are situated towards north of the Murrumbidgee River.

The Main Canal receives water from diversion at Berembed Weir to serve the Yanco, Leeton, Griffith and Carrathool areas. The Main Canal continues on past Leeton, Murrami, Yenda, Beelbangera and Griffith, finishing at Tharbogang. It can accommodate flows of up to 6,500 ML/day (MIL 2013). The Sturt Canal receives water diverted at Gogeldrie Weir to supply the Whitton and Benerembah areas, and can accommodate flows of up to 1,700 ML/day (MIL 2013).

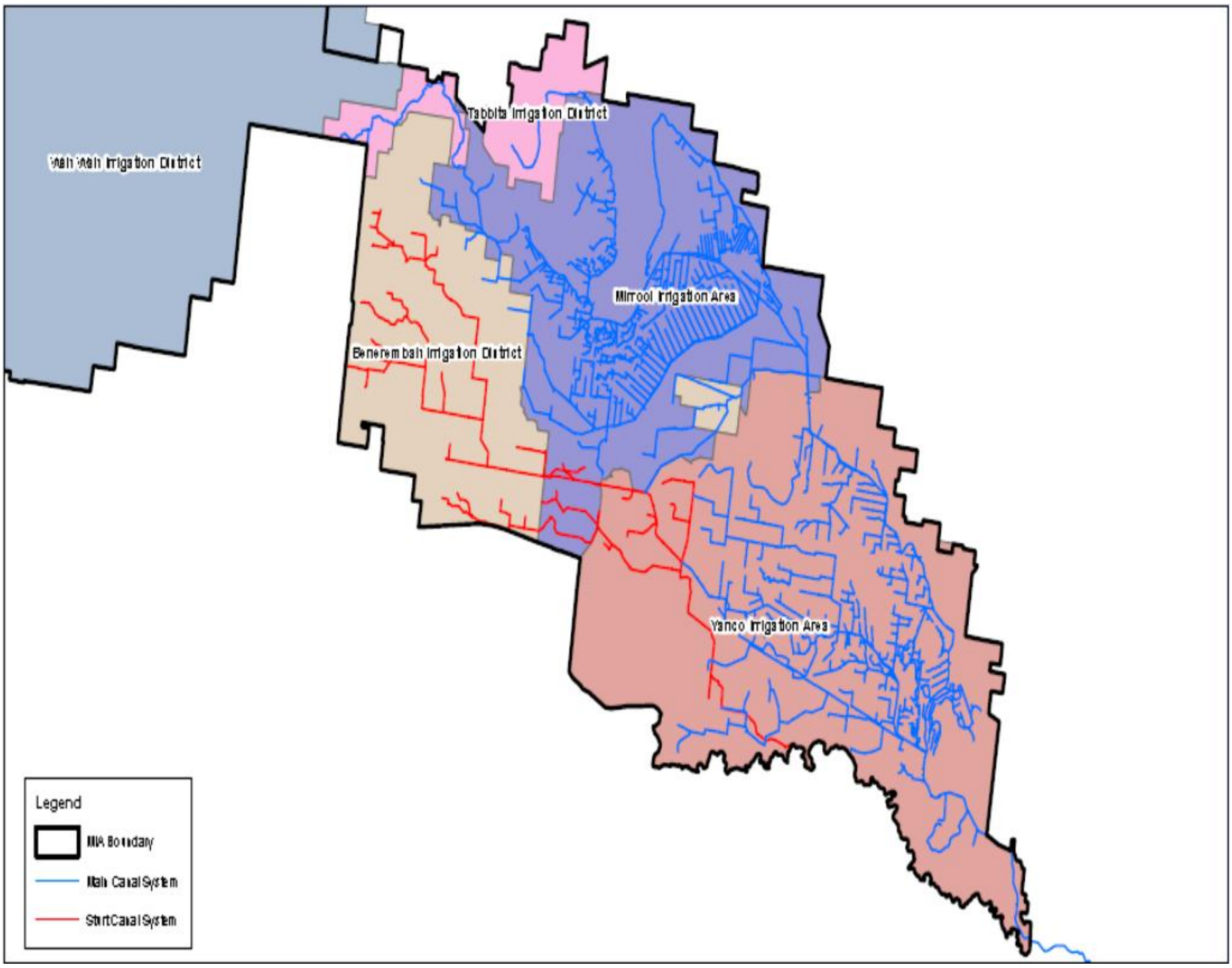

Figure 3.2 Irrigation districts under MIA Main Canal and Sturt Canal (MIL 2014)

3.3 Climate

The study area is part of the MIA and description about the MIA climate applies to the study area. Climate of the MIA is semi-arid and it ranges from hot and dry in summer to cold and moist in winter. In summer the MIA has an average maximum of 25°C for January, with extended periods above 35°C, and seasonal peak temperatures above 40°C. In winter the MIA has an average minimum of 7.5°C for July, with significant chill and frost factors.

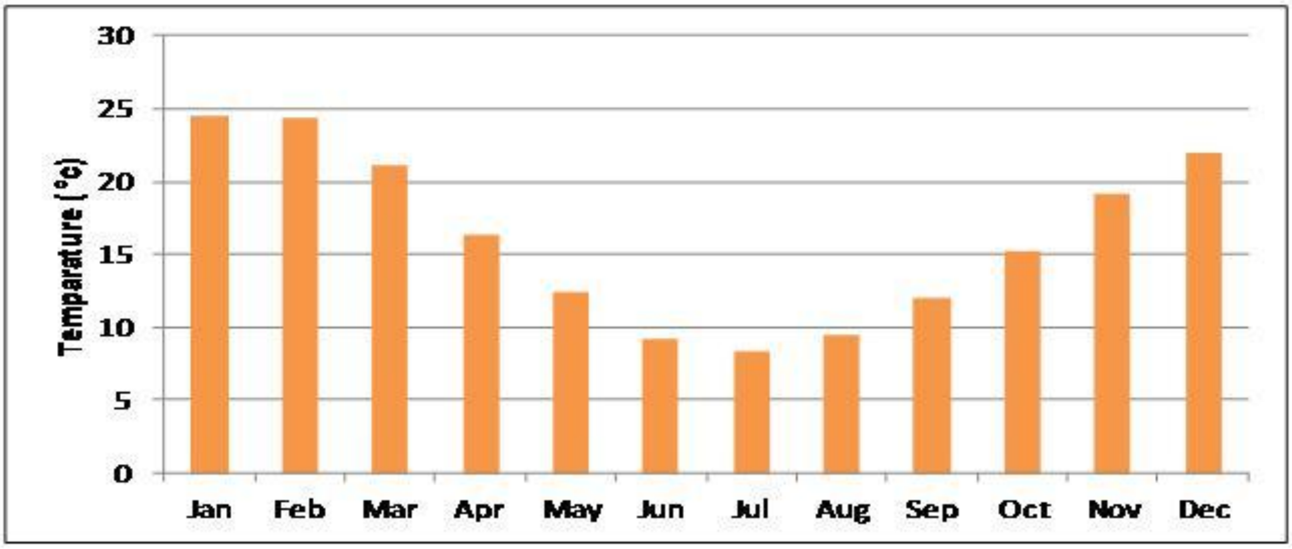

Figure 3.3 Average monthly temperatures from 1970 to 2012 taken at Griffith weather station (CSIRO 2013)

The annual average rainfall in the MIA ranges from 256mm to 609mm. Rainfall between June and October is more reliable than in summer. This period fits well with the moisture demands of winter crops. Summer rainfall occurs occasionally as heavy storms between October and March. It is usually of short duration and high intensity, hindering some of the farming operations. Annual average evaporation in the MIA is 1869 mm. The mean monthly evaporation peaks at 294 mm (9.5 mm/day) in January and drops to 43 mm (1.5 mm/day) in June (NSW Agriculture 1998 and Singh, Mullen & Jayasuriya 2005).

Towns of Merriwagga and Narrandera are situated in the north-west and south-east of the MIA respectively. Xevi et al. (2011) evaluated weather data from meteorological stations at Merriwagga, Griffith and Narrandera between years 1962-2007. They observed an annual trend of increasing rainfall from the drier north-west at Merriwagga (370 mm) to Griffith (390 mm) to the southeast at Narrandera (430mm) and a trend of reducing potential ET from Merriwagga (1430 mm) to Griffith (1360 mm) to Narrandera (1340 mm). Xevi et al. (2011) concluded that the marginal variation of climate did not warrant classifying the MIA into separate climate zones and Griffith climate could be adopted as representative of the MIA. Seasonal (April to March) climatic trends in years 2001-2007 indicated a prolonged period of drought with the exception of years 2000-01 and 2005-06, having a below long-term average rainfall (Xevi et al. 2011). Table 3.1 shows the figures of rainfall and potential ET for years 2000-01 and 2006-07.

Table 3.1 Distribution of Rainfall and ET for the MIA (Xevi et al. 2011)

YEAR	**RAINFALL** (mm/yr)	**EVAPOTRANSPIRATION** (mm/yr)
2000-01	432	1352
2006-07	160	1483

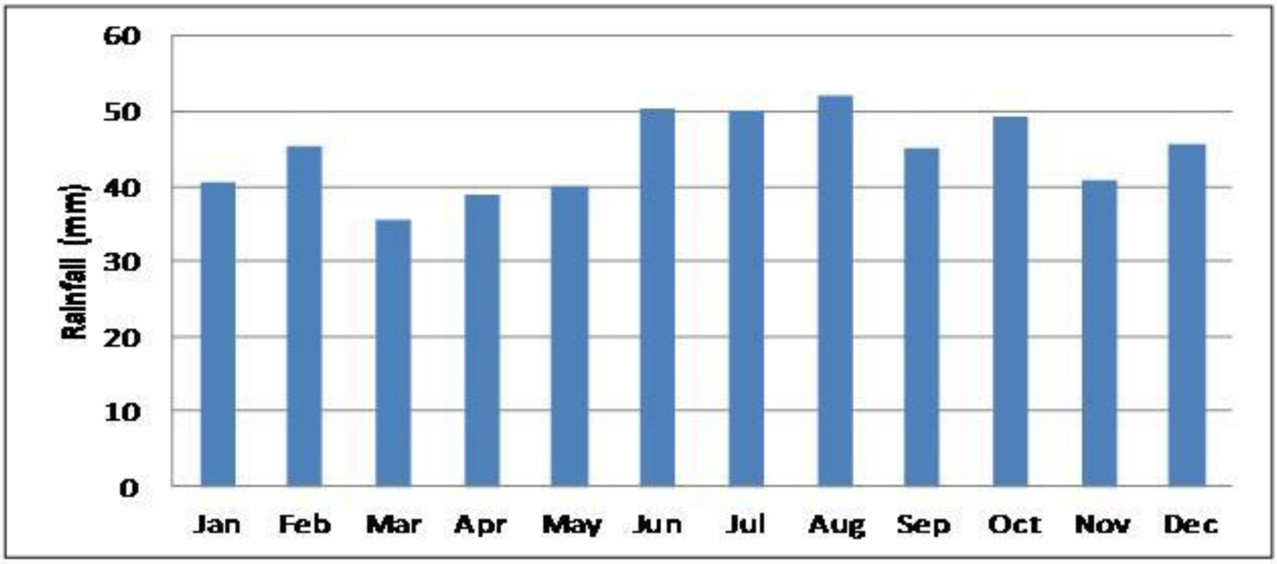

Figure 3.4 Average monthly rainfall from 1970 to 2012 taken at Griffith weather station (CSIRO 2013)

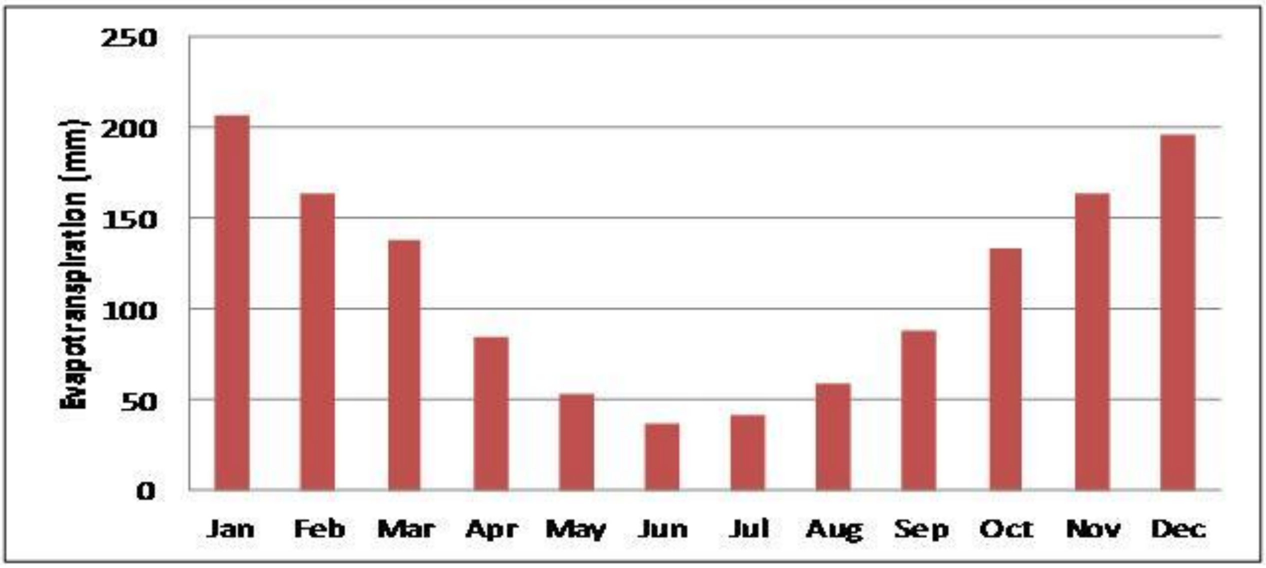

Figure 3.5 Average monthly ET from 1970 to 2012 taken at Griffith weather station (CSIRO 2013)

3.4 Geology and Hydrogeology

The study area is within the MIA on the northern side of a fluvial plain formed by the Murrumbidgee River. It is a combination of flat riverine plains and low forming hills. Majority of the study area has its elevations less than 200m above sea level with low hilly outcrops that raise upto 240m above sea level on the north-eastern flank of the study area. The land surface slopes generally towards the west with an average gradient of 380mm/km (Khan et al. 2004) and natural drainage is generally poor. The hydrogeology of the MIA is described by three major aquifer systems i.e. Shepparton, Calivil and Renmark Formations (Brown & Stephenson 1991) with the Shepparton Formation underlain by the Calivil Formation. Figure 3.6 shows the schematic of the MIA hydrogeology.

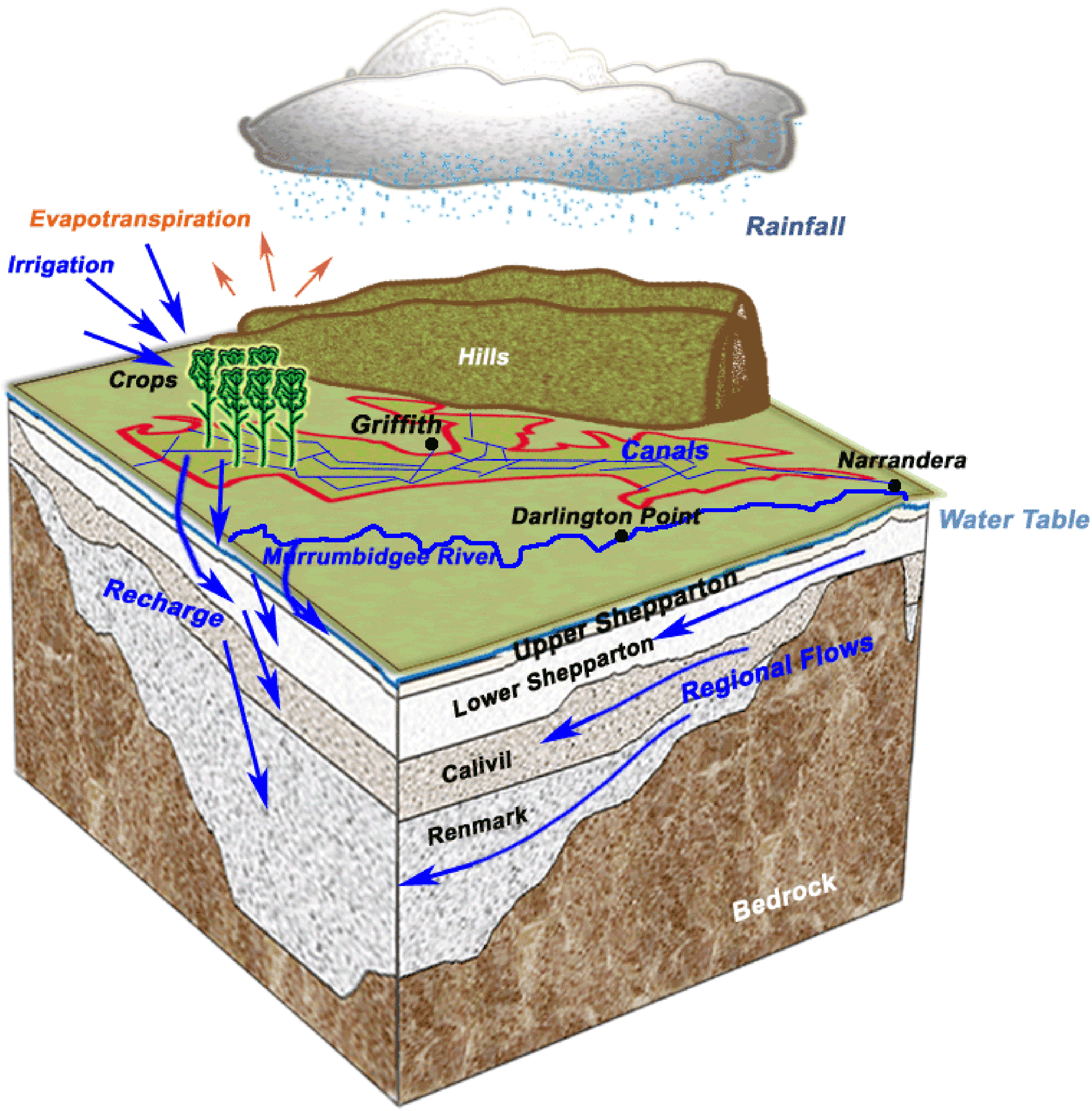

Figure 3.6 Schematic of the MIA hydrogeological systems (Khan et al. 2004)

3.4.1 Shepparton Formation

This partial aquifer system is a composite of aquifer and aquitard complex. This is the uppermost unit among aquifers and generally 40-70m thick with a maximum thickness of 100m. It belongs to late Pliocene to Pliestocene period. It comprises sediments of polymictic sands and variegated clays making it an unconfined aquifer system. The shallow nature of aquifers in this system leads to waterlogging and salinisation problems in irrigated areas. The aquifer yield is moderate between 5 to 20 L/s and generally used for stock use (Punthakey et al. 1994).

