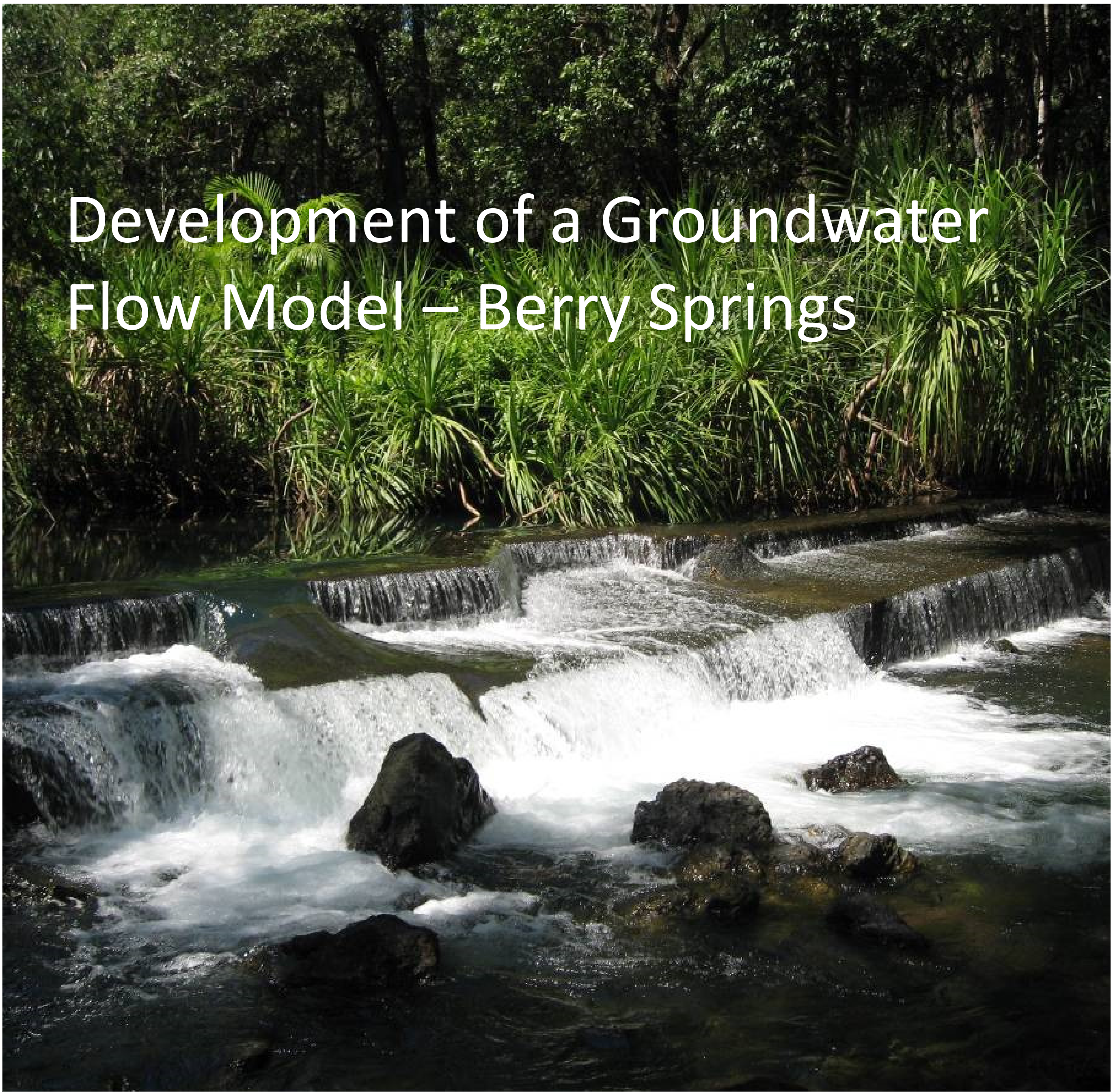
DEPARTMENT OF LAND RESOURCE MANAGEMENT
LAND RESOURCE MANAGEMENT

Development of a Groundwater Flow Model – Berry Springs



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NORTHERN TERRITORY GOVERNMENT

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Acknowledgements

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Glossary of Terms

aquifer a geologic formation that will yield water to a bore in sufficient quantities to make the production of water from this formation feasible for beneficial use; permeable layers of underground rock or sand that hold or transmit groundwater below the water table.

drawdown the difference, measured vertically, between the static water level in the bore and the water level during pumping.

electrical conductivity a measure of the ability of a water to conduct an electrical current. Specific conductance is related to the type and concentration of ions in solution and can be used for approximating the total dissolved solids (TDS) concentration in water. In general, conductivity multiplied by 0.64 approximates TDS. People monitoring water quality can measure electrical conductivity quickly in the field and estimate TDS without doing any lab tests at all.

evapotranspiration: the combination of evaporation and transpiration of water into the atmosphere from living plants and soil.

gauging station the site on a river where hydrologic data is collected.

gigalitre: (GL) 1000 million litres.

groundwater water within the earth that supplies bores and springs; water in the zone of saturation where all openings in rocks and soil are filled, the upper surface of which forms the water table.

head: see potentiometric head.

hydraulic conductivity: is a property of soil or rock that describes the ease with which water can move through pore spaces or fractures.

hydrogeology: the study of those factors that deal with subsurface water and related geological aspects of surface water.

hydrograph: a chart that measures the amount of water flowing past a point as a function of time.

megalitre: (ML) one million litres or 1000 cubic metres.

numerical groundwater model: a conceptual, mathematical system obeying certain specified conditions, the behaviour of which is used to understand the physical system which it represents.

permeability: The ability of material to transmit fluid. See also hydraulic conductivity and transmissivity.

phreatic aquifer: see water table aquifer.

porosity: the ratio of the volume of voids (openings) in a geological formation to the overall volume of the material without regard to size, shape, interconnection, or arrangement of openings.

potentiometric head: (or **head**) level below the earth's surface at which the ground becomes saturated with water. The surface of an unconfined aquifer which fluctuates due to seasonal precipitation.

recharge: refers to water entering an underground aquifer through faults, fractures, or direct absorption.

recharge zone: the area where a formation allows available water to enter the aquifer.

saturated zone: the subsurface zone in which all openings are full of water.

solute: any substance derived from the atmosphere, vegetation, soil, or rock that is dissolved in water

specific yield: the ratio of the volume of water that will drain under the influence of gravity to the volume of saturated rock or sediment.

steady state: steady state flow occurs when the magnitude and direction of flow is constant with time throughout the entire aquifer model domain. The steady state flow conditions simplify the groundwater flow equation significantly. This does not mean that in a steady state system there is no movement of groundwater, it simply means that the amount of water within the domain remains the same, and that the amount of water that flows into the system is the same as flows out. When steady state flow occurs, time is no longer an independent variable and thus the storage term in the groundwater flow equation disappears; since there is no change in the amount of water within the domain (no change in hydraulic head) there is no change in the amount of water stored in the domain.

TDS: (total dissolved solids) the sum or all inorganic and organic particulate material. TDS is an indicator test used to measure the mineral content of groundwater. There is a relationship between TDS and conductivity. In general, TDS divided by 0.64 approximates conductivity. Or, conductivity multiplied by 0 .64 approximates TDS. People monitoring water quality can measure electrical conductivity quickly in the field and estimate TDS without doing any lab tests at all.

transmissivity: is the ability of an aquifer to transfer water. Determined as saturated thickness of the aquifer multiplied by the hydraulic conductivity of the aquifer.

unconfined aquifer: an aquifer in which the water table is the upper boundary. There is no confining layer between the aquifer and the surface and the pressure at the water table is atmospheric. Water level in an unconfined aquifer may move up and down in response to local recharge or discharge.

unconsolidated formation: means naturally occurring, loosely cemented, or poorly indurated materials including clay, sand, silt, and gravel.

unsaturated zone: The subsurface zone, usually starting at the land surface that is not fully saturated and contains both water and air.

water table: the level below the earth's surface at which the ground becomes saturated with water. The surface of an unconfined aquifer which fluctuates due to seasonal precipitation.

water table aquifer: (phreatic aquifer) an aquifer confined only by atmospheric pressure (water levels will not rise in the bore above the confining bed).

water bore: any artificial excavation constructed for the purpose of exploring for or producing ground water.

yield: quantity of water expressed either as a continuous rate of flow (megalitres per day, etc.) or as a volume per unit of time. It can be collected for a given use, or uses, from surface or groundwater sources.

Executive Summary

Background

The Berry Springs spring complex lies in the wet / dry tropics of northern Australia. Its rainfall and runoff is characterised by a four month wet season with significant runoff and an eight month dry season with negligible surface runoff. During this period, aquifers within the Berry Springs region supply approximately 0.25 m^3/s (250 l/s) of baseflow to the Berry Creek through the river bed and springs.

Increased development within the area for irrigation or other land use is likely to increase demands on groundwater resources. Additional groundwater abstraction from the high-transmissivity aquifers could lower groundwater levels and thereby reduce the spring discharge during the dry season. To ensure sustainable development, a groundwater model of the Berry Springs aquifer system has been developed. This model will be used as a management tool to assess impacts on dry season spring discharges for a range of development scenarios.

Objectives and scope

The objectives of this investigation were to assess the impacts of climate and water resources development on the water resources of the Berry Springs aquifer system using two different scenarios:

- Scenario A - historical climate (based on the period 1900 – 2011) and no development,
- Scenario B - recent climate (based on the period 1900 – 2011) and current development,

Given that currently the majority of exploitable water resources available for development are groundwater resources the focus of this study was, therefore, to examine the components of the groundwater systems of the Berry Springs aquifer system.

Model description

The groundwater model consists of a three dimensional finite element (FE) ground water model implemented using the groundwater modelling software FEFLOW.

The FE model encompasses an area of approximately 90 km2 and includes the entire extent of the aquifer system referred to as the Berry Springs Dolostone.

The model was developed with available aquifer geometry data. The model was calibrated with all available rainfall, river flow and groundwater level data.

The recharge input to the FEFLOW model for the scenarios was generated using the MIKESHE model (DHI, 2008).

Reported metrics

- The water balance is documented for the Berry Springs model domain.
- Water levels are documented for 11 groundwater level sites within the model domain.
- Groundwater discharge is reported at 2 sites, 1) in the Berry Springs spring complex and 2) in the area around Parson Spring on the Darwin River.