3.4.2 Calivil Formation

This unit lies below Shepparton Formation and is of late Miocene to Pliocene period. The system is generally 30-50m thick and ranging upto 80m in Darlington Point area. It mainly consists of poorly consolidated, pale grey, poorly sorted, coarse to granular quartz and conglomerate, with white kaolinitic matrix. Aquifers in the system yield extractions upto 150-400 L/s although groundwater is not extracted in the study area. Salinity in the system is lowest near Narrandera, where recharge occurs, and increases towards west (Punthakey et al. 1994).

3.4.3 Renmark Group

This basalt tertiary unit lies between the Calivil Formation and pre-tertiary bedrock. It belongs to the late Eocene to early Miocene period and overlies the basaltic bed rock from the Palaeocene to Miocene period. The Renmark formation is distinguished from the Calivil formation by the presence of grey, carbonaceous clay and dark brown lignite with thick sequences of grey, medium-grained quartzose sand. The thickness of the system varies considerably due to the underlying bedrock and reaches a maximum of 360m. The water quality is generally poor with salinities ranging between 640-2560 mg/L. It is not used for groundwater extraction in the study area (Punthakey et al. 1994).

3.5 Soils

The study area represents a major portion of the MIA. Hence, the classification of soil types and distribution of soils for the MIA applies to the study area. Hornbuckle and Christen (1999), Stannard (1970), Taylor and Hopper (1938) and van Dijk (1958 &1961) have mapped soils in the MIA between 0-5m depth. They found that there are more than 90 soil types in the MIA. Basing on their hydraulic characteristics they grouped soils into five distinct groups:

Clays: These self mulching and hard setting (non self mulching clays) soils either consist of crumbly calcareous shallow horizons (self mulching) or hard setting non-calcareous surface soils (non self mulching clays). The hydraulic conductivity of top horizons of self mulching clays (up to 0.5 m depth) is normally high (around 30 mm/day) whereas the hydraulic conductivity for deeper horizons (1.5 to 3 m) is relatively low (0.5 to 1mm /day). The reported hydraulic conductivity values for shallow non-self mulching clays are around 4 mm/day.

Red-Brown Earths: This group of soils consists of loamy or sandy surface horizons of more than 0.1 m depth which abruptly change to clay subsoils. The reported hydraulic conductivity values for this soil group vary greatly between 58 mm/day to 1039 mm/day.

Transitional Red Brown Earths: These soils have hydraulic characteristics of clays and red brown earths. The top clay layer is very shallow (0.08-0.1m). The deeper profiles contain lime and gypsum. The reported hydraulic conductivity of these soils in the 0.2-0.6 m depth ranges between 0.026 to 10 mm/day, with most values falling at the lower end of this range.

Sands over clays: These soils mainly consist of sandy top soils (0.1 to 0.6 m) with a dense sub clay soils. The hydraulic conductivity of some of the soils of this group is greater than 100 mm/day.

Deep sandy soils: These soils are of aeolian origin and contain coarse sands to a depth of 4 meters. The hydraulic conductivities for this soil group may be greater than 1000 mm/day.

3.6 Land use

The total land area of the study area is approximately 519,000 ha and the MIA is 660,000 ha. Table 3.2 shows the amount of land area under irrigation starting from 2000-01 to 2011-12. At the level of the MIA, it is suitable for three types of irrigated farming systems: horticulture, vegetable, and broadacre farms.

Table 3.2 Irrigated land in the study area from 2000-01 to 2011-12 (MIL 2014)

	IRRIGATION DISTRICT LAND USE (ha)				
YEAR	**YANCO**	**MIRROOL**	**TABBITA**	**WAH WAH**	**TOTAL IRRIGATED AREA**
2000-01	46916.5	51057.8	3353.1	23009.8	124337.2
2001-02	47394.0	54715.1	3917.5	20453.8	126480.4
2002-03	48837.2	52477.7	4460.8	13727.9	119503.6
2003-04	42070.4	51124.4	3915.9	14929.5	112040.2
2004-05	37884.3	46646.9	3701.5	11083.9	99316.6
2005-06	41912.5	49170.3	3402.0	13184.1	107668.9
2006-07	32023.6	39891.2	3401.2	8011.0	83327
2007-08	17353.6	29105.9	2918	6420.4	55797.9
2008-09	16932.2	31232.7	1911	6232.1	56308
2009-10	20636.5	32552.0	3125	6799.3	63112.8
2010-11	32869.0	40045.7	4502.8	11351.8	88769.3
2011-12	41015.2	47377.4	3681.5	11938.6	104012.7

3.6.1 Horticultural Farms

The study area is suitable for horticultural farms due to its well-drained soils. Grapes and citrus are the major crops grown in these irrigation districts accounting to 97 percent of area. The rest of the area is under prunes, apricots, peaches, plums, nectarines, nuts etc. Typical water usage is high at 12 ML/ha (Singh, Mullen & Jayasuriya 2005). In 1971 there were 935 horticultural farms in the MIA. The total area of permanent planting on these farms was 10,405 ha (Kennedy 1973). In 2003 there were more than 1,000 horticultural farms with a total area of 24,800 ha.

3.6.2 Vegetable Farms

Major vegetables grown in the MIA are onions, carrots, pumpkins, gherkins, melons, and tomatoes. Vegetable industry in the MIA owes it to its well developed irrigation supply system, warm climate and highly productive soils. Irrigation water allocations are made treating them as large area farms despite of being smaller size. In 1990 the total area under vegetables was 2,681 ha. In year 2002-2003 2,940 ha were under vegetable crops with a total value of production of $24.3 million.

3.6.3 Broadacre Farms

Rice in summer and wheat in winter are the most important crops grown on broadacre farms. Singh, Mullen and Jayasuriya (2005) observed that area under these crops has significantly increased from 1991 to 2001 although the acreage depended on market requirements and problems from rising watertables and soil salinity. Canola and soybean are other winter crops grown on these farms (Singh, Mullen & Jayasuriya 2005). Although sheep enterprises were major activities on these farms until 1998 they are at a minimum after 1998 (ABS 1998, CRC Rice 2000) Table 3.3 shows the distribution of irrigated area in the MIA from 2001-02 to 2011-12 according to the type of crops grown and the proportion of crops.

Table 3.3 Cropwise irrigated land distribution in the study area from 2000-01 to 2011-12 (MIL 2014)

CROP	**AREA** (ha)	**CROP PROPORTION**
CITRUS	90677.1	0.09
COTTON	6804.0	0.01
INDUSTRIAL	351.0	0.00
OTHER CROPS	10997.3	0.01
OTHER FRUITS	22895.2	0.02
PLANTATION	1953.8	0.00
RICE	124406.1	0.12
STOCK & DOMESTIC	7653.6	0.01
SUMMER CEREALS	32864.3	0.03
SUMMER OILSEEDS	12774.4	0.01
SUMMER PASTURE	40697.6	0.04
TOWN SUPPLY	4247.0	0.00
VEGETABLES	18189.5	0.02
VINES	182107.8	0.18
WINTER CEREALS	337468.9	0.33
WINTER OILSEEDS	41086.5	0.04
WINTER PASTURE	81730.5	0.08

Table 3.4 shows the amount of water diversions from the Main Canal into each of the irrigation districts in the study area from 2001-02 to 2011-12.

Table 3.4 Diversions to irrigated areas in the study area from 2000-01 to 2011-12 (MIL 2014)

YEAR	**IRRIGATION DISTRICT DIVERSIONS** (ML)				
	YANCO	**MIRROOL**	**TABBITA**	**WAH WAH**	**TOTAL DIVERSIONS**
2000-01	236832.3	264392	17150.3	128244.7	646619.3
2001-02	264519.8	308742.2	18820.3	111335.2	703417.5
2002-03	227754	277386.2	14707	68661.3	588508.5
2003-04	177511	249976.3	12614.3	63035.5	503137.1
2004-05	182136.4	243524.4	14364.9	68033.6	508059.3
2005-06	236351.1	276703.4	16806.6	82048.6	611909.7
2006-07	118848.6	183466.5	8684.6	31669.3	342669
2007-08	48210.4	118198.5	5365.9	14657.8	186432.6
2008-09	67063.2	141552.2	6069.9	20897.4	235582.7
2009-10	87415.9	168611.6	7562.4	26648.1	290238
2010-11	133731.8	163335.6	8770.8	40989.6	346827.8
2011-12	212913	249024.7	13112.5	79142	554192.2

3.7 Groundwater Levels

Within the MIA groundwater piezometers are being managed by the MIL and the NoW separately. The records show that groundwater levels within Calivil and Renmark aquifer systems have dropped since extractions began in 1994. Levels declined by 2-10 m between 2000 and 2005, but in some areas of Renmark group levels fell by more than 10m (MDBC 2008a). Groundwater for irrigation is extracted from the lower Murrumbidgee Alluvium groundwater management unit, which is downstream from Narrandera. Figure 3.7 shows the change of groundwater depths in the MIA starting from March 1997 to March 2013.

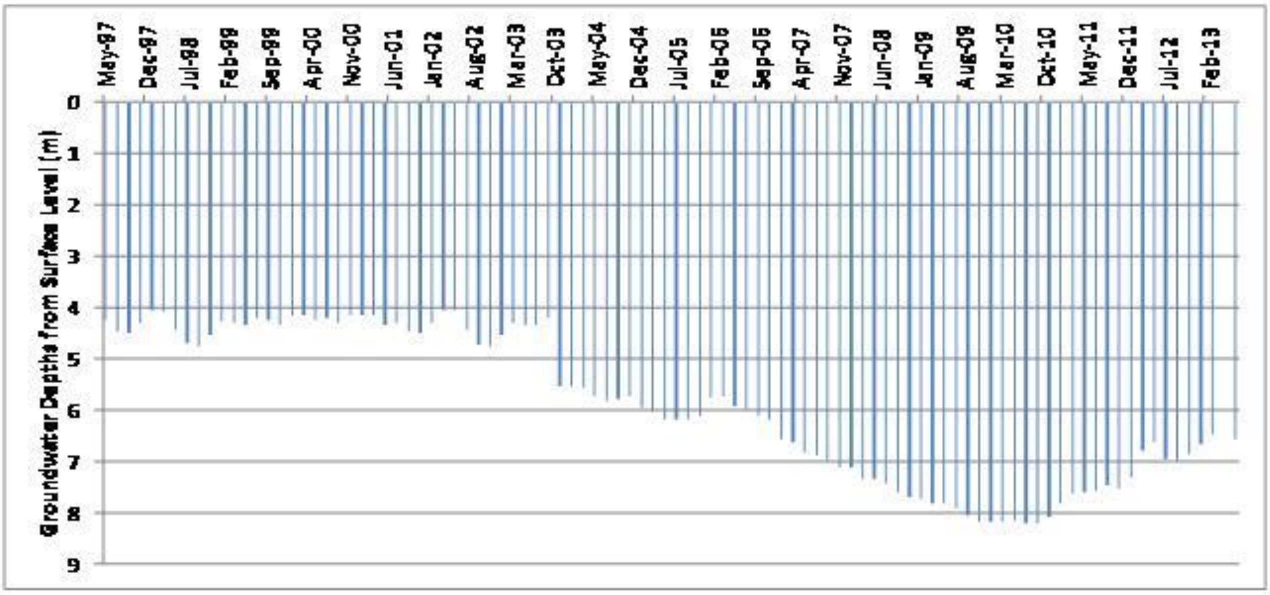

Figure 3.7 Groundwater table depths from May 1997 to July 2013 (MIL 2014)

3.8 Recharge studies within the MIA and lower Murrumbidgee

Literature review has identified several studies or reviews of groundwater models made within the MIA and the lower Murrumbidgee, shown in figure 3.8. These models and reports have also estimated groundwater recharge. It is observed that the groundwater models have estimated recharge by water balancing within a given period of years. There are also farm scale studies that have utilised direct methods to estimate recharge. Recharge estimations from all the sources have been included in the literature review in the following subsections.

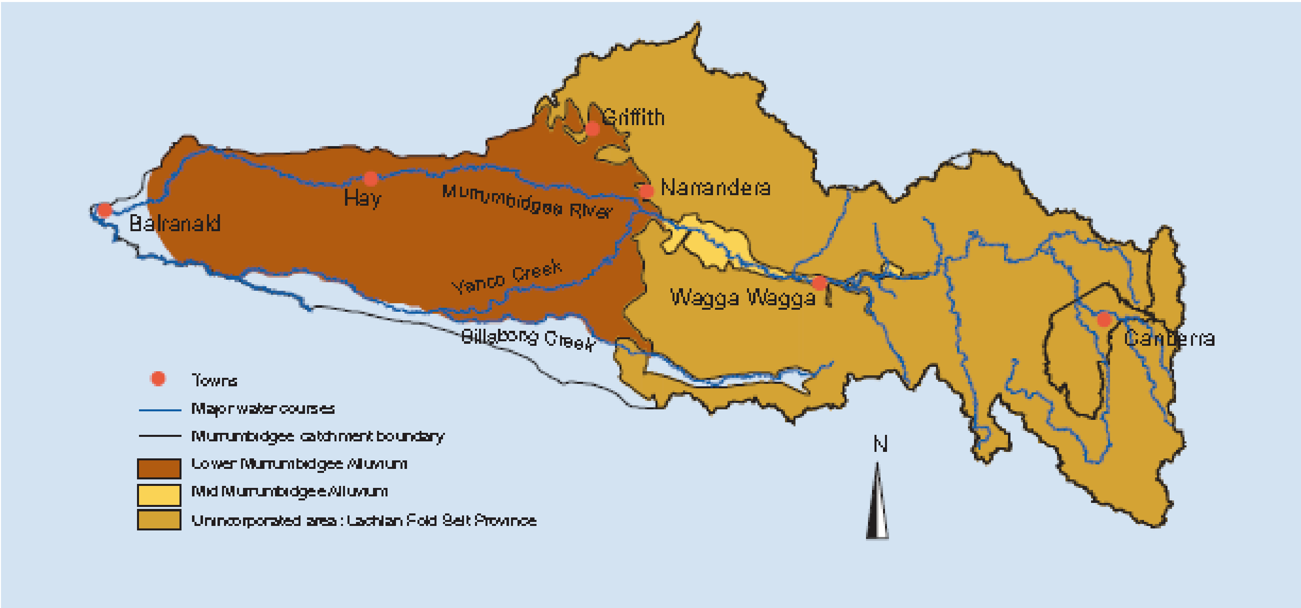

Figure 3.8 Lower Murrumbidgee catchment (CSIRO 2008)

3.8.1 Recharge estimates from the MIA

3.8.1.1 License Compliance Reports, MIL

MIL published groundwater recharge estimates under rice fields within the MIA for the year 2004-2005 and 2005-2006 in its license compliance reports. Khan et al. (2004 & 2005) have estimated the recharge by making a water balance of the soil profile, crop water uptake and groundwater conditions. Recharge was estimated for minimum, median and maximum groundwater depths. Table 3.5 and 3.6 show the recharge estimates for year 2004-05 and 2005-06. Recharge for Wah Wah was not calculated (n/c) due to insufficient groundwater data.