Results

Under historic climatic conditions and no groundwater development the water budget estimates:

- Recharge to the Berry Springs aquifer system is estimated at 38 GL/yr.
- Discharge to Berry Springs spring complex is estimated at 13.8 GL/yr

- Discharge to Darwin River spring complex is estimated at 24.3 GL/yr

Under historic climate and current pumping estimates the water budget indicates:

- Recharge to the Berry Springs aquifer system is estimated at 39.5 GL/yr.
- Discharge to Berry Springs spring complex is estimated at 12 GL/yr
- Discharge to Darwin River spring complex is estimated at 21.9 GL/yr

Conclusions

Conclusions from the study were:

- Recent climatic conditions over the past 50 years have resulted in recharge being much greater than the long term average.
- Discharge from the Berry Springs Dolostone occurs in a ratio of approximately 1:2 into the Berry River and the Darwin River respectively with less discharge into the Berry Springs complex (Wildlife Park, Berry River) than the Darwin River springs complex (Parsons, Twin Farms, in-channel).
- Future development of the model will need to focus on differentiating the recharge and discharge responses into sub-catchments for the Berry River and the Darwin River as separate zones.
- Groundwater elevation surface has been assumed to follow topography. Additional monitoring boreholes are required to determine the standing water levels at the hydrographic divide between the Berry River and the Darwin River.
- Flow data in the Darwin River is required for improved calibration of the model in particular reinstating the gauging site at the Old Military Road (G8150441) and improved measurements of springs discharge in the lower reaches of the Darwin River.

1 Introduction

1.1 Background

In recent years development in the rural area surrounding Darwin has resulted in significant increase in the groundwater demand particularly for domestic and industrial purposes.

Groundwater supplies for Berry Springs are sourced from a local aquifer system, which also sustains a number of local groundwater discharge features like - Berry Springs, Parson Springs, Twin Farm Springs and Lake Deane. A number of ephemeral creeks and rivers are also sustained in the early dry season by the groundwater discharge.

Additional groundwater abstraction from the high-transmissivity aquifer could lower groundwater levels and thereby reduce the discharge to the springs during the dry season. It is expected that over pumping of the aquifer could result in groundwater levels declining to the point where:

- dry seasons flows at Berry Springs cease;
- reduced flows at Berry Springs lead to poor water quality and early closure of the pools;
- groundwater levels fall and impact upon Groundwater Dependent Ecosystems including the vine rainforest within the Territory Wildlife Park;
- salt water ingress to the aquifer where tidally influenced rivers (Darwin River) overlie the aquifer.

To ensure sustainable development, a groundwater flow model of the Berry Springs groundwater system has been developed. This model will be used as a management tool to assess impacts on dry season river flows for a range of development scenarios.

1.1 Aim of the study

This modelling study is focused on the Berry Springs aquifer system and the dry season groundwater discharges to the Berry River and Darwin River spring complex.

The study aims to:

- confirm the conceptual model of the Berry Springs aquifer system;
- provide water balance data for the groundwater system discharging to the Berry River and Darwin River spring complex;
- inform groundwater allocation planning by providing a groundwater model suitable for running various scenarios including climate change predictions and development;
- provide a groundwater model that can be used to incorporate new data as it becomes available.

2 Site Description

2.1 Study area location

The study is centred on the aquifer system discharging to the Berry Springs spring complex approximately 40km to the southeast of Darwin. The spring complex is located within the Territory Wildlife Park, a major tourist attraction for the Northern Territory. Discharge also takes place through an array of springs located along the Darwin River upstream of its confluence with the Blackmore River.

The location of the dolostone aquifer in relation to major centres of Darwin and Palmerston is presented in **Figure 1**.

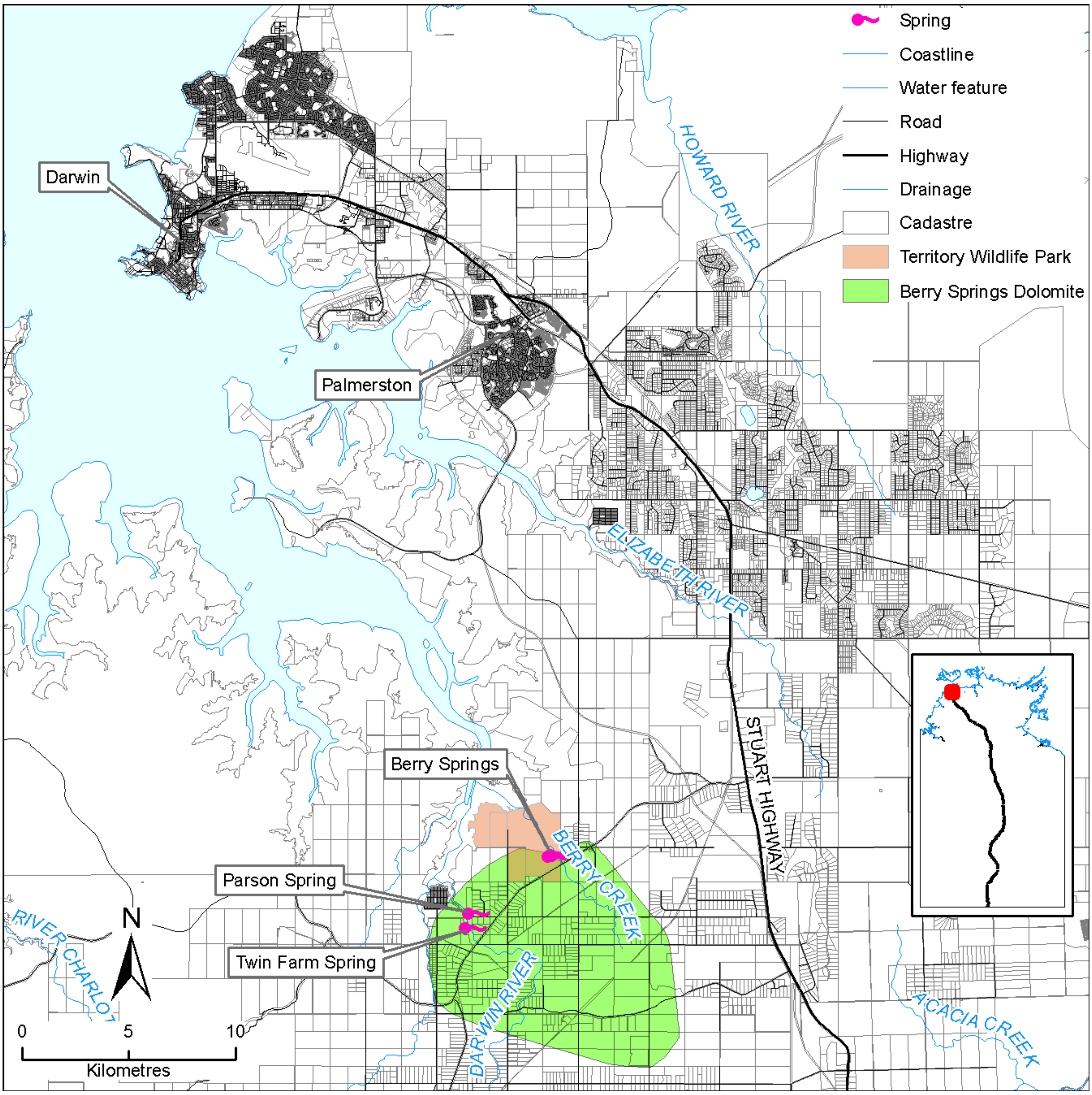


Figure 1Location of the Berry Springs dolomite aquifer system

The study area is drained by two major drainage features the Darwin River and Berry River, two lagoons (Lake Deane & Woodfords Lagoon) and several recognised perennial springs (including the Berry Springs complex, Parson Springs & Twin Farm Spring). There are other springs along the Darwin and Blackmore Rivers as well as Berry Creek.

The Berry Springs are located on a fault at the geological contact between the dolostone and the Burrell Creek Formation (Verma, 1995). There are also man-made features like dams in the immediate area including the Darwin River Dam to the south which provides low volume environmental releases (5-20L/s) into the upper Darwin River.

2.2 Climate

The study area in the north of the Northern Territory experiences hot and humid conditions, with an annual wet-dry monsoon and is classified as Tropical Savannah (Peel et al., 2007). The wet season is from October to April and the dry season spans the remainder of the year. During the wet season the area comes under the sporadic influence of convective thunderstorms, the monsoon, and intense rainfall depressions resulting from decaying tropical cyclones. Convective thunderstorms typically occur in the period from October to December, locally known as the “Build-up” season.

Rainfall and evaporation data are available at several sites around the Berry Springs region, however, the discontinuous nature of the rainfall and evaporation data required the use of synthetically derived data from the Bureau of Meteorology’s SILO Data Drill, which was used for a nominated site centred on the Berry Springs region.

The SILO Data Drill accesses grids of data derived by interpolating the Bureau of Meteorology’s station records. Interpolations are calculated by splining and kriging techniques. The data in the Data Drill are all synthetic; there are no original meteorological station data left in the calculated grid fields. However, the Data Drill does have the advantage of being available for any set of coordinates in Australia.

2.2.1 Rainfall data

The SILO Data Drill daily climate data at location -12.75 S, 131.0 E was downloaded on 3/04/2016. Annual rainfall data are presented in **Figure 2a**, the annual average is 1540 mm. A 10 year running average of the annual data is also plotted to illustrate long term trends. A slight rising trend is observed in the running average data of approximately 4 mm/yr over the 116 yr period with increasing rainfall from the mid 1980s onwards.

The rainfall data was used to generate a cumulative mass residual curve (**Figure 2b**). The rainfall residual mass technique or cumulative difference from the mean reveals trends in the rainfall data. Declining trends indicate that rainfall is less than the long term average; rising trends indicate that rainfall is above the long term average. The cumulative mass residual curve of daily rainfall indicates that the past decade and a half has experienced higher than the long term average rainfall.

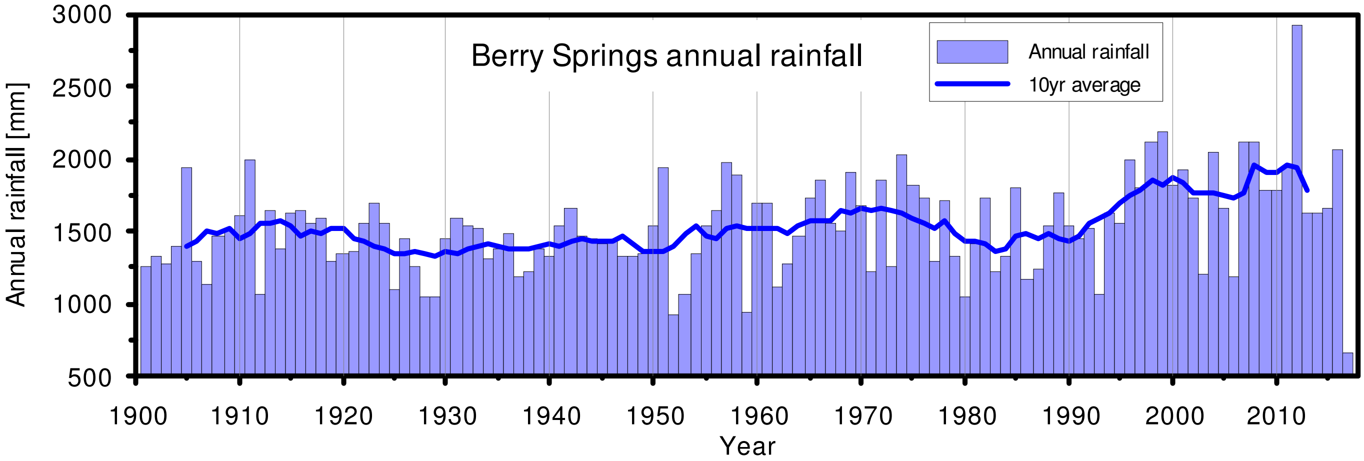


Figure 2a)

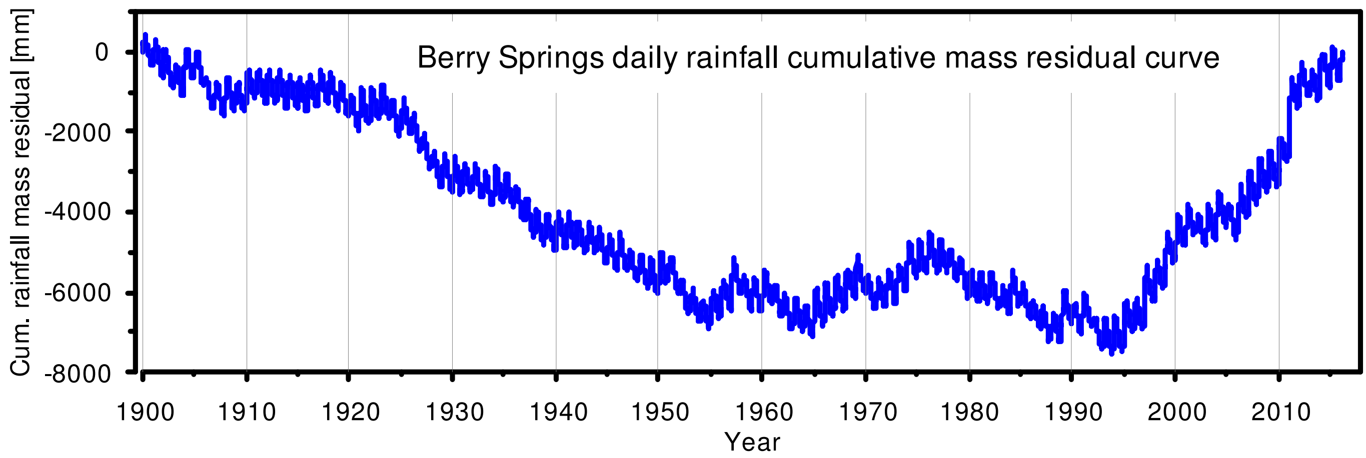


Figure 2b)

Figure 2a) Annual rainfall and b) cumulative mass residual curve of rainfall for Berry Springs area demonstrating long term trends in rainfall from 1900 - 2016.

2.2.2 Evaporation data

Interpolated potential evaporation values have been computed using data recorded from Class A pans. Observational data prior to 1970 have not been interpolated because various measuring devices were in use before 1970, resulting in inconsistent and unreliable data (Queensland Dept of Natural Resources and Mines, (2009)). The annual computed average evaporation is 2,274 mm and is relatively consistent over the period 1970-2015 (Figure 3).

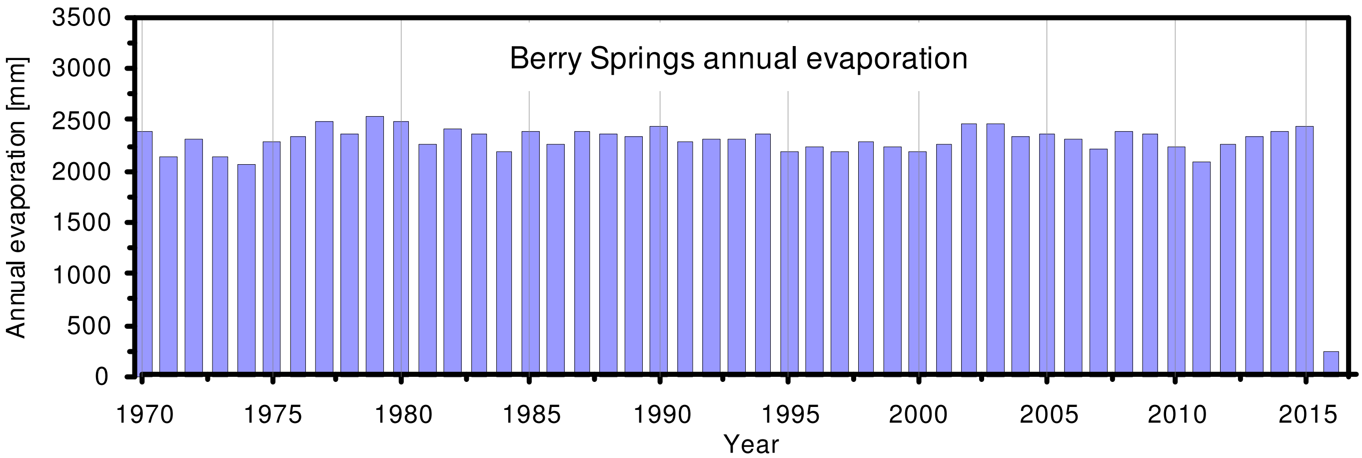


Figure 3 Annual evaporation for Berry Springs area.

2.3 Hydrology

The Berry River and Darwin Rivers can be described as perennial streams showing low inter-annual variability and have historically shown no more than occasional zero flow days.

2.4 Land use

Land use has been mapped under the Land Use Mapping Project (LUMP) based on the Australian Land Use Management classification scheme (Berghout et al., 2008) at 1:25000 using classification of satellite imagery and recent field verification from 2016 imagery. **Table 1** summarises the land use description of properties and the total area classified within each landuse category.

Table 1 Areas of classified land uses in the Berry Springs area

Land Use Description	Properties	Area (Ha)	% of Total Area
Conservation and Natural Environments	360	5644	65
Intensive Uses (Rural Residential)	226	1050	12.1
Production from Dryland Agriculture and Plantations	96	972	11.2
Production from Irrigated Agriculture and Plantations	80	955	11
Production from Relatively Natural Environments	2	26	0.3
Total	**803**	**8595**	**100**

Land use mapping has been used to estimate the area of irrigated land in the Berry Springs area. **Figure 4** shows the landuse classification for properties in Berry Springs according to the LUMP database. For the purposes of this study, an annual crop water usage per hectare was assumed for properties classified as Class 4: Irrigated Agriculture to estimate the associated annual groundwater usage for irrigation (refer to **section 5.6**).

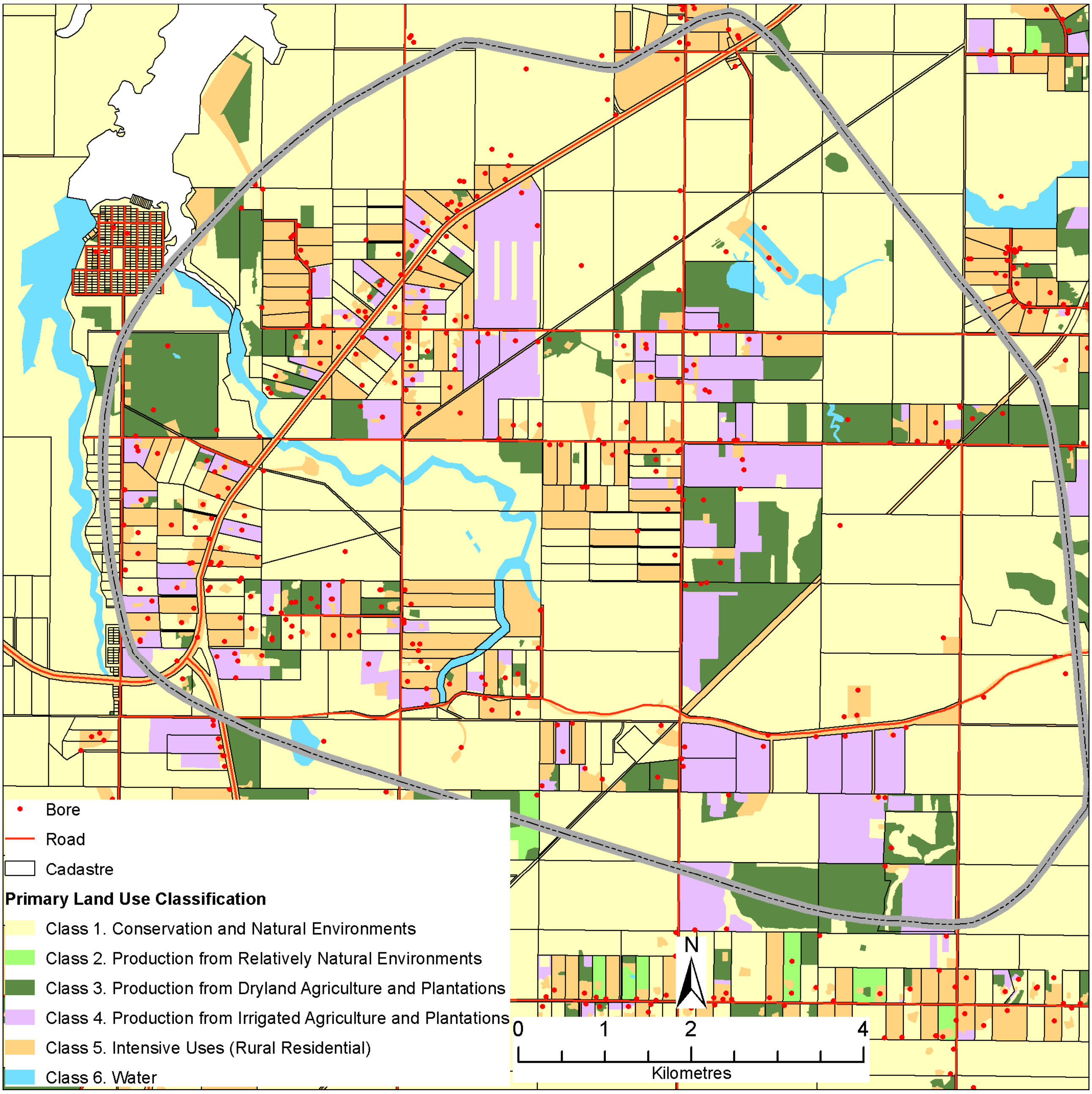


Figure 4 Land use in the Berry Springs region showing distribution of bores with registration numbers.