Table 3.5 Rice recharge for 2004-05 (MIL 2005)

IRRIGATION AREA	**MINIMUM RECHARGE** (ML/ha)	**MEDIAN RECHARGE** (ML/ha)	**MAXIMUM RECHARGE** (ML/ha)	**NET RECHARGE** (ML/ha)
Yanco	0	0	0.53	0.02
Mirrool	0	0	0.1	0.07
Tabbita	0	0	0.27	0.86
Wah Wah	n/c	n/c	n/c	n/c

Table 3.6 Rice recharge for 2005-06 (MIL 2006)

IRRIGATION AREA	**TOTAL RICE AREA** (ha)	**TOTAL WATER APPLIED TO RICE** (ML/ha)	**MINIMUM RECHARGE** (ML/ha)	**MEDIAN RECHARGE** (ML/ha)	**MAXIMUM RECHARGE** (ML/ha)	**NET RECHARGE** (ML/ha)
Yanco	9100	12.8	0	0.45	0.91	0.24
Mirrool	7949	12.8	0	0.26	0.78	0.09
Tabbita	320	13.6	0	0.04	0.35	0.02
Wah Wah	1874	14	0.57	1.31	1.71	n/c

3.8.1.2 SWAGMAN Destiny

SWAGMAN Destiny is a point scale soil water balance and crop growth simulation model with crop growth affected by water, salt and aeration stress. Xevi et al. (2011) used SWAGMAN Destiny to simulate the impacts of land use, soil type, climate, and watertable depth on evapotranspiration and recharge within the MIA. SWAGMAN Destiny was used to simulate recharge/discharge from

1963 to 2007 for 315 combinations of land use, soil type, watertable depth and climate. A database was created from the results of simulations and was subsequently used to generate maps of seasonal ET and recharge/discharge. Analysis of these maps showed the largest net contributor of drainage was rice, but this contribution declined over the study period, which was characterised by a prolonged drought and a large reduction in the area of rice. The largest contributor to discharge was irrigated winter wheat located in areas with groundwater depths less than 2 m. The contribution varied from season to season depending on seasonal weather and on the changes in the areas with different groundwater depths.

Table 3.7 shows annual water balance components calculated as area-weighted means over whole of the MIA for the seasons 2000-01 to 2006-07. Negative drainage values indicate upward flow or discharge (Xevi et al. 2011).

Table 3.7 Recharge estimates from SWAGSIM Destiny for period 2000-01 to 2006-07

SEASON (starting April 1)	AREA-WEIGHTED ANNUAL					
	RAINFALL	IRRIGATION	RUNOFF	ET	DRAINAGE	SOIL STORAGE
	mm/yr					
2000/01	433	220	45.5	577	61.9	-32
2001/02	295	296	34.1	535	34.1	-12
2002/03	177	200	33.7	399	-13	-44
2003/04	318	147	22.6	451	0.4	-9
2004/05	254	169	9.5	439	-15.1	-10
2005/06	395	227	56.4	493	42.9	31
2006/07	164	142	7.4	353	-21.9	-33

3.8.1.3 Murrumbidgee groundwater model

A surface-groundwater interaction model for the MIA was developed by Khan et al. (2004). It was built using MODFLOW coupled with MT3D solute transport simulator. The model covers an area of 674000 ha. The spatial domain represented in the model consists of four layers of 106 rows and 113 columns with a cell size of 750mx750m. For calibration purposes, irrigation periods are specified over a 6-month period, from October through to March. External stresses such as wells, areal recharge, evaporation, drains and streams are simulated to calculate the water budget of each irrigation district of the MIA and the average values in ML/season are presented for the whole calibration period. Water balancing was used as a means to express the model results. Water budget for the calibration period of September 1995 - August 2000 has been presented in the results. The recharge is estimated to be 118.5GL during irrigation period and 16.58 GL during non-irrigation periods (Khan et al. 2004).

3.8.1.4 SWAGSIM Model

SWAGSIM was developed by Prathapar et al. (1994) to predict watertable fluctuations in an extensively irrigated subregion. A locally calibrated Penman model is used to estimate actual evaporative demand from climatic variables. Recharge to the watertable is estimated using an analytical solution for Richard's equation, with actual evaporation as the surface boundary conditions and the watertable as the lower boundary condition. The model was applied to the Camarooka project area near Griffith. The model estimates a net recharge of 327ML over an area of 3750ha for the year 1989/90.

3.8.1.5 Simulations of groundwater flow and solute transport at Whitton farm

A two layered model to simulate groundwater flow and solute transport was developed by Khan et al. (2000) using MODFLOW. The grid size varied between 10mx10m to 200mx 200m. The model was applied on rice paddock of approximately 3km^2 area in Whitton. Recharge into the model domain was considered to be mainly from rainfall, and was set to be 10% of the rainfall as recorded at Yanco site.

3.8.1.6 Collate of various studies in the MIA

Groundwater recharge rates under irrigated agricultural areas within the MIA from various research studies have been collated in table 3.8. These data contain information about the location, soil type, crop type, recharge amount, and source of the data. The commonly used recharge estimation/determination methods by the collated research studies are: lysimeters, chloride mass balance method, water balance equation, one dimensional (1D) unsaturated zone models, and Darcy's law. Irrigated cotton, maize, wheat, soybeans, and rice are the most studied crops. A large number of studies focus on heavy textured soils. Fewer studies focus on light textured and duplex soils. Estimation of recharge under ponded rice has also been the focus of few studies.

Table 3.8 Recharge estimates from various studies in the MIA

LOCATION	SOIL TYPE	CROP	RECHARGE (mm/yr)	SOURCE
Griffith	Cracking grey clay	Cotton	32-42% crop water use from upflow	Mason et al. (1983)
	Red brown earth		5-11% cropwater use from upflow	
Whitton	Transitional Red brown earth	Rice	510	Muirhead et al. (1989)
Whitton	Transitional Red brown earth	Rice	270	Humphreys et al. (1989; 1991)
Coleambally	Transitional Red brown earth	Rice	510	Humphreys (1994)
Coleambally	Transitional Red brown earth	Rice	270	Humphreys (1994)
Griffith	Transitional Red clay loam	Maize	10-20	Downey (1971)
Griffith	Red brown earth	Maize	-212	Smith et al. (1993)
Griffith	Transitional Red brown earth	Maize	-57	Prathapar & Meyer (1992)
Leeton	Red brown earth	Wheat	0-90	Cooper (1979, 1980)
Griffith	Red brown earth	Wheat	71 49 81	Meyer et al. (1984)
Griffith	Red brown earth	Wheat	-140	Meyer et al. (1985)
Griffith	Red brown earth	Wheat	66	Meyer (1988)
Griffith	Transitional Red brown earth	Wheat	-76 -157 -42	Meyer et al. (1988)
Griffith	Red brown earth	Wheat	41 -6 19 11	Steiner et al. (1985)
Griffith	Red brown earth	Soybeans	-216	Meyer et al. (1990) and Dugas et al. (1990)
Griffith	Transitional Red brown earth	Soybeans	46	Meyer & Mateos (1990) and Meyer (1988)

-ve sign represents upflow

3.8.2 Recharge estimates from lower Murrumbidgee groundwater models

Two catchment scale groundwater models have been developed by the NoW representing lower Murrumbidgee. Both of them have been constructed using MODFLOW. The difference lies in the cell sizes that have been adopted for each model.

3.8.2.1 Lower Murrumbidgee Model (Punthakey et al. 1994)

This is a transient groundwater flow model for the lower Murrumbidgee groundwater flow systems. MODFLOW was utilised for modelling. The model consists of several packages representing various aspects of the hydrologic system. The cell sizes within the model are 7500m x 7500m and comprise three layers with each layer representing a major regional aquifer system. The model covers an area of approximately 39000km^2. The model was used to simulate aquifer response to seven land and water management scenarios during the period September 1980 to August 2020. Results from the scenario “Increased Irrigation” are discussed below.

Increased Irrigation considers a 50% increase in Irrigation areas and districts, and on properties with irrigation>40 hectares. The results for the scenario are presented in water balance format in table 3.9 as below:

Table 3.9 Recharge estimates from MODFLOW for period 09/1980 to 08/2020 (Punthakey et al. 1994)

COMPONENT	**IN**(m^3/d)	**OUT**(m^3/d)	**Net**(m^3/d)
Storage	541710	1310340	768630
Wells	0	97540	-97540
Net Recharge	1087680	599370	488310
River Leakage	458260	77000	381260
Boundary Flows	50600	54000	-3400
TOTAL	2138250	2138250	0

Kumar (2002) calibrated the model during the period 1975 -1990. It does not include the actual recharge from applied (irrigation) water and current pumping distribution. Model output results are summarised in table 3.10.

Table 3.10 Recharge estimates from MODFLOW for period 1975 to 1990 (Kumar 2002)

	SHALLOW SOURCE (Shepparton) in GL/yr	**DEEP SOURCE (Calivil+Renmark)** in GL/yr
Rainfall Recharge	233	n/a
River Recharge	164	n/a
Vertical Leakage	n/a	335
Throughflow	1	22
Total	398	357

3.8.2.2 Lower Murrumbidgee model (O'Neill 2005)

This three-dimensional finite difference numerical model was developed using MODFLOW with a uniform grid size of 2500m x 2500m. The model covers an area of 33,000sq.km approximately. It consists of three layers corresponding to the principal hydrogeological units present in the lower Murrumbidgee area. Percentage of recharging rainfall is assumed constant at 0.8% over the entire model (spatial and temporal) area and is applied to Layer 1. This value is equivalent to 2.8 mm/y. For historic data, recharge from rainfall was calculated as 6.4 mm/year (median) and 3.9 mm/year (dry). Groundwater ET is represented in the model through the ET package of MODFLOW which simulates the effects of plant transpiration and direct evaporation in removing water from the saturated groundwater regime.

The model was calibrated for the period September 1975 to June 2002 and later extended to 2010. The model assumes that the proportion of irrigation application to become recharge is equal for surface water and groundwater sources for irrigation. Irrigation recharge was used as a calibration parameter for PEST. The recharge is determined to be 9.6% of irrigation application through manual trial and error calibration. This model determined recharge from individual irrigation plots using the concept of irrigation intensity which is the percentage of area proposed to be irrigated annually. For rice areas and other irrigation areas, recharge rates of 43.2 mm/yr and 5.8mm/yr were derived from calibration of model. Hence, net recharge sums to 51.8mm/yr for 2010.

The model was calibrated by CSIRO (2008) during the period of 1996 to 2001. The mass balance for the model is presented graphically in figure 3.9. Total mass in was 424 GL/year and total mass out was 308 GL/year. Lateral groundwater flow out of the model is an important groundwater discharge. This flow is predominantly across the western model boundary. Inflow to the aquifers is made up of fluxes from the Murrumbidgee River to groundwater, recharge (rainfall recharge and irrigation recharge) and lateral groundwater flow in.

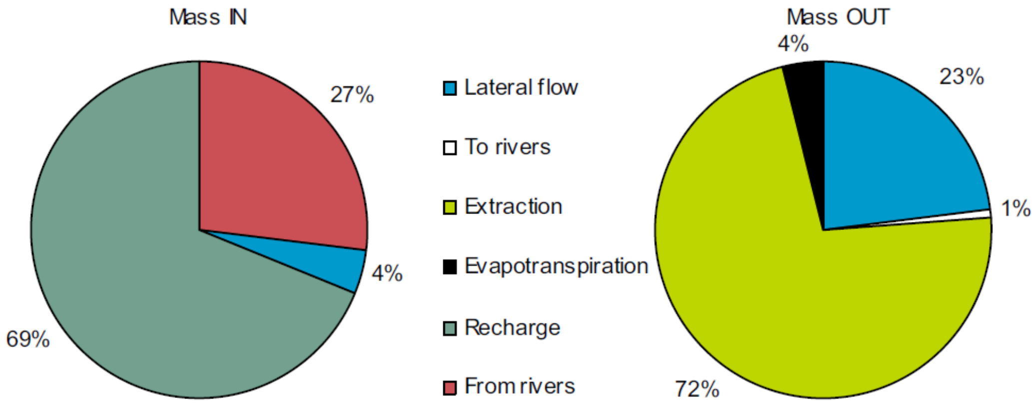

Figure 3.9 Mass balance for period 07/1996 to 06/2001 (CSIRO 2008)

Table 3.11 shows the results from the water balance output for the period July 1997 to June 2002. The results were published by Kumar (2010) and they indicate an average annual recharge of 395 GL for the Shepparton aquifer and a net vertical leakage of 275 GL for the Calivil and Renmark aquifers due to pumping observed for that period.

Table 3.11 Recharge estimates from MODFLOW for period 07/1997 to 06/2002 (O'Neill 2005)

	SHALLOW SOURCE (Shepparton) in GL	**DEEP SOURCE (Calivil+Renmark)** in GL
Rainfall and Irrigation Recharge	286.3	n/a
Recharge from rainfall	108.4	n/a
Average annual recharge from rainfall, recharge and river	394.7	n/a
Gain from net leakage or net vertical leakage	-274.8	274.8
Gain from throughflow	-0.4	-56.6
Groundwater extractions	-22.1	-231.5
Change in groundwater storage	97.4	-13

3.9 Summary

The study area chosen for the project is within the MIA, an agricultural area within a semi-arid region of NSW. A multitude of research studies and experiments that estimated groundwater have been done in the irrigation districts of the MIA. Availability of recharge estimates from other studies is vital to the project which formed the basis for choice of the study area. Section 3.8 consists of recharge estimates from various sources with units in original format which have been reduced to mm/year in chapter 4.

A good understanding of the climatic factors, soil properties, land use and the hydrogeological processes surrounding the study area is necessary to appreciate the hydrological cycle associated with the region. This, inturn, would assist in determining an appropriate recharge estimation technique which is pertinent to the study area. The chapter provides a comprehensive overview of the climate and its changes, surface water resources and underground aquifers along with the types of crops grown in the study area for the entire period of study. This study helps in making an initial assessment of the water balance for the study area.

4. MODELS AND METHODOLOGY

4.1 Introduction

The chapter describes the development of a groundwater recharge optimisation method for the study area. The optimisation method is a simple error based statistical tool that can be used to arrive at estimates of groundwater recharge for a given catchment based on a set of prediction parameters. Inorder to develop an optimisation method it is necessary to have an existing groundwater or surfacewater model that would also calculate groundwater recharge. An optimisation method is important to reduce the uncertainty associated with any surfacewater or groundwater models in calculating groundwater recharge. This uncertainty is a major impediment to reliably quantify groundwater resources, which in turn affects groundwater sustainable yield assessments and allocation to the irrigation industry.

The current project utilises AWRA-R irrigation model, developed by CSIRO, as its building block for developing an optimisation method. Further information about AWRA modelling system is provided in Appendix B. The irrigation model is made up of a diversions module and a recharge module. The optimisation method may be considered as an extension to the irrigation model that refines the recharge estimates from the irrigation module in such a way as to minimise the uncertainty that manifests as a part of the process in the irrigation model. The primary purpose of the project is to arrive at prediction parameters for the study area and utilise them to predict recharge. The inputs to the irrigation model specific to the study area are applied to obtain simulation outputs of recharge which are subsequently used to arrive at prediction parameters. The methodology described in the later sections of the chapter provides information on applying the optimisation method to obtain prediction parameters.

4.2 AWRA-R Irrigation Model

AWRA-R irrigation model is a broadscale surfacewater model that simulates the behaviour of any irrigation district in terms of irrigation diversions, volumes, and soil-moisture balance. It also captures the district's response to changing water availability (Hughes et al. 2013). It consists of two components: 1. Diversions modelling module and 2. Recharge estimation module. Daily diversions are estimated using diversions modelling module while recharge is calculated using recharge estimation module (Hughes et al. 2014). Outputs from diversions module: diversions, irrigated area and soil-moisture content are used as some of inputs for recharge module. The recharge module estimates groundwater recharge using OFR equations discussed in section 2.4.3.

Diversions modelling Module: Diversions to irrigated agriculture have an impact on available water resources. Hence, irrigation diversion is an important element of water balance in regulated river systems. Availability of diversion data from the past is necessary inorder to analyse it and make accurate predictions for unknown diversions in the past or in future. But, historical data for diversions is often difficult to source. Diversions module incorporates methods to simulate diversions from past based on available data (Hughes et al. 2013). In addition to diversions the module simulates total irrigated area and behaviour of soil-moisture balance for the irrigation district in a lumped calculation. It also captures the response of irrigated area to changing availability of water (Hughes et al. 2013). The module produces daily estimates of diversions as output which are useful as input parameters for AWRA-R (Hughes et al. 2013).

As part of establishing components for water balance AWRA-R irrigation model calculates groundwater recharge from rainfall events or irrigation applications within crop fields for any district. The model utilises OFR equations for estimating recharge. It is due to the inherent advantages listed in section 2.4.3, the method has befitted the irrigation model. The input data available for diversions module may be parsimonious. Also, calibration of diversions module demands multiple iterations requiring less consumption of time. Above such constraints related to diversions module are well complemented by advantages of OFR method making it ideal to use in the irrigation model. The model, however, employs a modified form of OFR method for estimating recharge (Doble et al. 2013) which may be considered as a particular case of the original OFR equations.

Recharge estimation Module: The rationale to modify OFR method to suit its application to irrigation model is provided below: Different types of crops are grown in Murray Darling Basin. Recharge may or may not occur in irrigated areas and is influenced by factors like climate, soil properties and water requirements of crop types. In areas such as rice farms which require high loading of water the soilwater is converted into recharge as the soil beneath is saturated. It is a similar scenario to that of overbank flooding in lowlying floodplains. Similar effect is also observed during flooding within farm bunds due to rainfall. The original OFR method calculates ΔS and I considering extent of flooding in one dimension (x_w). The equations are modified by considering flood extents in two dimensions, area (a_{cur}) to enable estimating of recharge in crop fields.

Irrigation model assumes perfect scheduling of irrigation application. This means irrigation to fields is stopped immediately after the top soil is saturated to ensure there is no excess irrigation water above soil surface (h_w). This applied to OFR equations; the term (h_w/d_c) in equation for infiltration becomes 0. Also, modified OFR method does not take transmissivity into account. Hence, the term Q is omitted from the calculation for recharge. The remaining terms K_c, d_{gw}, S_y, and soilCap are the other input parameters that are required for estimating recharge (Hughes et al. 2014).