2.5 Groundwater extraction

Drilling for groundwater extraction started in the Berry Springs area in the mid 1970s. The distribution of bores is shown in **Figure 4**, with the greatest density of bores occurring within the rural residential land use areas. The cumulative bore count in the Berry Springs Aquifer, with a constant increase in number of bores drilled each year from around 1975 to date is shown in **Figure 5**. The increase in bores is directly correlated with an increase in water usage over the period. Groundwater extraction figures have been derived on the basis of land use with a volume of 3.5ML/year assigned to Stock and Domestic bores, and a volume of 6 ML/year assigned to Irrigation bores.

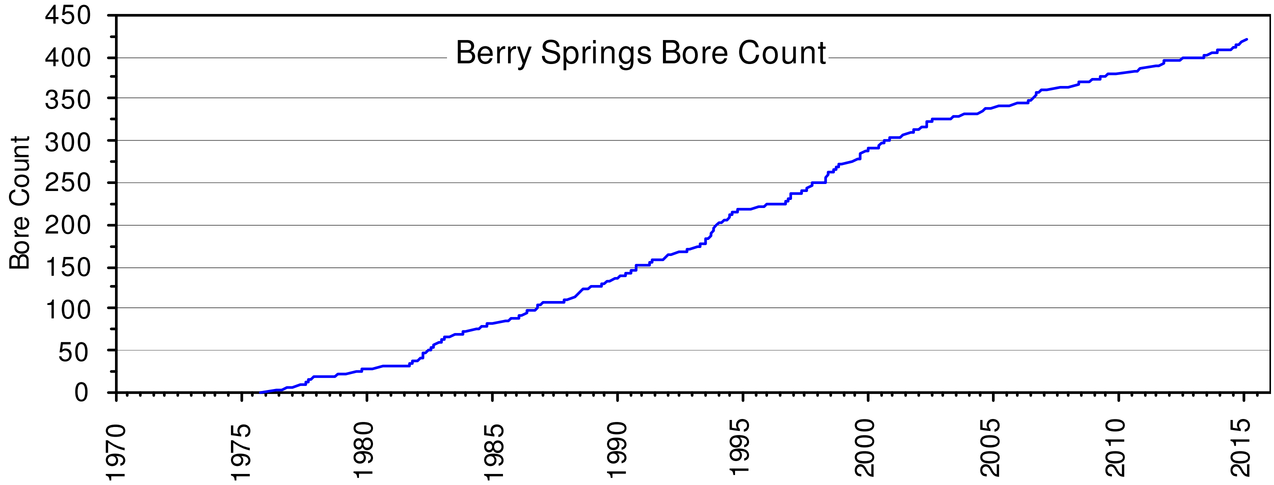


Figure 5Cumulative bore count in the Berry Springs aquifer.

2.6 Water quality

Water quality has been investigated at Berry Springs Pool over the 1987-88 hydrological year for salmonella and faecal indicators (Townsend, 1992). The highest bacterial concentrations occurred from September to December in the transition period between the dry and wet seasons. At the time of the study, the Berry Springs catchment had a low level of development with just 30 septic tanks estimated in the area and the source of bacterial activity was attributed to native fauna.

Since November 2005 water quality sampling has been conducted at the Main Pool of Berry Springs. Samples of E. Coli have been taken at roughly monthly intervals with values of counts per 100ml reported. As with the earlier study by Townsend (1992) a similar pattern of peak concentrations occurs in the late dry and early wet season. Samples with values greater than 500 counts per 100ml have resulted in closure of the pools. EColi monitoring was terminated in 2012 and Enterococci bacterial counts are now used as an indicator for water quality in the pool. Time series counts of E. Coli and Enterococci at the Main Pool are presented in **Figure 6**.

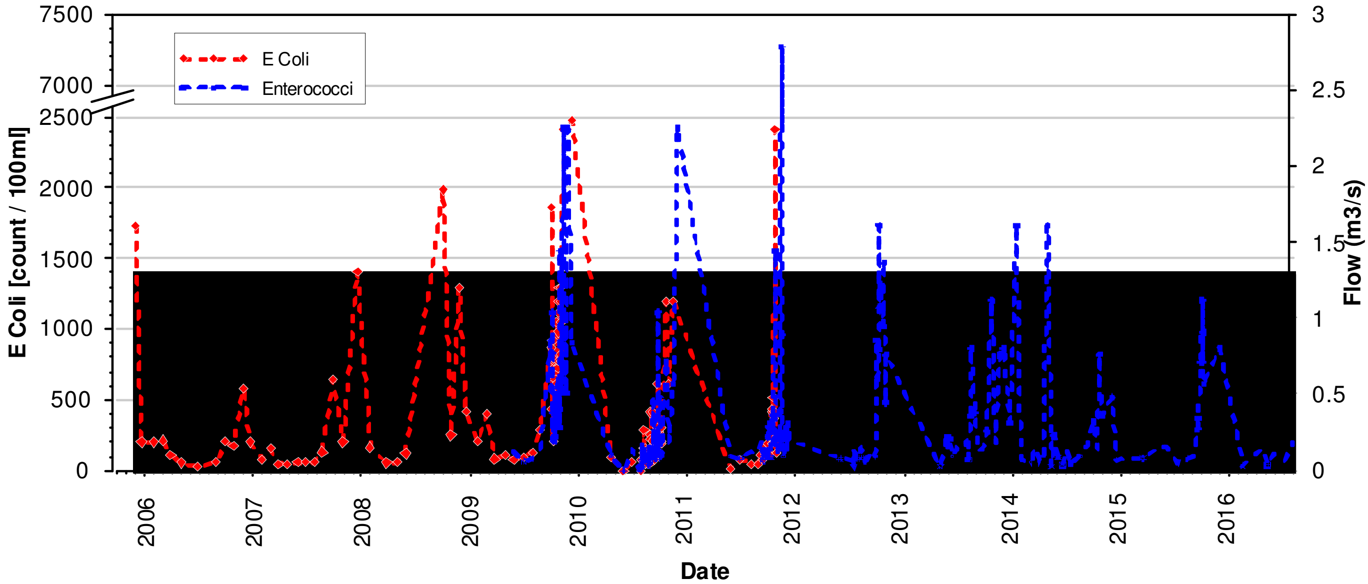


Figure 6Water quality data for Berry Springs Main Pool showing E.Coli and Enterococci counts per 100ml.

3 Hydrogeology

The major hydrogeological feature of the Berry Springs area is the fault bounded sedimentary basin which has an area of approximately 90 km^2. The major aquifer in the basin is an unnamed dolostone unit (Psd), known as the Berry Springs Dolostone which has been weathered to form karstic features.

Previous studies relating to the hydrogeology of the Berry Springs region have been largely confined to mapping the geology (Crick, 1983; Pietsch, 1986; Pietsch and Stuart-Smith, 1987). Hydrogeological mapping was undertaken in 1994 to examine the hydrogeology and groundwater dynamics of the area (Verma, 1995). This work identified the extent of the dolomite basin, groundwater discharge areas and the likely groundwater movement (Verma, 2002).

3.1 Geological formations

3.1.1 Mount Bonnie Formation (Pso)

The Mount Bonnie Formation of the South Alligator Group consists of interbedded pelite, felspathic greywacke, sandstone, pyritic siltstone & shale, phyllite and rare banded iron formation (BIF).

3.1.2 Unnamed Dolostone Unit (Psd): Berry Springs Dolostone

The unnamed dolostone (Psd) is the upper layer of the South Alligator Group and overlies the Mount Bonnie Formation (Pso). Weathered dolomite is exposed in the northern region - along the springs inside the Wildlife Park and the Berry Springs Nature Park; and in the Berry Creek at the Hopewell Road crossing. It consists of silicified dolomite, dolomitic siltstone, saccharoidal quartzite (after carbonate), calcite crystals, siltstone, shale, phyllite, commonly carbonaceous, pyritic, cherty & siliceous. Yields from this formation are generally > 5.0 L/s, which may be higher if fracturing and/or weathering is present (Verma, 1995).

3.1.3 Burrell Creek Formation (Pfb)

The Burrell Creek Formation (Pfb) of the Finniss River Group conformably lies over the South Alligator Group and consists of mica schist, siltstone, shale, phyllite, greywacke, slate which are very similar to that of the Mount Bonnie Formation. Bore yields from this formation are generally < 0.5 L/s which may be higher if fracturing and/or weathering or fractured quartz veins are present. Higher yields (up to 5.0 L/s, airlifted) have been obtained in the highly fractured graben between the eastern boundary of the dolostone (Psd) and the Mt Bonnie Formation (Pso).

3.1.4 Depot Creek Formation (Ptd)

The Depot Creek Formation (Ptd) of the Tolmer Group is of Proterozoic age and lies unconformably over the Lower Proterozoic sediments (mostly dolostone in this area) and they are nearly flat lying. This formation occurs in the Darwin River subcatchment. It consists of pink quartzite, quartz sandstone with ripple marks.

3.1.5 Petrel Formation (JKp)

The Petrel Formation (JKp) is of Jurassic age and consists of friable quartz sandstone, quartz-pebble, conglomerate, conglomeratic sandstone, ferruginous sandstone, and minor breccias. This formation is flat lying and overlies the Depot Creek Formation (Ptd). The base of this formation is exposed along the Darwin River near Old Bynoe Road. This formation is also very porous and good for recharging the underlying layers.

3.1.6 Darwin Member (Kld)

Darwin Member (Kld) of the Bathurst Island Formation is Cretaceous aged and consists of kaolinitic claystone, silty in places, glauconitic and calcareous, basal conglomerate, clayey, sandstone & sandy claystone. This formation unconformably lies over the Proterozoic age rocks.

It is interpreted that areas of the unnamed dolomite unit (Psd) without the thick Cretaceous sediments cover, show less karstification and have lower yields (< 1.0 L/s).

3.2 Geological structure

The dolostone basin of the Berry Springs area is fault bounded and surrounded by the metasediments of the Burrell Creek Formation. Groundwater discharges at the northern boundary of the basin are associated with a zone of increased permeability associated with the fault between the dolostone aquifer to the south and the Burrell Creek Formation to the north (**Figure 7**). The surrounding rocks of the Burrell Creek Formation are highly folded; however, no structural disturbances are evident in the dolostone aquifer (Verma, 1995).

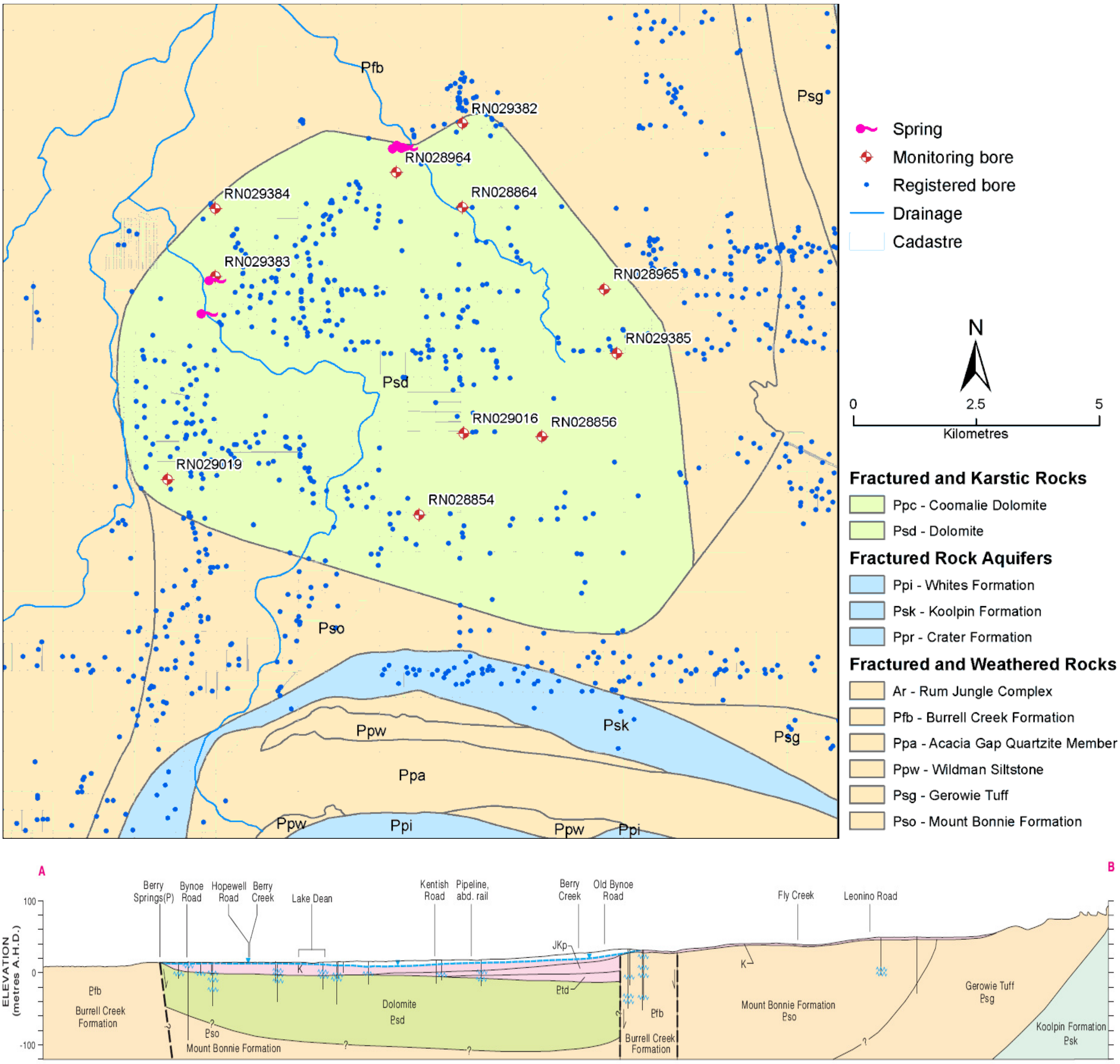


Figure 7Hydrogeology of the Berry Springs region and cross-section through Berry Springs (Verma, 1995).

3.3 Aquifer characteristics

A major karstic aquifer occurs in the weathered and fractured silicified dolostone. In areas where the Cretaceous sediments are saturated, aquifers exist within the basal unit which is comprised of conglomerate, coarse sandstone, some clay, silt and sand (Verma, 1995).

Yields of up to 32.0 L/s have been obtained in the karstic dolostone aquifer, however, in the fresh dolostone below the weathered zone, yield is very low to nil. Depth of extent of this aquifer varies from 10 to 88 m below ground level (Verma, 1995) and the average thickness of the aquifer is about 50 metres.

The aquifer of the Berry Springs dolostone is considered to be typical of karstic aquifers, where chemical weathering has produced wide spread secondary porosity and permeability in the carbonates. The carbonate aquifer is expected to have greatest permeability within this weathered zone, up to a maximum of 50 metres below the top of the formation. The karstic nature of the aquifer means that on a local scale groundwater flow is via preferential pathways, however, on a basin wide scale the aquifer can be considered to behave as an equivalent porous media with very high transmissivities and relatively low storage coefficient.

Although the system can be conceptualised as a porous media, it is more accurately described as a dual permeability aquifer.

3.3.1 Hydraulic conductivity

An estimate of 500 – 1000 m^2/d has been used previously for aquifer transmissivity by Verma, (1995).

3.3.2 Storage coefficient

Based on recharge estimates of 200 mm/yr (Hatton et al., 1997; Cook et al., 1998c), in a study of Howard East, and the maximum variation in groundwater levels in the study area (approximately 10 metres) the storage coefficient of the aquifer system is estimated to be between 0.02 and 0.05.

4 Groundwater hydrology

4.1 Groundwater flow

A total of thirteen (13) bores and eight (8) spring and surface flow gauging sites are currently monitored in the Berry Springs region (**Figure 8**).

Based on the monitoring bore information and the locations of the known discharge points and the assumption that the groundwater levels are a subdued reflection of the topography, then groundwater movement is from the south to the north to the Berry Springs area and northwest to the Parson's and Twin River Farm Springs area. During the dry season, the groundwater slope is 0.00068 (4.4 m drop in 6,500 m) and in the wet it is 0.00137 (8.9 m drop in 6,500 m). The variation in discharge along the rivers, creeks, springs and lagoons reflects the dynamic nature of the groundwater levels.

During the wet season the aquifer can become fully saturated and during these periods runoff is significant. This also indicates that the aquifer is recharged annually by the rain.

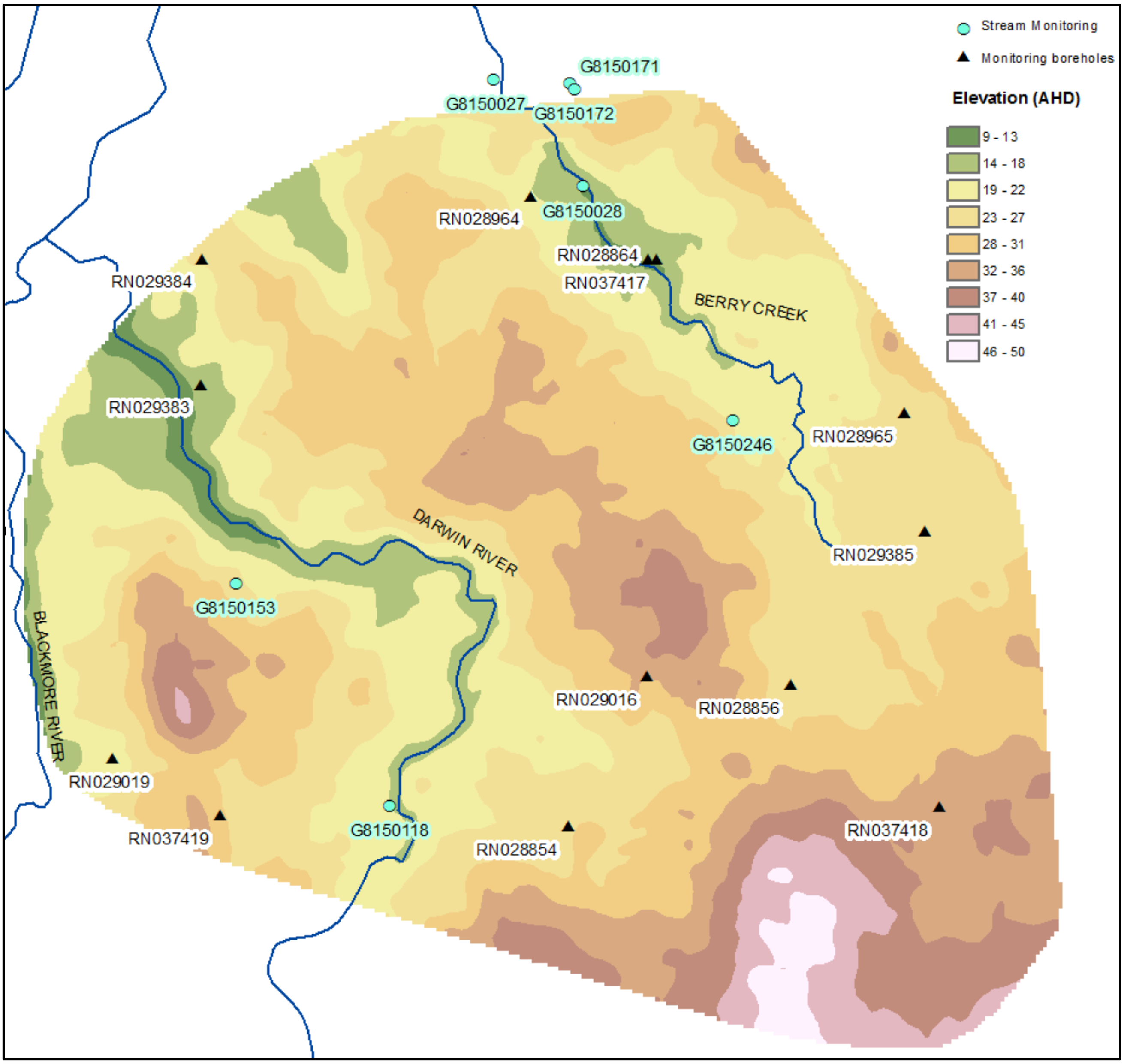


Figure 8 Groundwater and streamflow monitoring of the Berry Springs region.