Figure 4.1 shows the connection between the diversions and recharge modules interms of input and output parameters. For each simulation run of AWRA-R irrigation model, with a set of input parameters, daily groundwater recharge is also output along with other results.

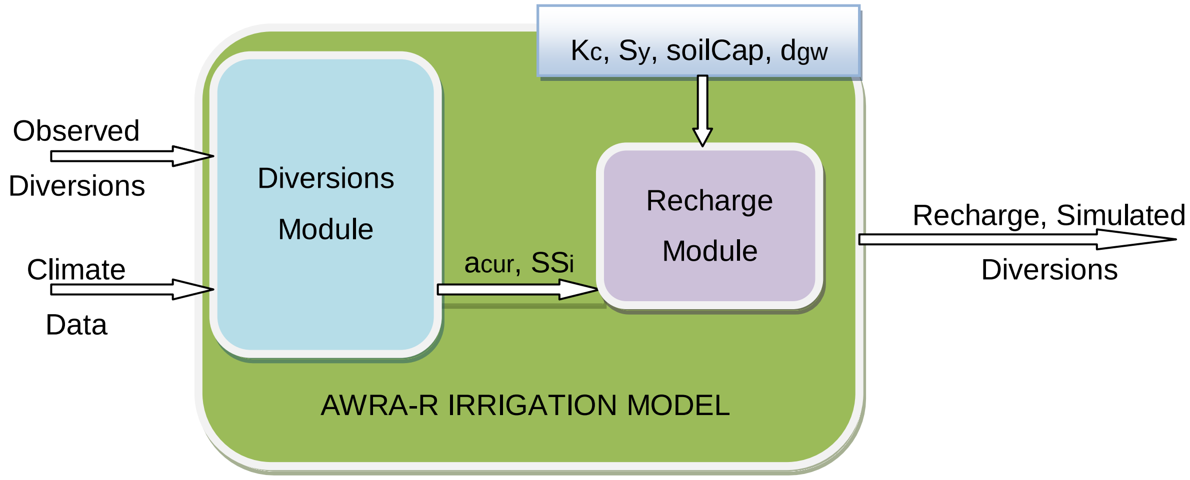

Figure 4.1 AWRA-R Irrigation model

AWRA-R irrigation model is built using C language. Though C is used to build the model the simulations are performed using R. R is a statistical programming tool. Specific to the irrigation model there are several benefits in using R:

1. Input datasets for irrigation model i.e diversion data and climate data are provided in .csv format.

2. Compared to other programming tools it is relatively less arduous to code in R.

3. It is necessary to generate multiple trial and error simulations inorder to reduce the error between observed data and simulated outputs. Given that irrigation model is a broadscale model, it is necessary to perform each simulation trial quickly. R is effective in reducing time running through the program.

4. The outputs from final simulations can be extracted in .csv format.

Current project is set in a semi-arid region where the depth of groundwater levels is greater than 9m at places across the study area which makes meteorological water balancing and water fluctuation method (described in sections 2.4.1 and 2.4.2) unsuitable for the project purpose. Modified OFR equations consider infiltration, soil-moisture storage for determining the amount of recharge. Owing to this advantage besides other benefits described earlier in the section, modified OFR method is chosen as prescribed recharge model for the current project.

4.3 Calculation of Groundwater recharge

Current project utilises AWRA-R irrigation model for the purpose of estimating groundwater recharge in the study area. As discussed in the previous section, the input parameters required for the calibration of recharge module are obtained partly as simulation output parameters from diversions module and partly as direct inputs. The parameters vary depending on the irrigation district under consideration for modelling except for the daily timestep (tw). The values of acur and

SSi depend on the daily diversion and allocation data, and the climate data. In a given irrigation district, the soil and aquifer characteristics vary due to the geographic size. Hence, the values of direct inputs, Kc, Sy and soilCap, need to be determined from a range of possible values. Also, the simplicity of recharge module demands that only single values of Sy, Kc and soilCap are used for representing a particular irrigation district. These values are determined by adopting the sensitivity analysis approach. Firstly, the inputs specific to the study area for calculation of groundwater recharge have been obtained and discussed as below:

4.3.1 Time Series Data

4.3.1.1 Depth to Groundwater (d_{gw})

As indicated in section 3.7, bi-monthly borehole data from all the piezometers across the MIA from years 1997-2013 has been obtained from the MIL. The data was processed by culling out the data from piezometers inside towns and near drainage/irrigation channels. Further, it was averaged to obtain a mean groundwater level for the MIA. This bi-monthly data was subsequently interpolated to a daily timestep.

Borehole data is not available for years 1970-1997. Inorder to bring the borehole data on par with diversion data in terms of historic data availability, an assumption regarding groundwater level was made. A constant depth of 5m has been assumed basing on the average depth from 1997-2000. Thus, the dataset of borehole data for the MIA was prepared for years 1970-2013 and utilised to run in the recharge model.

4.3.1.2 Observed Diversions (License Volume) and Climate Data

The data is required as inputs for irrigation model inorder to generate transition outputs; current area and soil-moisture content. These transition parameters inturn are useful as inputs for running recharge model. Daily diversion data and allocation data for the Main Canal were provided by the NoW for years 1980-81 to 2012-13 in spreadsheet format. Climate data was obtained from CSIRO databases. The database contained daily information on rainfall, temperature and Evapotranspiration for years 1970-2012 recorder at Griffith weather station.

4.3.1.3 Current Area (a_{cur})

Acur is a transition output from irrigation model that is supplied to recharge model as an input. The irrigation model performs computation of several variables in the process of calculating current area. The intial step is to calculate the maximum area (areaMax) available for cultivation during summer and winter separately. The next step is to deduce the current area under crop utilising areaMax. The model employs equation 4.1 to calculate maximum area (km^2) available for cultivation in a year during summer and winter seasons.

$\text{areaMax} = \text{volMax}/(\sum_{i=1}^{366} \overline{ET}_{o,i} * K_{w,i} * \text{efficiency})$ 4.1

Where volMax is the maximum available water in any single year (ML); it is also the license volume of irrigation diversion in a given year. $\overline{ET}_{o,i}$ is the average ET_o by julian day i (mm), $K_{w,i}$ is the weighted crop factor on Julian day i (dimensionless), and efficiency is the irrigation efficiency factor (dimensionless and set at 1.5).

ET is Evapotranspiration that are supplied to model as input parameters. K_{wi} is crop factor that represents aerial distribution of crops grown in a district and the irrigation water consumed and is calculated within the model. K_{wi} encapsulates in its calculation the allocation of water for summer and winter crops. This is to ensure possible saving of water for the next season.

The next step is to calculate the areaC_i (km^2) of crop planted on a day i. The following equation 4.2 is incorporated into irrigation model to calculate areaC_i.

$$\text{areaC}i = \frac{\text{volA}_i}{\text{volMax}} * \text{areaMax} * \frac{\alpha}{\left(\frac{\text{volA}_i}{\text{volMax}} + \beta\right)} \quad \text{...} \quad 4.2$$

where α and β are parameters (dimensionless) that are calibrated for each reach against observed diversion data. volA_i(ML) is the total volume of water resources available on day i. It represents the product of allocation for the district and license volume of diversions.

Finally, a_{cur} is calculated as product of areaC_i and the proportion of area sown to crop (areaActi), a dimensionless quantity, which is received as an input parameter. areaActi contains daily data that apportions irrigated area sown to the kind of crop based on winter or summer seasons. Irrigation model calculates areaC_i on a daily basis and hence a_{cur}. Inorder to arrive at area under crop during each season, the maximum value of acur in each season is chosen for winter and summer season separately. The areas are summed up to result in crop area for a particular irrigation year.

4.3.1.4 Soil Moisture Content (SS_i)

SSi is a transition output calculated from the simulation run of irrigation model. Its units are mm/day. It is utilised as input for recharge model to calculate infiltration. SSi is the depth of soil water available on day *i*. Soil water available can become negative, in which case a maximum irrigation requirement is utilised. The soil water-irrigation function is illustrated in figure 4.2. Soil water from the previous time step is updated with the depth of irrigation, rainfall and crop demand. Any excess water i.e., SSi greater than soilCap, is considered to be runoff.

$$SS_i = SS_{i-1} - \left(\frac{Kw_i * E_i}{\text{areaAct}_i}\right) + \left(\frac{\text{irr}_{i-1}}{\text{areaC}_i * \text{areaAct}_i * \text{eff}}\right) + P_i \quad \text{...} \quad 4.3$$

Where E_i is the evaporation losses and P_i is the precipitation which is supplied to irrigation model as inputs.

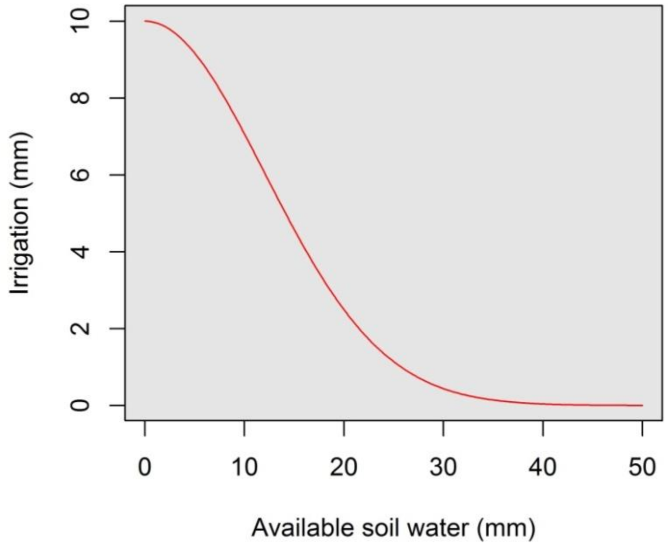

Figure 4.2 Soil-Water irrigation function (Hughes et al. 2012)

4.3.2 Input Parameters

4.3.2.1 Aquifer Specific yield (S_y)

Khan et al. (2004) determined Sy values pertaining to the MIA as a part of developing groundwater model. They arrived at the Sy values based on experimental data. Sy values are provided for 2 layers of aquifers in ranges of 0-5m and 5-10m depths. The units are m/m/day. A value of 0.093 has been adopted for the purpose of calibrating the irrigation model.

Table 4.1 Aquifer Specific Yield values for the MIA (Khan et al. 2004)

	Sy≤5m	**Sy>5m and ≤ 10m**
Mean	8.55E-02	9.30E-02
Standard Deviation	3.44E-02	4.00E-02
Skewness	1.99E+00	1.14E+00
Range	1.55E-01	1.55E-01
Minimum	5.50E-02	5.50E-02
Maximum	2.10E-01	2.10E-01
Count	1.99E+03	1.44E+03

4.3.2.2 Hydraulic Conductivity (K_c)

The study area is distributed with majorly 5 varieties of soils with different Kc values (Khan et al. 2004). Table 4.2 shows the different values of Kc occurring within the study area. A range of values between 1E-09 to 1E-06 m/sec have been utilised in the irrigation model.

Table 4.2 Hydraulic conductivity values for the MIA (Khan et al. 2004)

	Kc (mm/day)	**Kc** (m/sec)
Clay	0.5 - 1	6E-09 – 1.2E-08
Red-Brown Earths	58 -1039	7E-07 – 1.3E-05
Transitional Red-Brown Earths	0.026 - 10	3E-10 – 1.2E-07
Sands over clay	>100	>1.2E-06
Deep Sandy soils	>1000	>1.2E-05

4.3.2.3 Maximum Soil Storage Capacity (soilCap)

The thickness of top soil in agricultural fields varies depending on the type of crops grown. It also depends on the type of soil and agricultural management methods. A range of values 50mm - 150mm is taken as thickness of top soil for calibration of recharge model.

4.3.3 Calculation of Infiltration potential (I) and Unsaturated Storage (ΔS)

Crop irrigation requirement varies from crop demand depending on soil moisture storage and rainfall (Hughes et al. 2013). Within an irrigation district, there are variety of soil types with different soil-moisture storage capacities, irrigation structures, and management methods. Hence, to account for the effects from such factors soil-moisture storage based function is used to trigger irrigation. As soil-moisture (SS_i) becomes more depleted, increasingly more irrigation diversion/consumption is triggered, until a maximum depletion where irrigation requirement is also maximised. The function used is based upon the normal distribution and soilCap (Hughes et al. 2013).

$$Irr_i = \left(\left(\frac{\gamma}{\sigma\sqrt{2\pi}}\right) e^{-\frac{(SSi-\mu)^2}{2\sigma^2}}\right) + areaC_i + areaAct_i + eff \qquad \text{if } soilCap \geq SS_i > 0 \quad \ldots\ldots\ldots\ldots \quad 4.4$$

$$Irr_i = \frac{\gamma}{\sigma\sqrt{2\pi}} + areaC_i + areaAct_i + eff \qquad \text{if } SS_i \leq 0 \quad \ldots\ldots\ldots\ldots \quad 4.5$$

$$Irr_i = 0 \qquad \text{if } SS_i > soilCap \quad \ldots\ldots\ldots\ldots \quad 4.6$$

Where irr_i is the irrigation requirement on day i, $areaAct_i$ is the proportion of $areaC_i$ actively growing crops on day i, eff is the irrigation efficiency, σ, μ, and γ are constants of normal distribution function (Hughes et al. 2013).

From the above equation it is understood that SS_i can have three cases of irrigation requirements:

i) $SS_i \leq 0$: This is the case in which there is a maximum requirement for irrigation.

ii) SS_i > soilCap: In this case, there is no irrigation requirement and excess water above soil surface (due to, for eg: rainfall) becomes runoff.

iii) soilCap $\geq SS_i > 0$: Groundwater recharge occurs in this case. Modified OFR equations are utilised to calculate infiltration, soil storage and ultimately groundwater recharge. The modified equations are given as below:

Infiltration, I = minimum of (K_c of top soil x timestep, soilCap-SS_i) $*$ area under irrigation

I = min(Kc.tw, soilCap-SSi).acur 4.7

Soil storage, $\Delta S = d_{gw}.S_y.a_{cur}$ 4.8

4.3.4 Calculation of Recharge

The infiltrating volume will be accumulated in the topsoil until it exceeds the unsaturated storage. Infiltration begins after this stage. As the infiltrated water reaches the watertable, recharge will increment at the same rate as the vertical infiltration. The actual infiltration into the aquifer is taken as the minimum of change in storage and actual infiltration.

Groundwater Recharge = minimum of (Infiltration, Soil storage)

R = min(I, ΔS) 4.9

Observation of recharge calculations reveals that recharge does not depend on soil storage as infiltration is always lower than soil storage. It means that recharge varies as infiltration in the study area.

4.4 Recharge Optimisation

The method of recharge optimisation is developed as an extension to the recharge module within the framework of the irrigation model. It is a simple error based statistical method that aims at optimising the recharge estimates from any groundwater or surfacewater model so that they are pertinent to the irrigation district under investigation. The need for refining comes from the uncertainty associated with any groundwater or surfacewater models in quantifying recharge accurately. Recharge can be measured directly using instruments or indirectly through modelling employing several methods. Each of those methods may utilize different factors to estimate recharge. Given a catchment, few factors control the recharge more than others. The appropriate application of an estimation technique lies in recognizing the dominant factors representative of that catchment which otherwise might result in poor estimates of recharge. Uncertainty comes from the inability to identify the influencing factors of recharge for a given catchment. The recharge optimisation method is developed by identifying the most pertinent factors for a given catchment and evaluating their values at which they result in precise estimates of recharge.

The purpose of the project is to arrive at a set of factors or input parameters for the study area that could be used for prediction of recharge corresponding to past or future diversions in a required period of time. The methodology to identify the controlling parameters and their values is described in the following sections.

4.4.1 Methodology for predicting recharge for the study area

It has been stated in section 2.4.3 that OFR method equations have been developed recently and the relations between the input parameters to the recharge module and recharge output have not been tested on a national scale. Hence, a knowledge based estimation of prediction parameters is not possible and a mix of uncertainty approach and calibration method is followed to arrive at the prediction parameters. Uncertainty approach is utilised when there is no deterministic method to ascertain the relationship between variables wherein in such cases sensitivity analysis is adopted. The methodology to develop an optimisation method and obtain prediction parameters is discussed in below two steps and the following section:

Step 1: Check the degree of dependency of recharge values on the input parameters: K_c, S_y, and soilCap. A process of elimination is followed for achieving this. A range of values of input parameters pertinent to the study area are applied to the irrigation model and generate trial simulations. The average of total sum of annual recharge over the period i.e 1970-2012 is obtained for each simulation. Subsequently, by performing a sensitivity check for average-annual-total-recharge against each parameter, the dependence of recharge on each of the parameters is determined.

Step 2: The groundwater recharge estimates from other research studies done previously are collated on an annual timescale and utilised in calibration process. Since the recharge estimates from other studies are obtained annually, the daily recharge output for each simulation is summed up to annual series. The simulation outputs are generated for a combination of K_c and soilCap values. Subsequently, the optimising parameters are calibrated by fitting the simulated recharge to collated recharge.