4.2 Recharge

Groundwater recharge or deep drainage is a hydrologic process where water moves downward from surface water to groundwater. This process usually occurs in the vadose (unsaturated) zone below plant roots and is often expressed as a flux (the flow per unit area per unit time) to the water table surface.

Groundwater levels in the Berry Springs aquifer respond strongly to rainfall events and the lag between initial rainfall and the corresponding increase in groundwater levels is relatively short. Similarly groundwater levels begin to decline just before or soon after rainfall ceases. **Figure 9** shows the groundwater hydrograph for RN029016 in relation to daily rainfall for the period 2005 - 2011.

Figure 10 shows the mass residual rainfall curve compared to the groundwater hydrograph for RN029016. The direct correlation in the timings between rainfall and groundwater levels is evident.

Approximately 240 mm of rain was required prior to the groundwater levels rising in 2009/10. It should be noted that the increase in groundwater levels also coincides with an event in excess of 310 mm over 2 days.

Groundwater levels show considerable seasonal range with approximately 15-20 metres between the highest levels at the end of the wet season to the lowest levels at the end of the dry season. An example of the variation in groundwater level is seen in **Figure 10**, which shows manually collected water levels for RN029016, continuous logger data are also available at this site from late 2009 to early 2010. The logger data demonstrates the rapid rise in groundwater levels in response to rainfall.

4.2.1 Water balance method

Verma (1995) assumed a recharge of ~480 mm which is approximately 30% of mean annual rainfall (1600 mm).

Cook et al (1998), in a study of Howard East approximately 35 km away in a similar climatic and hydrogeological setting, using water balance methods, identified that recharge was approximately 200 mm/yr which is 11-12% of the rainfall (1720 mm average annual). They did note however that:

> *'The uncertainty on the estimated recharge rate is believed to be approximately ±50%. Also, the figure represents a spatial average, and it is likely that groundwater recharge will be higher than this in some areas and lower in others.'*

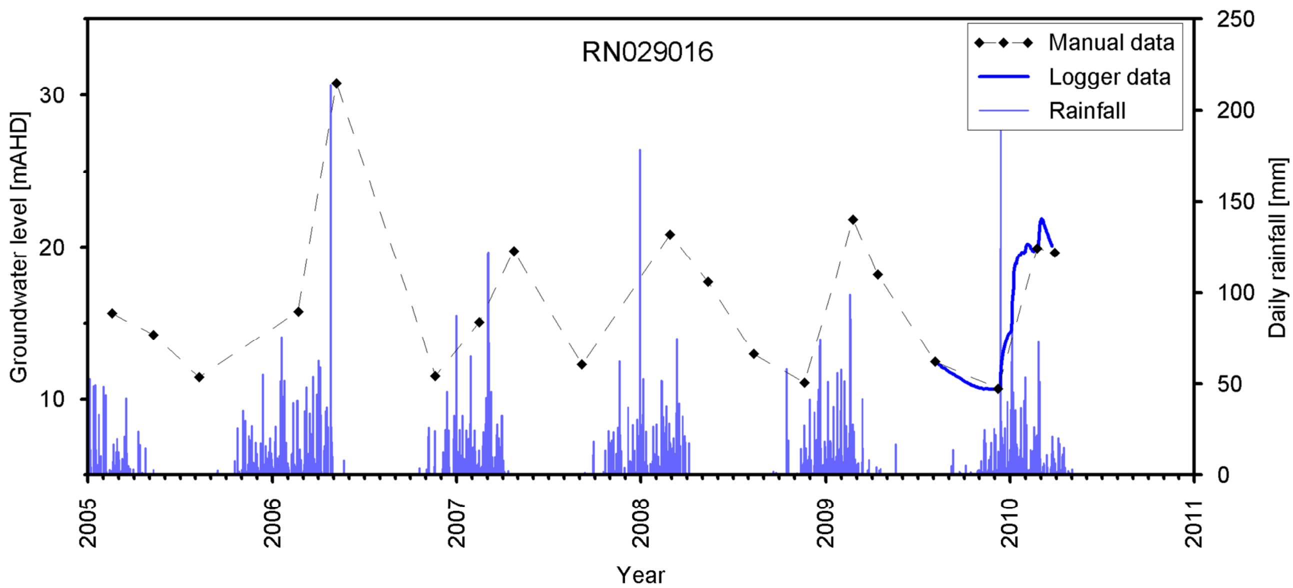


Figure 9Comparison of daily rainfall manual groundwater levels and logger data for RN029016 from 2005 - 2010.

4.2.2 Water table fluctuation method

The water table fluctuation method of recharge determination (Scanlon et al., 2001) uses the rise in groundwater levels and an estimate of storage to determine the required recharge. The hydrograph for RN029016 shows water level variations of up to 15-20 metres. Assuming that the specific yield of the aquifer is between 0.01 and 0.04 then the recharge is expected to be between 150 mm and 800 mm. A value of 0.02 gives a recharge value of 300-400 mm.

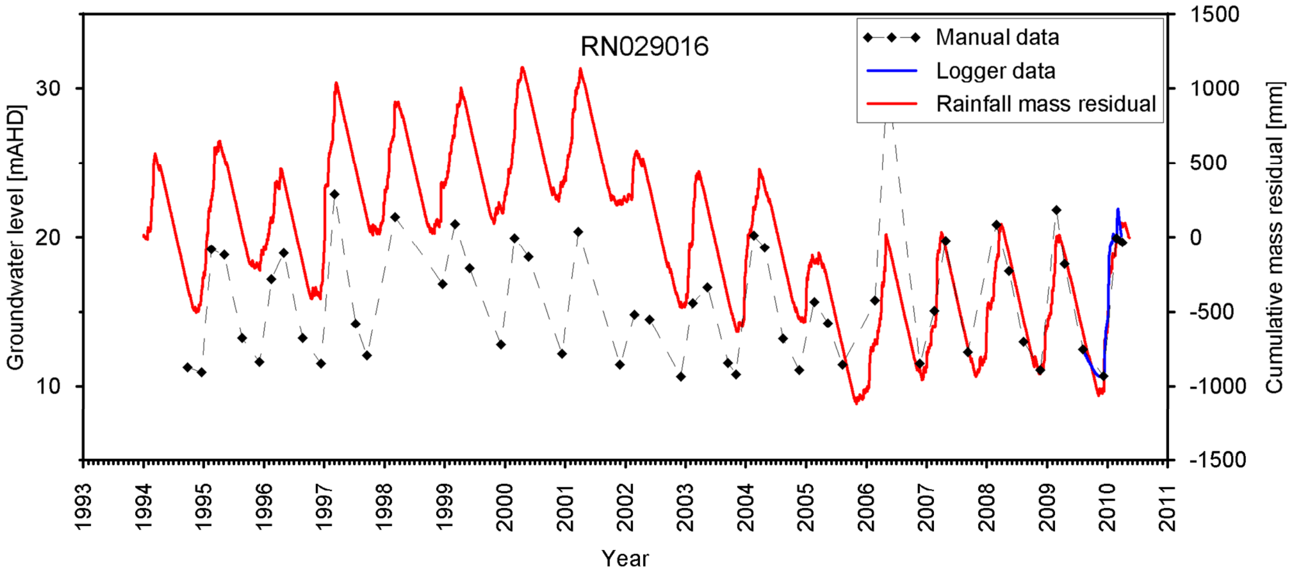


Figure 10 Comparison of cumulative mass residual, manual groundwater levels and logger data for RN029016 from 1993 - 2010.

4.2.3 Spring discharge

The most obvious discharges from the Berry Springs aquifer system are the springs. 5 major springs have been mapped in the area including Parson Spring, Twin Farm Spring and several in the Berry Springs spring complex (**Figure 11**).

The Berry Springs spring complex is located on an east-west trending fault along the contact between the Berry Springs dolostone to the south and the Burrell Creek Formation to the north. Minor faults are interpreted to be associated with the contact and provide pathways for groundwater to discharge at the smaller springs in the area (**Figure 11**).

The site at March Fly Weir downstream of Berry Springs (G8150027) has recorded river heights from 1960 to 1982.

Twin Farm Spring and Parson Spring occur where the river intersects the aquifer and are located in the tidal section of the Darwin River. Given the elevation of these springs it is likely that if groundwater levels were to fall below the mean tidal level salt water may be induced into the Berry Springs aquifer.

Parson's and Twin Farm Springs are within the tidal zone of Darwin River. The Lake Deane is a groundwater window through which discharge occurs. The water level from south of Lake Deane to the north of Berry Springs is nearly constant and therefore, in this region swampy condition prevails until almost mid dry season. In the northern region, the Goose Lagoon and surrounding areas are also groundwater discharge points, which have created swampy conditions. Numerous discharges are in the southern part of the Darwin River. Woodfords Lagoon in the southwest corner of the dolomite aquifers can be seen along the Darwin River in the northern region in the dry season.