4.4.2 Calibration of optimising parameters

Recharge calibration is an iterative process through which results from recharge module are compared against the existing recharge values from previous studies by adjusting soil and aquifer parameters. The process is complicated by the number of input parameters that can be adjusted, the number of variables available for calibration targets, and the possibility of achieving non-unique model solutions. Hence, it is not uncommon to make tens or hundreds of trial-and-error simulations before achieving an acceptable match. Figure 4.3 shows the flow of steps in parameter optimisation.

The first step in calibration is the identification of calibration targets. The transition outputs from irrigation model were not suitable as calibration targets. It is because they have unique values for the inputs supplied to irrigation model. Similarly, historic data obtained for watertable depths is distinctive and is unsuitable as a calibration target. The values of Kc, soilCap, and Sy vary across the study area and hence were used for calibration purpose.

The second step consists of determining the level of dependence of recharge on the calibration targets. 840 trial-and-error simulations were conducted with varying values of Kc, Sy and soilCap using the AWRA-R irrigation model. An R program was developed to convert the daily recharge output from the irrigation model for every combination of all three calibration targets into an annual series.

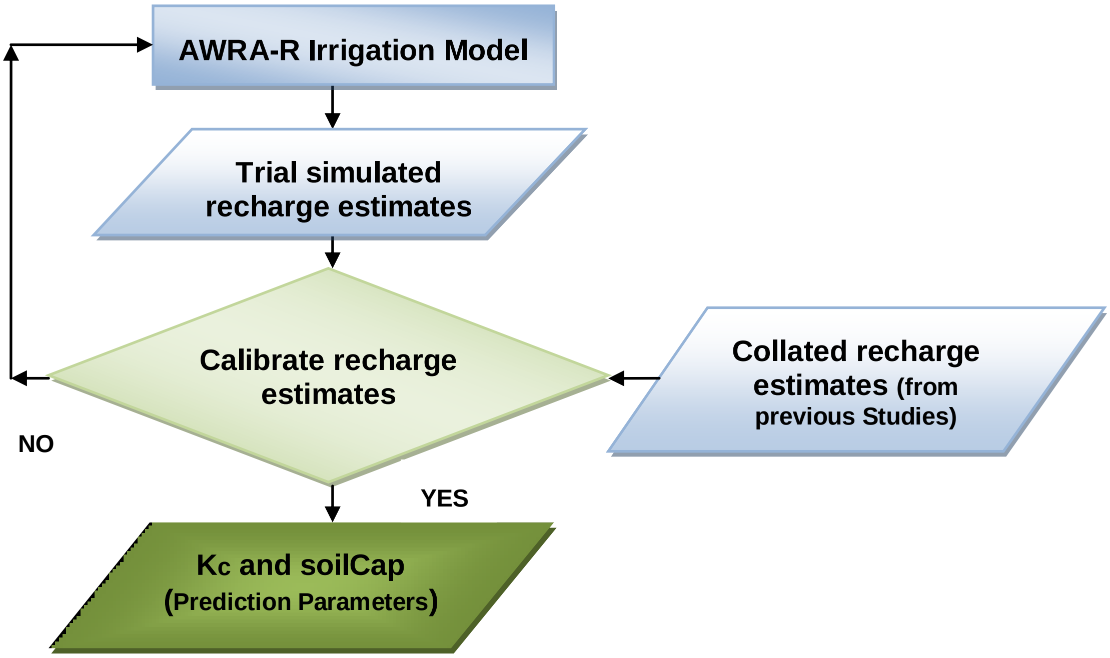

Figure 4.3 Flow chart for calibration of recharge estimates

The program also exports the annual recharge simulation outputs in spreadsheet format. Inorder to evaluate the degree of dependence, annual recharges for the entire period of modelling were summed up to a single value. This resulted in 840 values of total recharge for the complete span of trial-and-error simulations which, further, were averaged over the modelled period.

Utilising the 840 values a sensitivity analyses was conducted. The average-annual-total-recharge values were compared against each calibration target for all the simulations. The analyses revealed that the recharge is independent of any changes in Sy and varies with altering values of Kc and soilCap. This establishes Kc and soilCap as deterministic variables for calibration process.

The final step is to arrive at a set of prediction parameters. Annual recharge values from previous studies done within the MIA, discussed in section 3.81, are utilised for this purpose. It may be noted that most recharge estimates are at significantly smaller spatial scales than those modelled by the irrigation model. The units of the existing recharge estimates are converted into mm/year and collated on the same annual series as the simulated recharge. They are shown in table 4.3.

Table 4.3 Collated recharge estimates from previous studies

YEAR	LICENSE COMPLIANCE REPORTS	SWAGMAN DESTINY	M'BIDGEE GW MODEL	SWAGSIM MODEL	GW SIMULATIONS (MODFLOW)	LOWER M'BIDGEE GW MODEL)O'NEILL)	LOWER M'BIDGEE GW MODEL(O'NEILL)	LOWER M'BIDGEE GW MODEL(PUNTHAKEY)	LOWER M'BIDGEE GW MODEL(PUNTHAKEY)
1975-76								10.8	
1976-77								10.8	
1977-78								10.8	
1978-79								10.8	4.81
1979-80								10.8	4.81
1980-81								10.8	4.81
1981-82								10.8	4.81
1982-83								10.8	4.81
1983-84								10.8	4.81
1984-85								10.8	4.81
1985-86								10.8	4.81
1986-87								10.8	4.81
1987-88								10.8	4.81
1988-89								10.8	4.81
1989-90				8.72				10.8	4.81
1990-91									4.81
1991-92									4.81
1992-93									4.81
1993-94									4.81
1994-95									4.81
1995-96			8.012						4.81
1996-97			8.012				8		4.81
1997-98			8.012			10.76	8		4.81

1998-99			8.012			10.76	8		4.81
1999-00			8.012		94.4	10.76	8		4.81
2000-01		61.9				10.76	8		4.81
2001-02		34.1				10.76			4.81
2002-03		-13							4.81
2003-04		0.4							4.81
2004-05	92	-15.1							4.81
2005-06	169	42.9							4.81
2006-07		-21.9							4.81
2007-08									4.81
2008-09									4.81
2009-10									4.81
2010-11						51.8			4.81
2011-12									4.81

The annual recharge values output from each trial-and-error simulation are matched with collated recharge estimates made in the corresponding years. The error or residual is calculated utilizing the Root-Mean-Square formula as shown below:

$$\text{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(d_i - p_i)^2} \quad \ldots \quad 4.10$$

where n is the number of years for which collated data was matched with simulated data. d_i and p_i are the annual recharge values for simulated and collated data respectively.

Recharge estimates from the lower Murrumbidgee models were ignored in calculating the error due to their low outlier nature. The models estimated recharge for a period of years which resulted in an average value of recharge for the extent of the period. The estimates, if used for calibration of parameters, would tend to even out the simulated annual recharge values which would be misrepresentation of groundwater recharge in the study area. Similarly, estimates from license compliance reports from the MIL and simulations of groundwater flow at Whitton farm were also excluded. This is because of their high outlier nature due to increased recharge under rice farms.

An error surface was created from Root-Mean-Square (RMS) values of error between simulated recharge and collated recharge for the range of soilCap and K_c values discussed in sections 4.4.3 and 4.4.4. The region of lowest error was considered for evaluation. Subsequently, the values of K_c and soilCap corresponding to the lowest error were accepted as prediction parameters pertinent to the study area.

5. RESULTS AND DISCUSSION

5.1 Calibration Results

Figure 5.1 shows the RMS error surface. The patchy region shown in blue represents the area of least error. The combination of the parameters that gives the least RMS error is adopted as prediction parameter set. The least RMS error is found to be 19.162, the corresponding values of Kc and soilCap for which are 7.78E-07m/sec and 0.105m respectively.

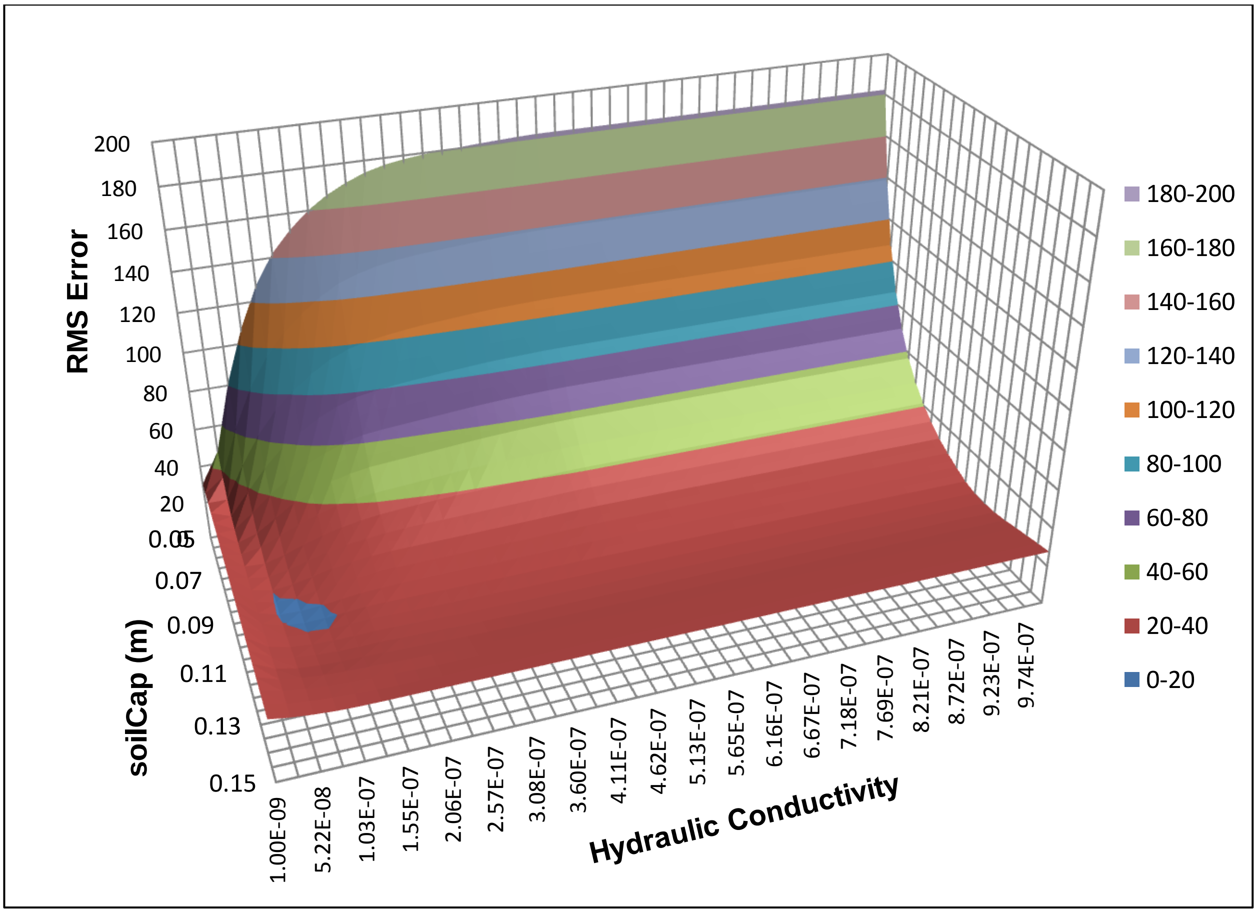

Figure 5.1 Root-Mean-Square error surface

From calibration, the values of Kc and soilCap, 7.78E-07m/sec and 0.105m are chosen as the prediction parameters. Utilising these parameters, a simulation is performed on the AWRA-R irrigation model and annual recharge estimates are obtained. These values represent spatially averaged annual recharge estimates for the study area from years 1970-2012. They are shown in table 5.1.

Table 5.1 Simulated groundwater recharge estimates

YEAR	RECHARGE FROM AWRA-R IRRIGATION MODEL(mm/year)		YEAR	RECHARGE FROM AWRA-R IRRIGATION MODEL(mm/year)
1970-71	21.84		1991-92	25.93
1971-72	0		1992-93	16.14
1972-73	1.012		1993-94	29.74
1973-74	52.31		1994-95	23.13
1974-75	34.45		1995-96	28.67
1975-76	0		1996-97	32.34
1976-77	0		1997-98	16.65
1977-78	49.31		1998-99	19.63
1978-79	13.69		1999-00	0
1979-80	0		2000-01	34.36
1980-81	13.05		2001-02	0
1981-82	41.55		2002-03	0
1982-83	13.1		2003-04	22.19
1983-84	45.47		2004-05	5.744
1984-85	26.53		2005-06	17.65
1985-86	0		2006-07	0
1986-87	31.73		2007-08	0
1987-88	60		2008-09	0
1988-89	44.85		2009-10	6.726
1989-90	3.63		2010-11	45.74
1990-91	79.49		2011-12	26.9

Figure 5.2 shows the distribution of groundwater depths and simulated recharge estimates within the study area for the years 1997-2012. A correlation has not been observed between the groundwater depths and recharge. Groundwater table has been on a decline since 1997 but the simulated recharge doesn't display any downward trend. It is possibly due to the dependence of recharge on infiltration (I) rather than soil storage (ΔS) in light of equation 4.9, Recharge = min(I, ΔS). It means that rate of recharge may depend on rainfall and irrigation water. The reason for the poor correlation might also be that the piezometric data was not comprehensive enough to represent total irrigated region within the study area.

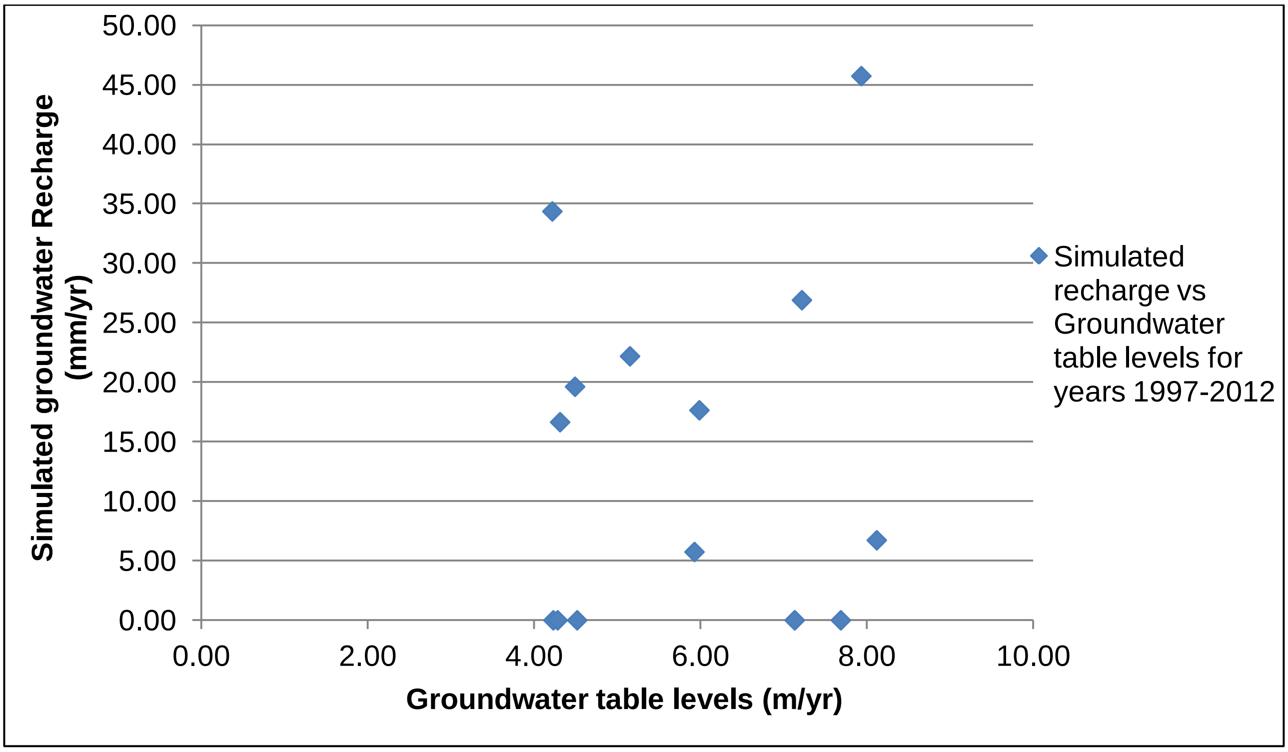

Figure 5.2 Correlation between groundwater recharge and groundwater depths in the study area

Figure 5.3 shows the correlation of rainfall with annual recharge. It is observed that a weak but correlation of 0.166 exists between them. It may be inferred that the area was under drought during the years when no recharge was estimated.

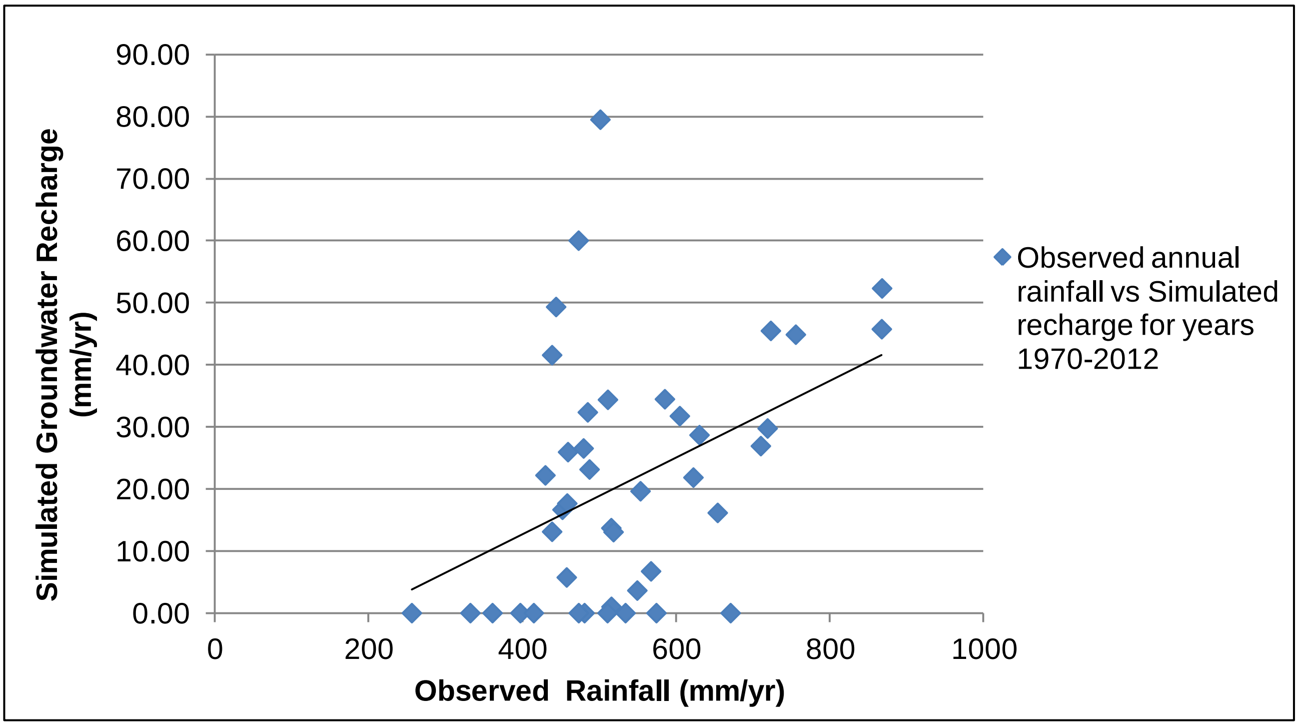

Figure 5.3 Correlation between groundwater recharge and rainfall

The chances of infiltration during rainfall are higher than during normal irrigation application because of the uniformity in application of water across the district. In a perfectly scheduled irrigation management only fields that grow crops like rice receive abundant water supply. Hence, occurrences of infiltration are possible more in rice fields than any other areas. This explains the existence of a poor correlation of 0.05 between diversions and annual recharge in figure 5.4.

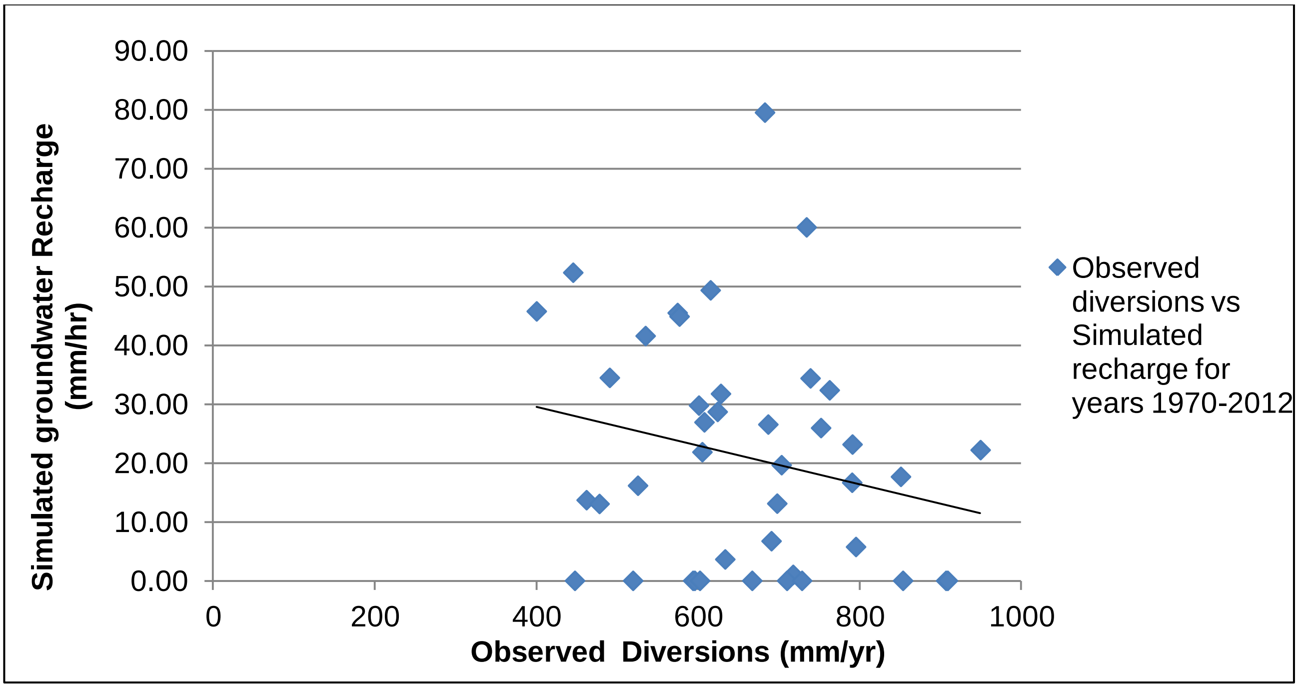

Figure 5.4 Correlation between groundwater recharge and irrigation diversions

Figure 5.5 shows the comparison of annual recharge with incoming water sources; annual diversions (License Volume), rainfall, and combined total of these resources. It may be deduced that the general shape of recharge graph follows the shape of rainfall graph more than that of diversions. It may be inferred that the diversions are scheduled leading to less infiltrations and recharge while rainfall provides excess water sufficient to emerge as recharge.

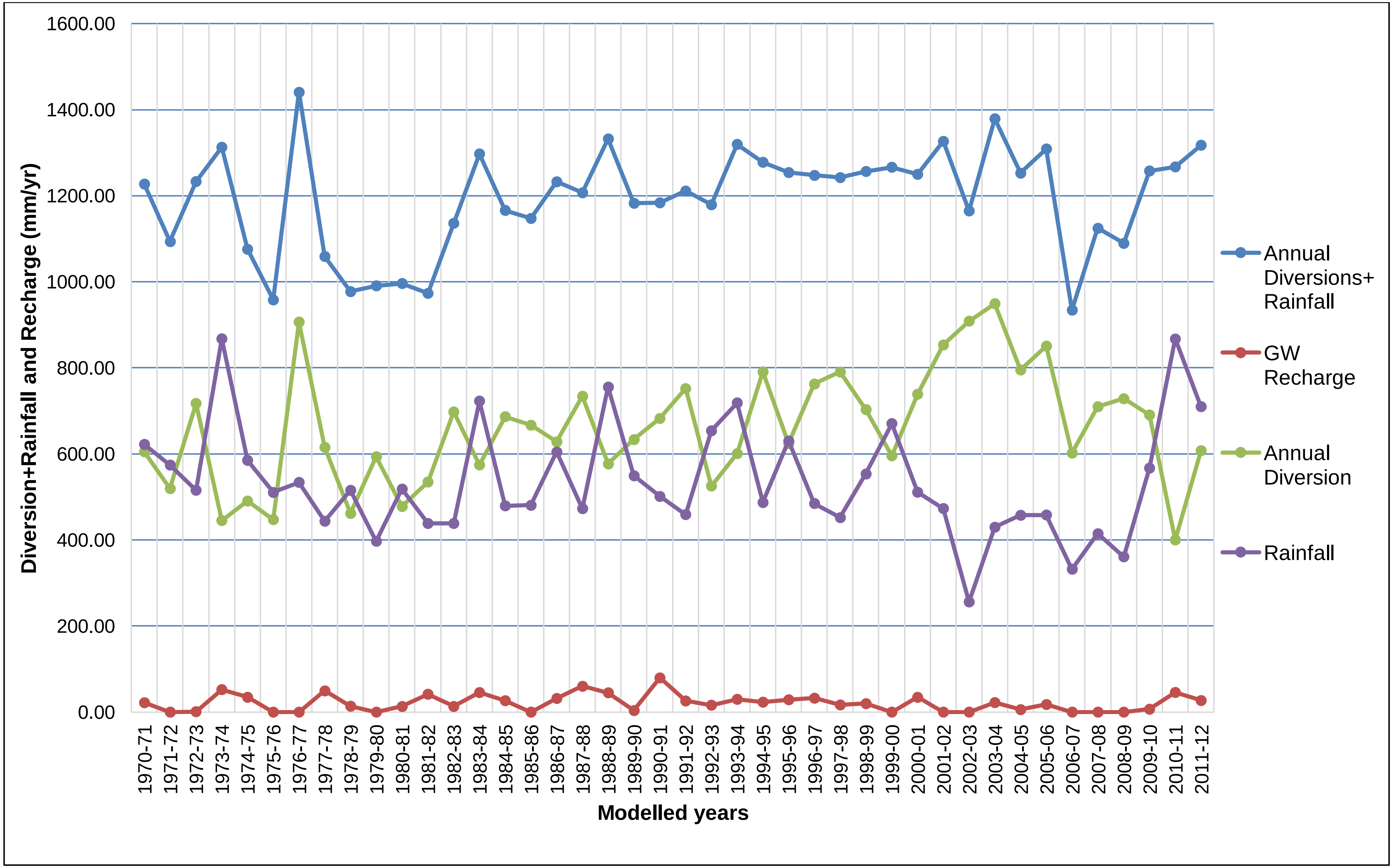

Figure 5.5 Comparison of groundwater recharge with diversions (License volume) and rainfall

Figure 5.6 shows the graph of correlation between groundwater recharge estimates from previous studies and simulated recharge estimates. Following the availability of recharge estimates from previous studies spread between the years 1987-2012 a moderate correlation coefficient of 0.5 has been established.

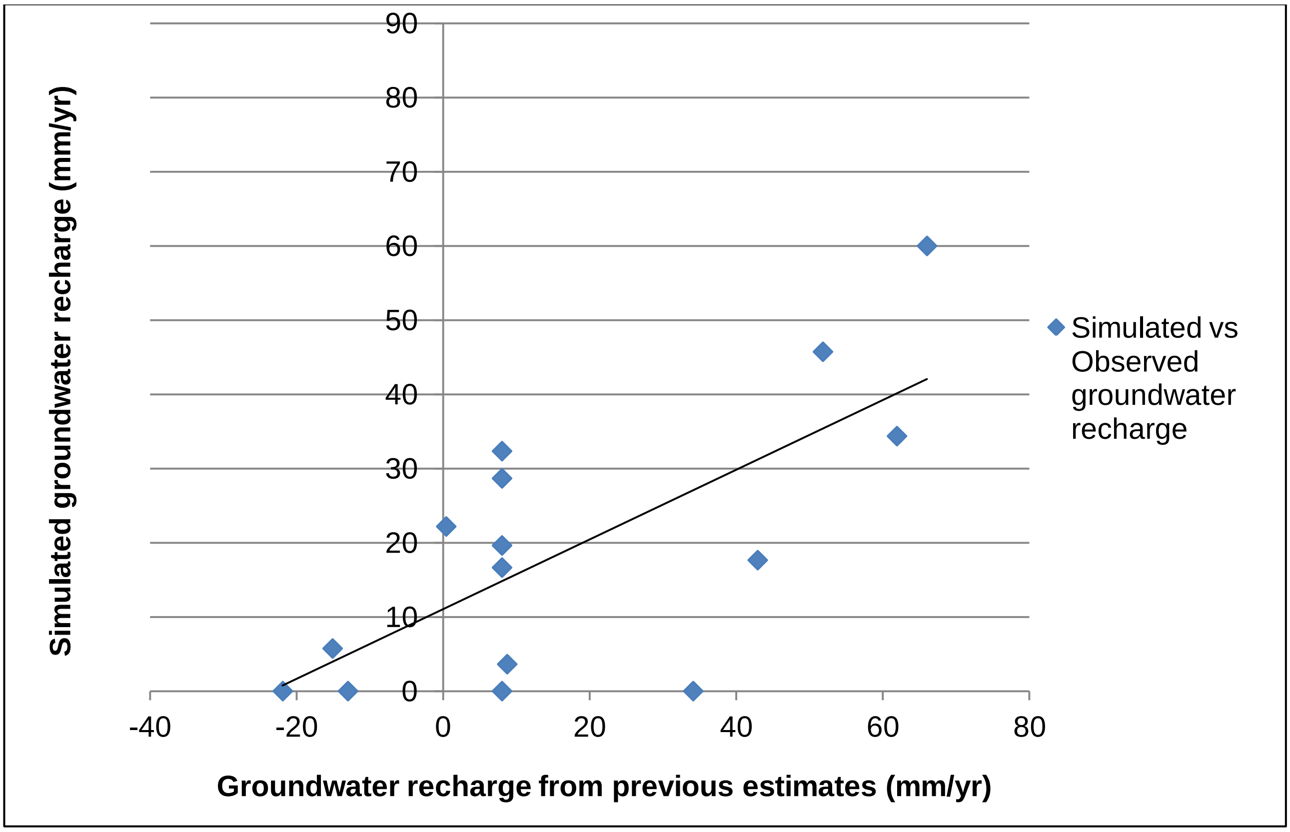

Figure 5.6 Correlation between groundwater recharge estimates

Figure 5.7 shows the final simulated recharge estimates along with the recharge estimates from previous studies used to fit the modelled data. The figure also shows the closest fit for simulated data that has been achieved with respect to the existing recharge estimates. It is observed that simulation output does not match with the collated estimates in several years. Some of collated data are estimates from direct measurements in the irrigated areas. The estimated recharge in influenced by the season, climate and types of crop growing at the time of measurement. The mismatch might also be because most recharge estimates are at significantly smaller spatial scales than those modelled by the AWRA-R irrigation model.

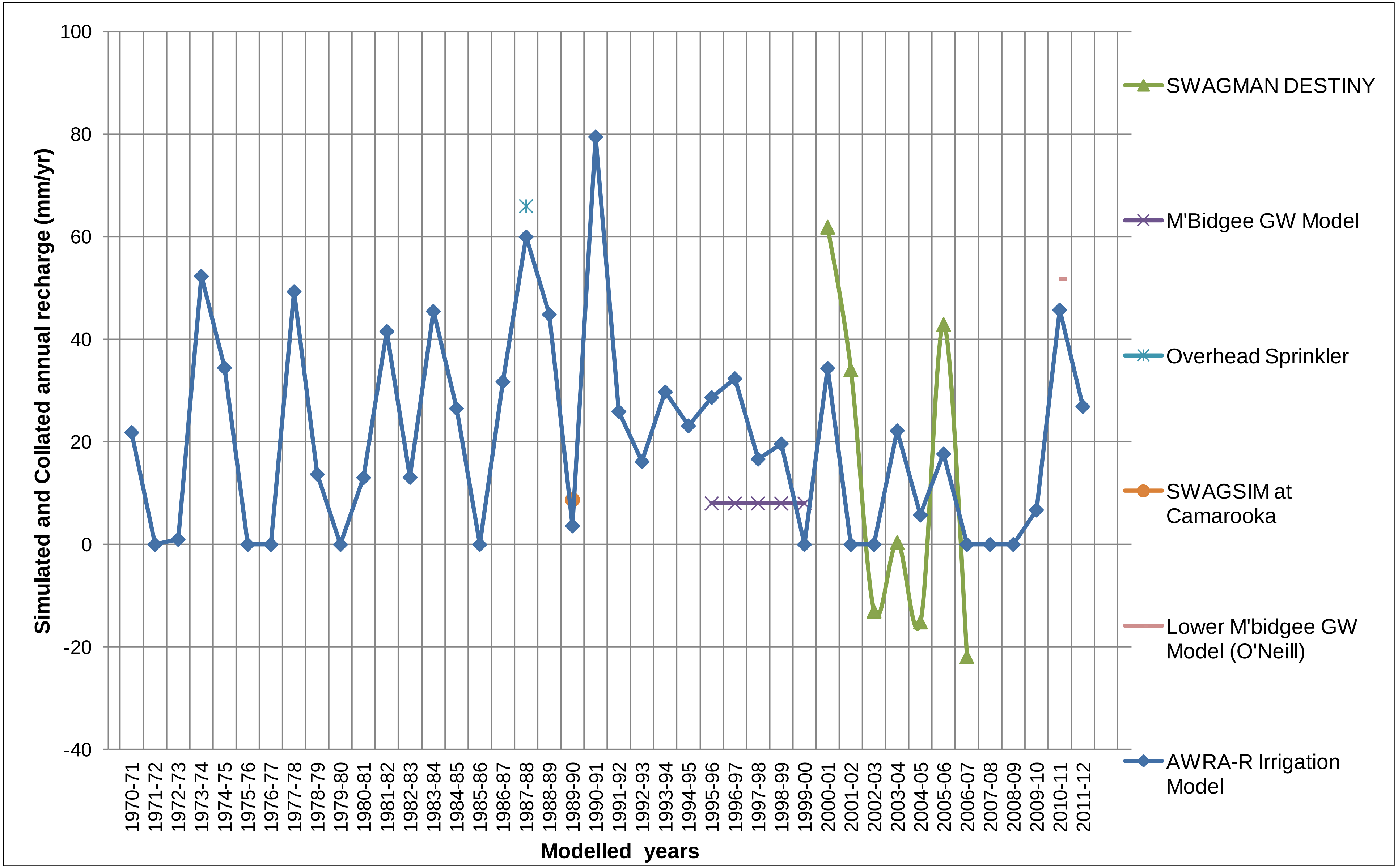

Figure 5.7 Simulated groundwater recharge estimates fitted with existing data

5.2 Sensitivity Analyses

Recharge estimation is a subjective process. The values for the same area may vary with time and due to variables like type of crops grown, season, irrigation management and type of measuring/modelling process adopted. Calibration errors arise when using such estimates for fitting to current modelled data. The purpose of parameter optimisation is to arrive at prediction parameters but the accuracy of these parameters is only as good as the fit. It may be understood that the smaller the calibration errors the better the prediction parameters and vice-versa. In such cases sensitivity analysis is used to deduce relationship between the input parameters and output. The analysis provides information about propagation of error from inputs through to output (Zhang, Walker & Dawes 2002).