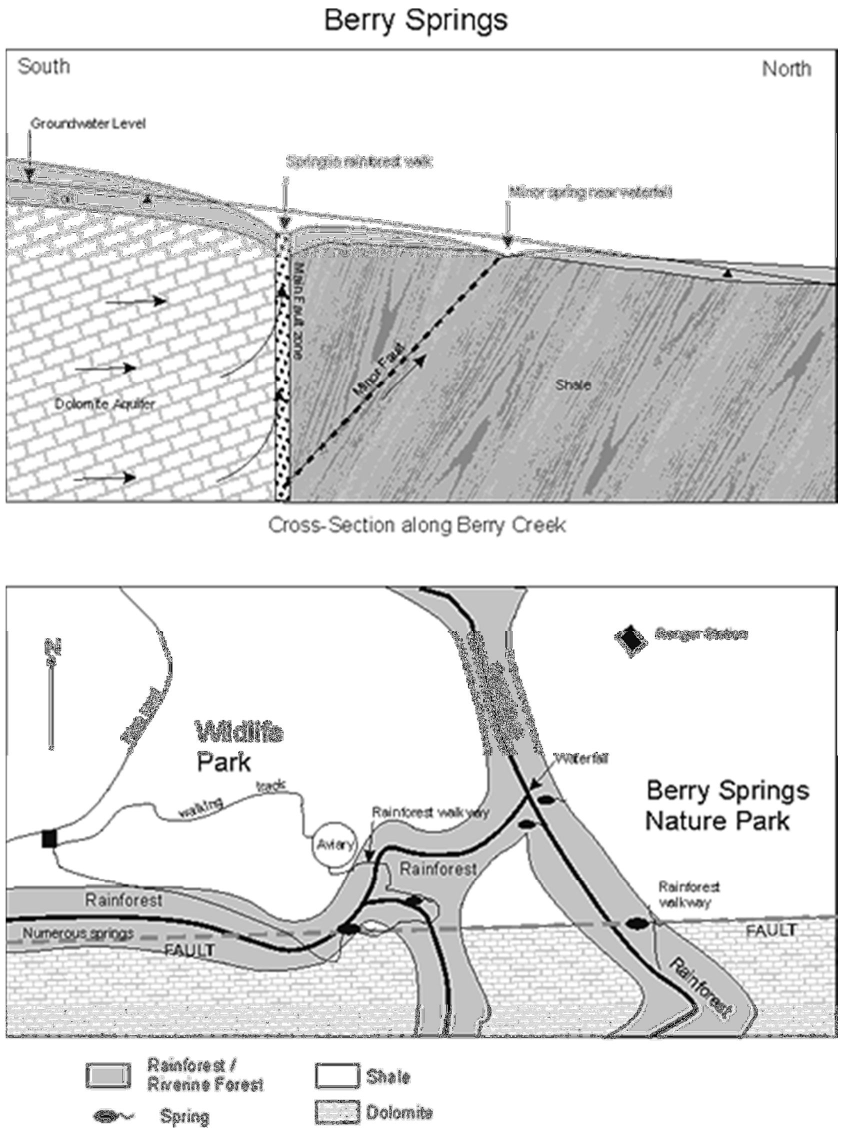


Figure 11 **Berry Springs spring complex located along Berry Creek (after Tickell).**

Groundwater discharge measurements from the springs exhibit a recession. Examining the recession data by plotting the timeseries discharge data as a semi-logarithmic graph shows that the groundwater discharge recession is linear and therefore obeys an exponential decay law refer to in **section 5.5.1**.

4.2.4 Evapotranspiration

Cook et al, 1998 found that the savannah woodland of the Howard East area (approximately 20km to the northeast) transpired approximately 1110 mm (this is approximately 65 % of rainfall). The ET from swamps was found to be similar, however, the actual transpiration from vegetation was estimated at 540 mm.

4.3 Rainfall-runoff modelling

The Berry Springs catchment (140 km^2) was modelled using DHIs NAM rainfall-runoff model (DHI, 2009) to generate metrics relating to the catchment water balance. The observed discharge and NAM simulated discharge are presented in **Figure 12**. The Nash-Sutcliffe coefficient of efficiency (NSE) for the calibrated simulation flows compared to the observed flows is 0.78, which is considered a satisfactory model calibration.

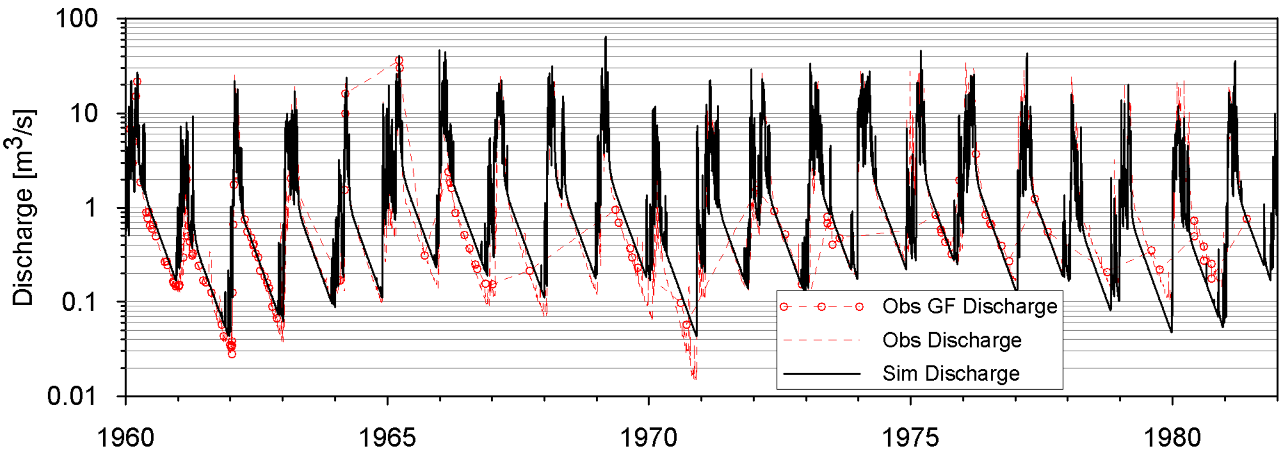


Figure 12 Graphical comparison of simulated and observed flows at G8150027.

Flow duration plots for the available observed flows and corresponding simulated flows are presented in **Figure 13**.

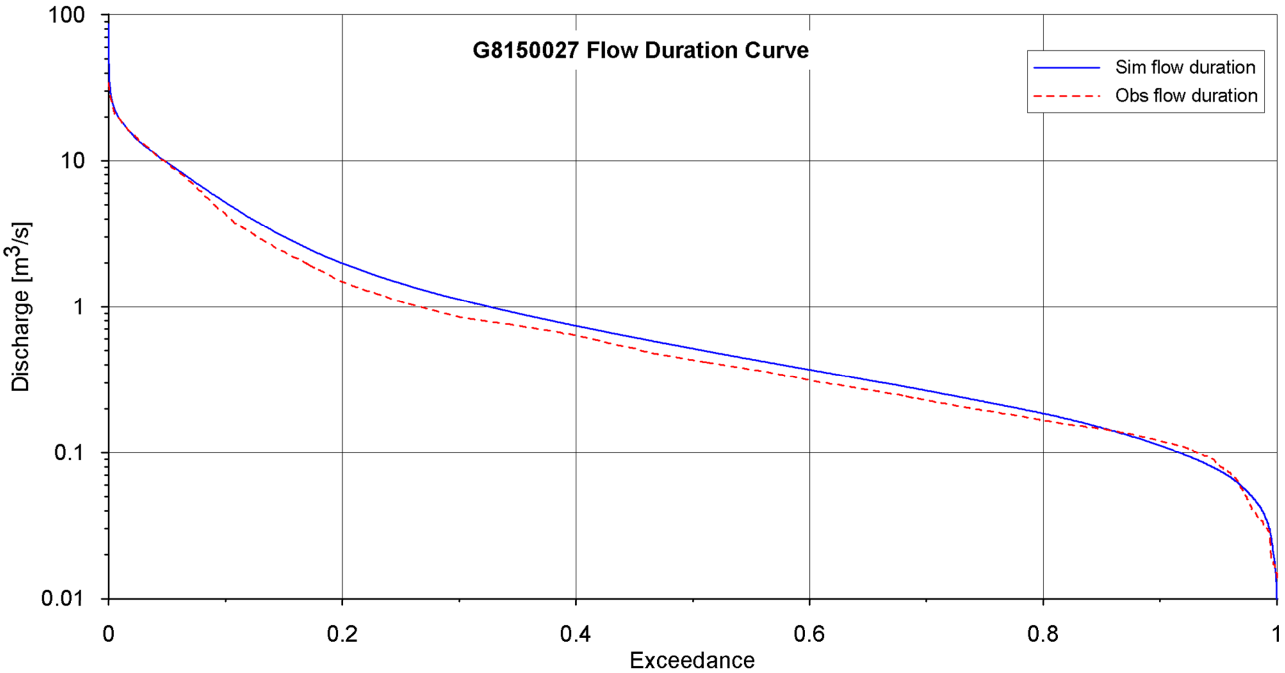


Figure 13 Observed (period 1950-1970) and simulated flow (period 1900-2010) duration curves for March Fly Weir (G8150027).

The NAM model was run using the available climatic data (1900-2010) and the average annual water balance components were determined. The water balance results are tabulated in **Table 2**.

Table 2 Average annual water balance components determined using NAM rainfall-runoff modelling.

Rainfall	Actual ET	Runoff	Overland flow / Interflow	Baseflow
[mm]	[mm]	[mm]	[mm]	[mm]
1520	1093	382	222	160.4
100%	71.9%	25.1%	14.6%	10.5%

Average actual ET is 1093 and is close to the figure determined by Cook et al, 1998. ET is ≈72% of average annual rainfall for the period 1900-2010.

Groundwater discharge is estimated at approximately 160 mm, however it should be noted that the groundwater system is approximately 45.3 km^2 or 32% of the surface water catchment, therefore the actual baseflow is 500 mm.

4.4 Predicted natural conditions compared to recent observed flows

Prior to 1980 only about 10 production bores existed in the Berry Springs region and it has been assumed that extraction has not impacted on the discharge observed at the springs prior to 1980. The expected dry season discharge at Berry Springs for 2010 was determined from climatic data and compared to observed dry season flows (**Figure 14**). It can be seen that the predicted discharge is greater than the observed flows. If the difference between the observed and simulated flows are compared for the period of record (**Figure 15**) the magnitude of the disparity can be more clearly seen. The flows in 2010 demonstrate the greatest difference and suggest that groundwater extraction impacts are present.