Sensitivity Aanalyses was conducted for calibration targets, Kc and soilCap in relation to average-annual-total recharge. Average-annual-total recharge in this context is the sum of annual recharges averaged over the modelled period of time; i.e., from 1970-2012. This approach facilitated in understanding the relationship between Kc and soilCap exclusive of time period. Figure 5.8 shows the plots of recharge against soilCap for different constant Kc values. The recharge possible is increasingly high at lower thickness of topsoil. The recharge tends to become zero as the thickness of topsoil increases. The curve shows a power relationship between the input and output with R^2 ≈0.99. It is also noted that as Kc increases, recharge increases at a decreasing rate and beyond Kc =1E-6.0m/sec recharge increments infinitesimally.

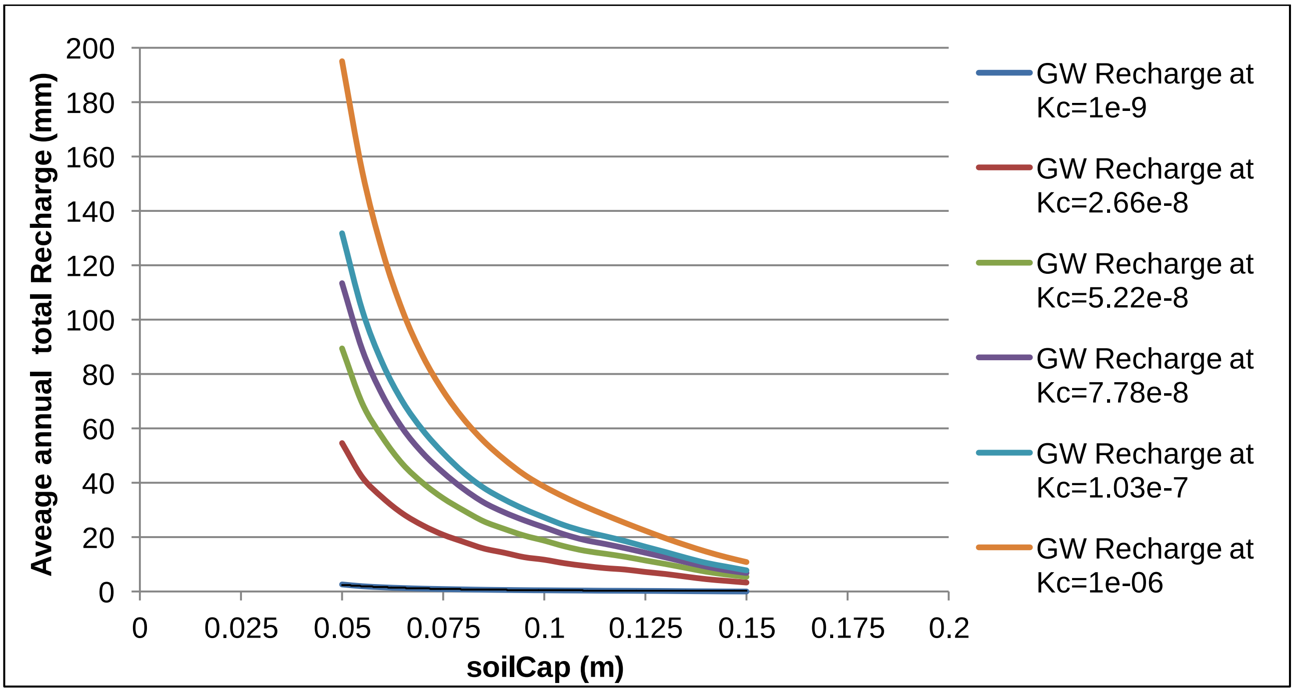

Figure 5.8 Sensitivity of groundwater recharge to soilCap

Figure 5.9 shows the distribution of Kc against average-annual-total-recharge on a logarithmic scale for different constant soilCap values. The graph of Kc vs recharge depicts a split between linear and power relationships beginning with recharge increasing linearly at constant slope and later continuing with power based relationship. Beyond this, after a certain value of Kc, recharge becomes near constant and with a little slope. Similar to figure 5.8, increasing soilCap values suggests only a decreasing rate in increments of recharge.

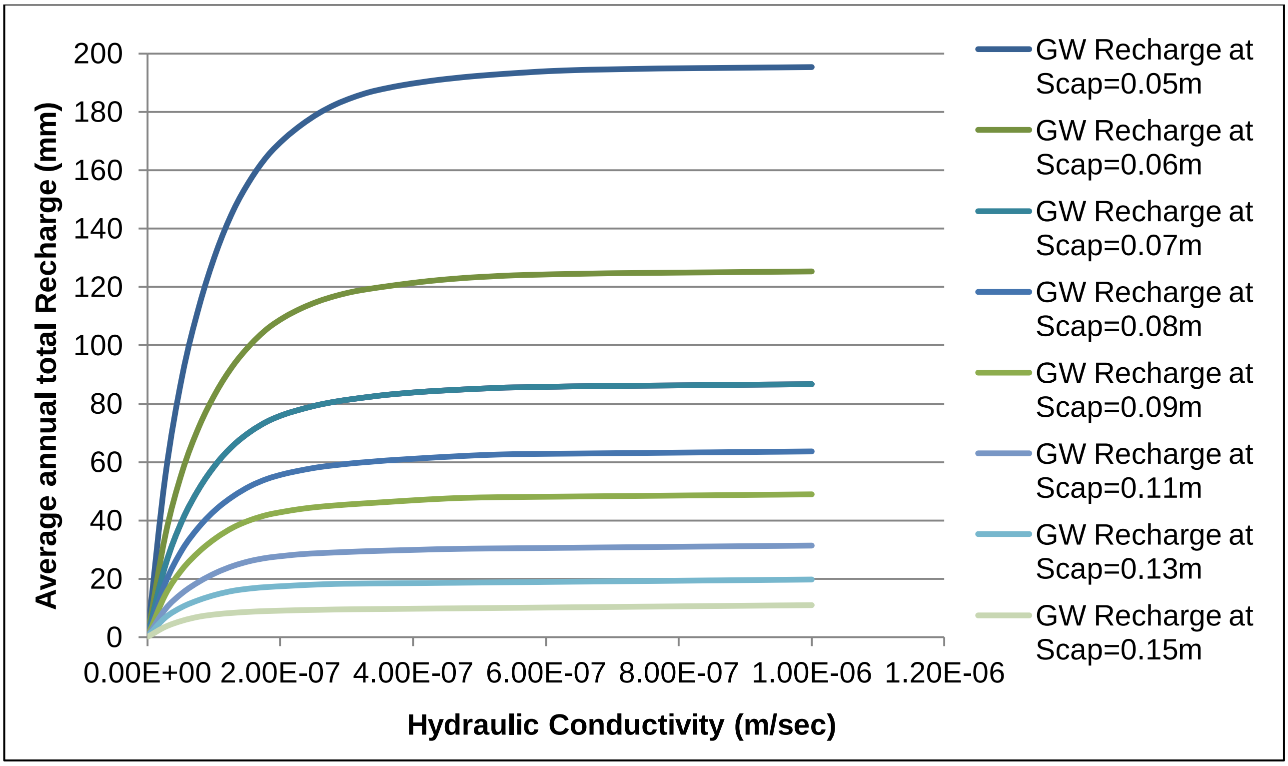

Figure 5.9 Sensitivity of groundwater recharge to hydraulic conductivity

It may be deduced from the graphs that recharge increases linearly until Kc = 1E-7.5m/sec; beyond Kc = 1E-06m/sec recharge becomes independent of Kc and asymptotes to a constant. Beyond soilCap = 0.150m, infiltration ceases to occur and the recharge becomes zero. The graphs mean that recharge increases with increasing Kc and decreasing soilCap values.

Irrigation districts in the MIA suffer from salinity problems due to rising groundwater tables. Reducing the groundwater recharge is an effective irrigation management strategy to curb salinity issue. The sensitivity analyses shows that recharge reduces as the thickness of topsoil increases and Kc decreases. By achieving a balance between soilCap and Kc the recharge may be kept at minimum economically. This is useful for managing rice growing fields and other crop fields with bunding.

5.3 Irrigation Model Simulation Performance

AWRA-R Irrigation model provides its outputs as simulated diversions and irrigated area other than recharge. The input data for this was made available by the NoW. The outputs were checked against an independent data for diversions and irrigated area for the irrigation districts under the Main Canal. The independent data was obtained from MIL. The efficacy of the irrigation model depends on the effectiveness of the diversions module and the recharge module, even more so, on the diversions module because some of the inputs for the recharge module are resulted as outputs from the diversions module. Hence, an assessment of performance of the outputs from the diversions module was made to ascertain the quality of the inputs to the recharge module. This, in turn, would provide confidence in using the outputs from the recharge module for the purpose of parameter optimisation.

Figures 5.10 and 5.11 show the graphs of simulated and observed values of irrigated areas and diversions. It is observed from the graphs that the observed and simulated data match only in some of the years between 2000-01 and 2011-12. However, the general shapes of curves match. This means that irrigation model was partly successful in identifying the reduction in irrigated areas during years of drought.

It may also be noted that irrigation model was developed as a broadscale model that caters to the extents of Murray Darling Basin. Hence, a degree of error is unavoidable when applied to much smaller catchments such as the study area. The level of error in the simulated and observed data was accepted as allowable by the developers of the irrigation model.

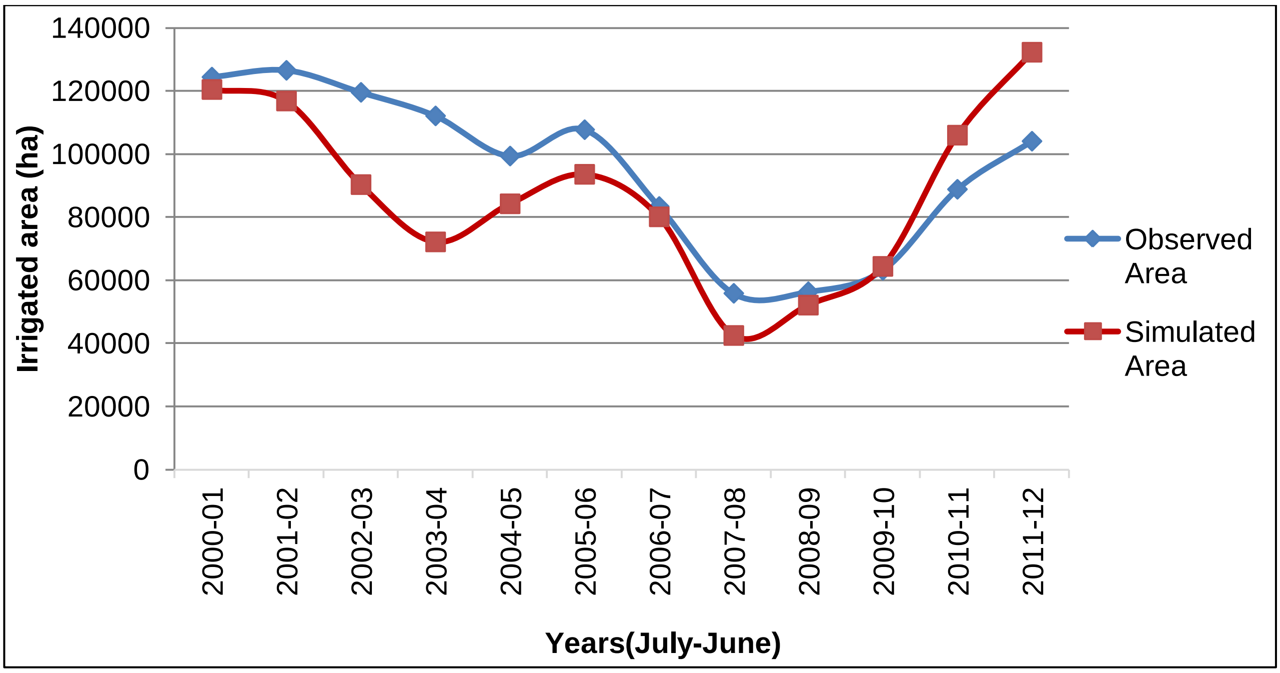

Figure 5.10 Comparison of simulated and observed annual irrigated areas

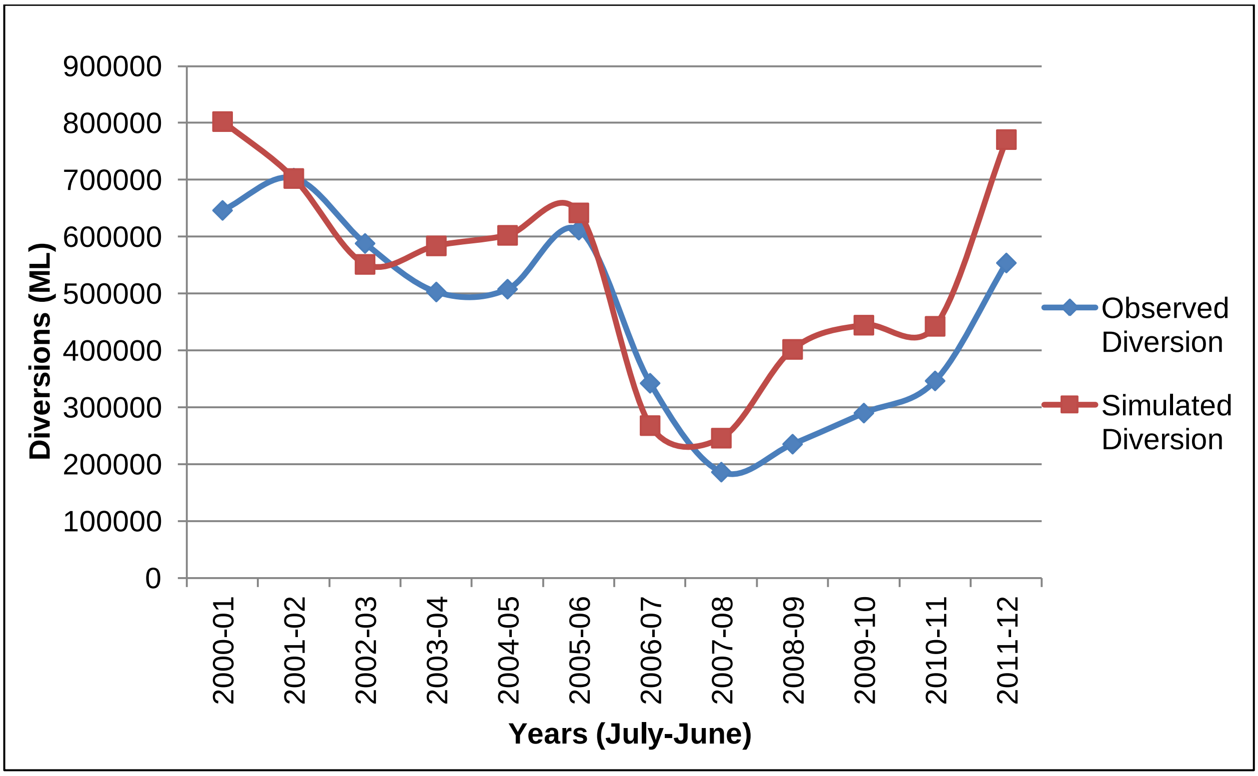

Figure 5.11 Comparison of simulated and observed annual diversions

The assessment performed above validated the adoption of AWRA-R irrigation model for the purpose of developing the parameter optimisation method and subsequently predicting parameters for estimating groundwater recharge in the study area.

5.4 Summary

The chapter describes the development of a parameter optimisation for estimating groundwater recharge for the study area. It identifies a hydraulic conductivity of 7.78 m/sec and a topsoil thickness of 0.105m as prediction parameters. The model arrives at annual recharge for the study area with a mean value of 21.05mm. The lowest estimate is 0mm which is the case for a few years while the highest is 79.49mm in the year 1990-1991.

The model has been applied for years 1970-2012 out of which the results for years 1987-2012 show a moderate correlation with recharge estimates from previous studies. Due to lack of sufficient previous recharge estimates data the correlation has not been tested for the remaining years. However, an inference could be made that a moderate correlation would exist for the untested period.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

6.1.1 Summary of the Parameter optimisation development

The project deals with estimating groundwater recharge based on the diversion data. Irrigation Model developed by CSIRO is utilised for this purpose. Parameter optimisation method was built as an extension to the irrigation model in order to arrive at recharge estimates specific to the study area. 840 trial-and-error simulations were conducted with a range of input parameters to the recharge module of the irrigation model for the modelled years 1970-2012. Separately, recharge estimates from previous studies within the MIA were collated. These collated estimates were compared with each of the trial-and-error simulation from the irrigation model using a RMS error analysis. The set of simulated estimates that gave the least RMS error were adopted as recharge estimates pertinent to the study area. The model arrived at annual recharge for the study area with a mean value of 21.05mm. The lowest estimate is 0mm which is the case for a few years while the highest is 79.49mm in the year 1990-1991. The model has also worked well for its intended purpose of deducing prediction parameters unique to the study area. It identified a hydraulic conductivity of 7.78 m/sec and a topsoil thickness of 0.105m as prediction parameters.

Detailed piezometric data have shown overall decline in the groundwater levels in the study area. This decline is attributed to improved land and water management practices as well as a relatively dry climate over the last decade.

6.1.2 Potential Benefits

1. Similar to the irrigation model the parameter optimisation can be calibrated. Hence, it can be applied to any irrigation district and derive prediction parameters precise to the area which can be used to estimate groundwater recharge. These estimates would become part of water balancing and assist with calculations for AWRA-R and NWA.

2. The recharge output from the model can be available to the extents of historic irrigation diversion data available. The model is robust enough to interpolate any missing data and hence a continuous recharge output is possible. A continuous data is helpful in making an assessment of fluctuations in groundwater resources over a period of time in response to rainfall or irrigation activity. This is useful in effective irrigation management. Knowledge of groundwater recharge is critical in irrigation management. Irrigated areas inherently suffer from salinity problems. In areas with perched groundwater tables recharge abets salinity problems. Depending on the amount of recharge it may be necessary to contain it.

6.1.3 Problems encountered

Several problems were encountered in the process of development of parameter optimisation.

1. Daily diversion data and allocation data for the Main Canal was an important input data for the AWRA-R irrigation model. The data needed to be obtained from the NoW. Several requests were made and a considerable amount of time was spent in procuring the data from them. The historic input data acquired from the NoW was a result of other models to some extent. The data was accepted for the project due to lack of reliable data from any other substantial source of information.

2. Diversion data and actual irrigated areas data for the MIA was also obtained from the MIA. Groundwater table data was also obtained from the MIA. The requested data was available with waiting involved.

3. The groundwater level information is not continuous due to a number of piezometers being abandoned with the privatisation of irrigation companies. There is a need to critically reassess the active measuring points and select a critical monitoring network for assessing the climatic and management impacts on shallow watertables.

6.1.4 Limitations of the model

The accuracy of recharge outputs is subject to availability of input data at two stages:

1. Quality of diversion data and allocation data as part of inputs to the AWRA-R irrigation model.

2. Number of recharge estimates from previous research studies and experiments done in agricultural areas and the quality of the estimates available for calibration as part of the parameter optimisation.

6.2 Recommendations

1. The current project arrives at prediction parameters and recharge estimates based on modelling. There is a need to validate the results and thus the model performance by comprehensive field measurements. There is also a need to investigate methods on improving the parameter optimisation and its calibration process.

2. Section 6.1.2 highlights the importance of results of the model in irrigation management. There is a need to research on other ways these results could prove helpful for water resource management and irrigation management.

3. Managing Groundwater resources is a vital part of water resource management in arid and semi-arid regions. There is a need to investigate how the results from the model can be used in understanding of interaction of surface water with groundwater.

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APPENDIX A Project Specification

1. Research the background information on ground water and groundwater recharge
2. Perform research on various factors responsible for recharge in irrigated areas in semi-arid regions
3. Research various models of ground water recharge estimation and select models pertinent to irrigated areas in semi-arid regions
4. Conduct literature review for any research studies done in the MIA using broadscale irrigation models that estimated recharge
5. Collate recharge estimates arrived at from the various studies done within the MIA and the lower Murrumbidgee
6. Collect digital information about the Murrumbidgee irrigated areas interms of diversion data, borehole data and climate data
7. Deploy AWRA-R irrigation model, developed by the CSIRO, to generate trial simulations of groundwater recharge for the study area
8. Optimise the simulated recharges using the collated data to represent the study area
9. Apply the model to predict ground water recharge for future years in irrigation

APPENDIX B AWRA Modelling System

1 Introduction

CSIRO has formed a research alliance with the BoM in 2008 to compile and deliver comprehensive water information in the form of national water accounts and assessments, water forecasting products and water data services for the water sector. It is called WIRADA. Since 2008 CSIRO researchers have been developing the AWRA modelling system as part of WIRADA and supporting the BoM in the production of national water accounts and assessment reports. These reports provide an overview of water fluxes and storages at a national scale (Vaze et al. 2013). Alliance researchers have developed an integrated system for detailed water balance assessment from sub-catchment to continental scale, capturing water in the landscape, river systems and in groundwater. The state-of-the-art AWRA modelling system is able to tell us how much water has been produced, how much water is used by the environment or through irrigation, how much water we have left, how this compares with the past, and whether extractions, land use, farm dams or bushfires are having an impact on water security and the environment. It draws on a wide range of on-ground and remote sensing data, to provide unprecedented coverage and insights into Australia’s water resources system. The scale of this endeavour requires ongoing innovation in model development, calibration, data assimilation and remote sensing.

2 AWRA

AWRA is a water balance modelling system developed using state-of the-art hydrological science and computing technology that quantifies water flux and storage terms and their respective uncertainties (where applicable and possible) using a combination of data sets (on-ground metering, remotely sensed data and model outputs). Figure 4.1 shows the AWRA modelling system and its different components.

The system is applicable across the continent and flexible enough to be able to use all available data sources (when modelling data rich and data limited regions) with the most appropriate modelling techniques and tools suitable for use with the available data to provide nationally consistent and robust estimates (Vaze et al. 2013). In the first 5 years of WIRADA, the AWRA modelling system was developed through three core components, together representing the Australian terrestrial water cycle. The model components represent processes between the atmosphere and the landscape (AWRA-L), in gauged rivers (AWRA-R) and in groundwater (AWRA-G), including all major water storages and fluxes in and between these components.

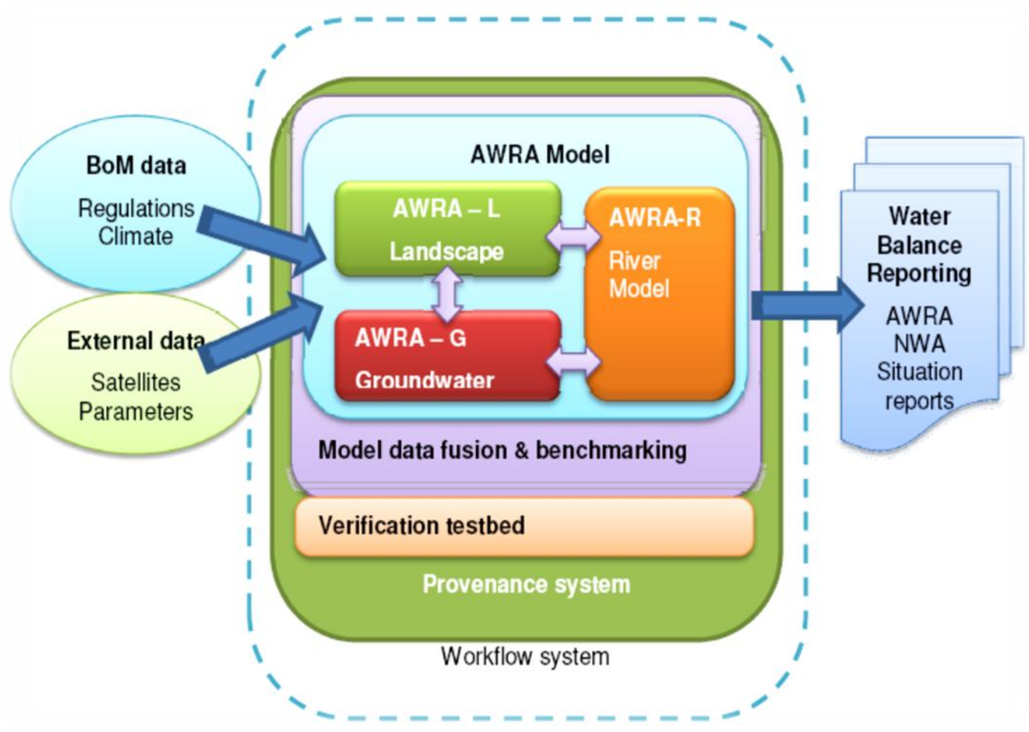

Figure B.1 The AWRA modelling system (Vaze et al. 2013)

3 AWRA-R

AWRA-R is a conceptual hydrological model designed for both regulated and unregulated river systems (Lerat et al. 2013). A river system is schematised into a simplified river network using a node-link structure. The river network begins and ends with a node, and all nodes are interconnected by links. Runoff from gauged or ungauged tributaries or local contributing area between two nodes is fed into the connecting link as an inflow at the relevant location and all other physical processes (such as diversions, groundwater fluxes, overbank flow) occurring between the two nodes are incorporated in the model. A link is used for transfer of flow between two nodes with or without routing and transformation.

The model is developed to provide retrospective estimates of the variables listed in the AWRA and NWA reports associated with the surface water store. It is built to make maximum use of observed data when available. It does not include management rules (dam operation, environmental flow releases, allocation). It is run at a daily time step. The model is developed at the reach scale and applied to headwater and residual reaches and includes six units: 1) rainfall-runoff response, 2) routing scheme, 3) irrigation modelling, 4) river-groundwater interaction component, 5) storages and 6) floodplain modelling.

APPENDIX C MIA and the Mirrool Creek catchment

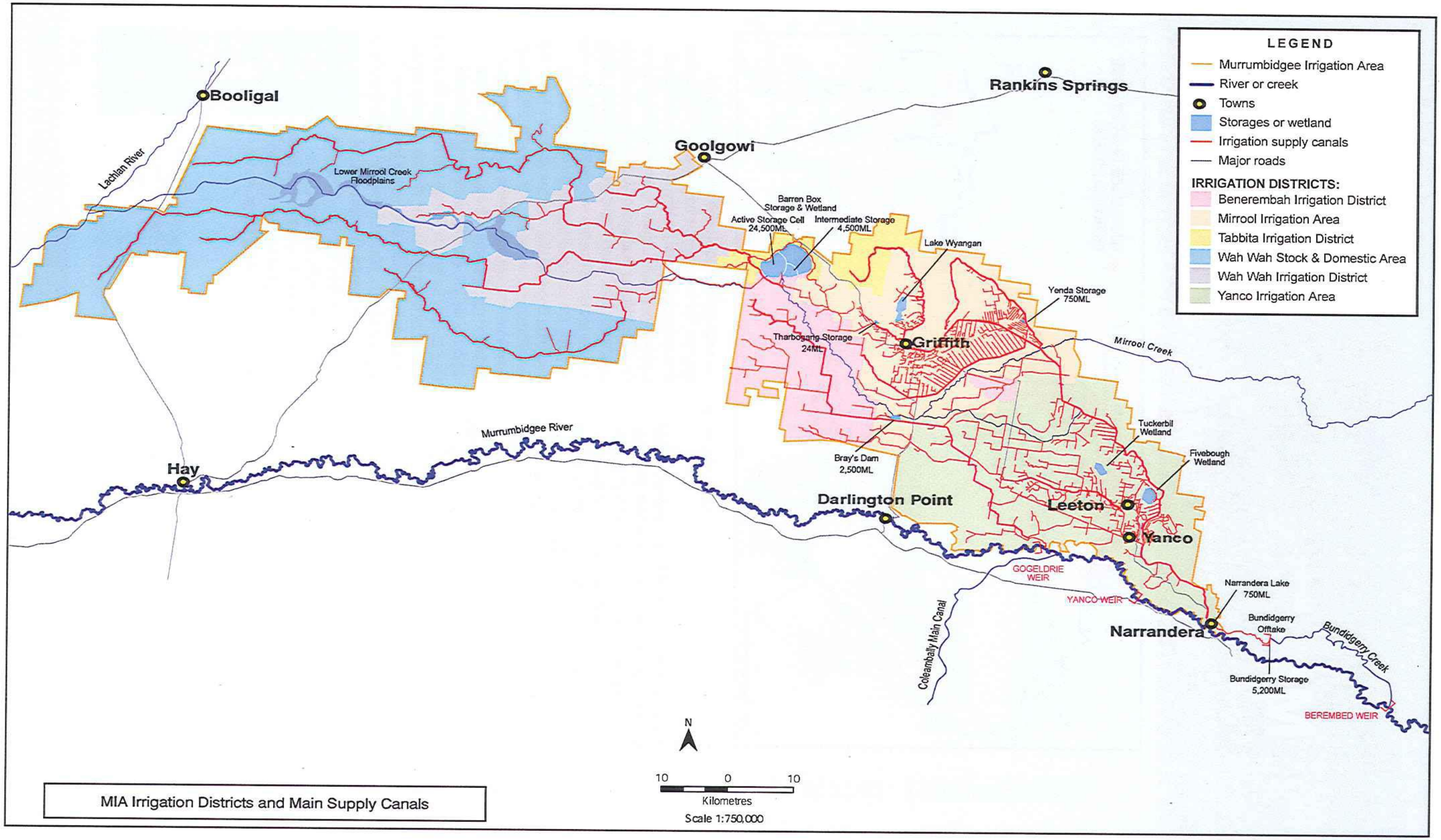

Figure C.1 MIA and the Mirrool Creek catchment (Source: MIL 2007)

APPENDIX D Water Distribution in the Murrumbidgee

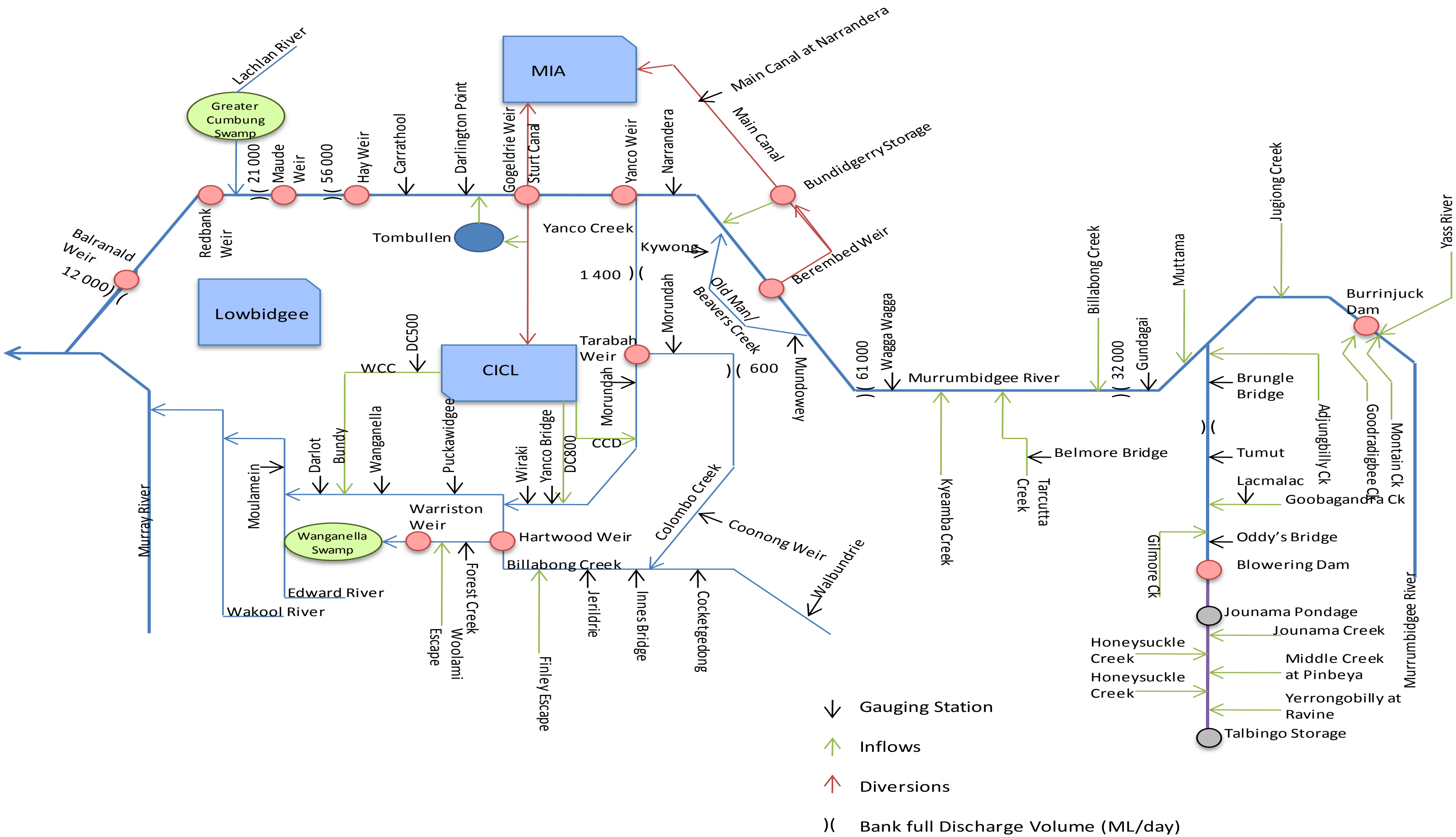

Figure D.1 Schematic showing distribution of Water resources in the Murrumbidgee Catchment (Sinclair Knight Merz 2011)