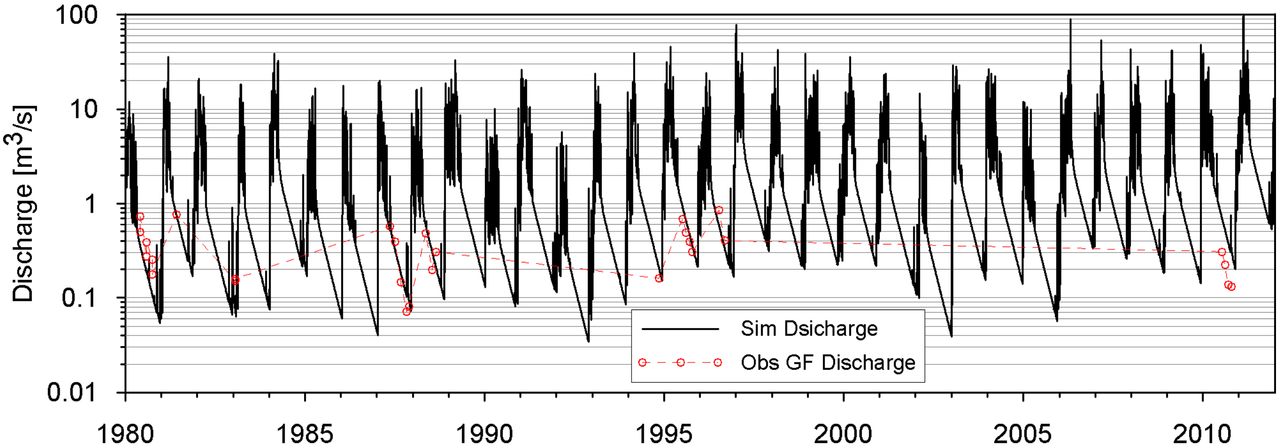


Figure 14 NAM results for period 1980-2012, prior to 2000 the available gaugings show a close match to the simulated results, recent gaugings suggest groundwater discharge is lower than expected.

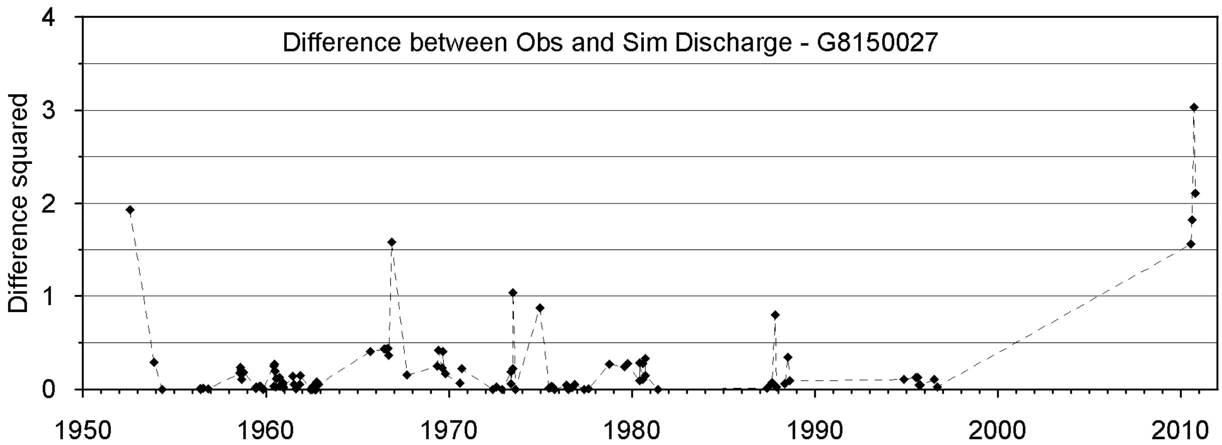


Figure 15 Difference between the observed and simulated discharge assuming no groundwater extraction in the model. The increased difference between observed and simulated results in 2010 are attributed to unaccounted for groundwater extraction.

4.5 Groundwater chemistry

The water from this aquifer system has a TDS of around 200 mg/L and is hard with elevated concentrations of Ca, Mg and bi-carbonate (HCO_3). Sodium and chloride contents are relatively low indicating that the water is of recent age (Verma, 1995).

5 Available data

Available data for the study site used to develop the groundwater model include:

- synthetically derived SILO climatic data (Queensland Dept of Natural Resources and Mines, 2009);
- groundwater levels from observation bores from the Northern Territory Government (NTG) groundwater database (NTG, 2009);
- manually gauged river discharge from the NTG groundwater database (NTG, 2009).
- drainage polylines
- vegetation mapping and remote sensing (MODIS images)
- digital surface geology maps (Geoscience Australia)
- borehole stratigraphy
- SRTM digital terrain model

5.1 Climate data

Recharge modelling requires a continuous record of rainfall and evaporation. The discontinuous periods of rainfall and evaporation data in the Berry Springs area required the use of synthetically derived data from the Bureau of Meteorology's SILO Data Drill.

The SILO Data Drill daily rainfall data was used to generate a cumulative mass residual curve. The cumulative mass residual curve of daily rainfall indicates that the past decade and a half has experienced higher than the long term average rainfall.

5.2 SRTM digital terrain model

Shuttle Radar Terrain Model (SRTM) data is available as an Arcview grid file. The data was clipped and reprojected from WGS84 to GDA94 MGA52 (refer **Figure 16**) The resulting grid was 'filled' using the Arcview Hydrology tools before using the Spatial Analyst tool Extract Values to Points to assign elevation data to the FEM nodes.

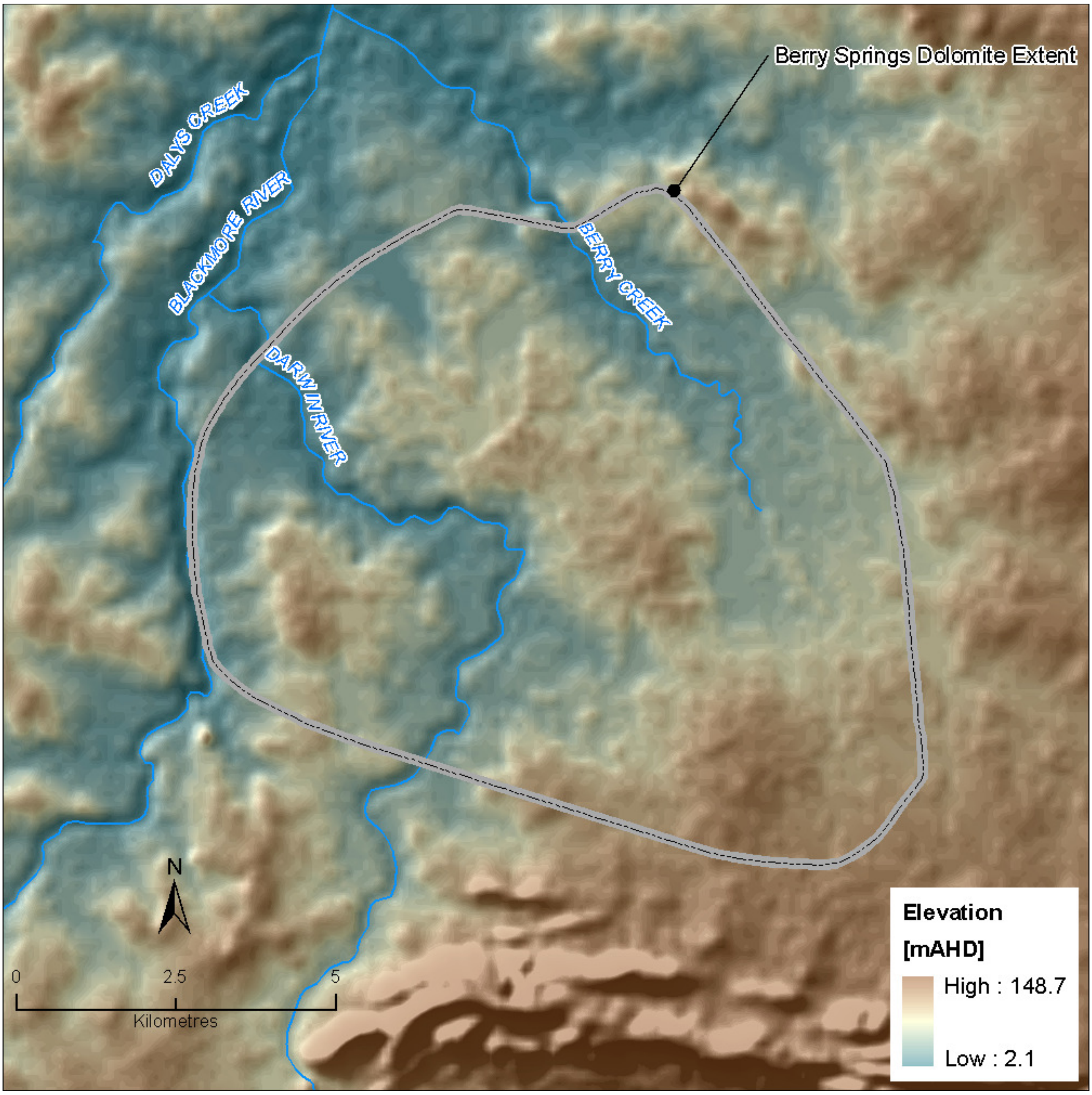


Figure 16 Digital elevation model of the Berry Springs area

5.3 Geological data

Water resources mapping of the area produced a polygon of the extent of the Berry Springs dolostone aquifer. The thicknesses of the important geological strata in the area were also estimated from previous works (Verma, 1995).

5.4 Groundwater level data

5.4.1 Steady state groundwater levels

11 groundwater levels from September 1994 are available for steady state model calibration (refer **Table 7**). The time of the year that these water levels were obtained is roughly in the middle of the dry season and assumed to be equivalent to the steady state or average heads of the system.

Table 3 September 1994 groundwater levels used in the calibration of the steady state model

Site	Date	SWL [mBGL]	RL [mAHD]	SWL [mAHD]
RN028854	23/09/1994	10.84	23.04	12.20
RN028856	23/09/1994	12.43	21.29	8.86
RN028864	23/09/1994	5.90	15.65	9.75
RN028964	23/09/1994	6.66	16.06	9.40
RN028965	23/09/1994	10.73	22.05	11.32
RN029016	23/09/1994	20.45	30.79	10.34
RN029019	23/09/1994	8.61	18.50	9.89
RN029382	23/09/1994	21.86	25.73	3.87
RN029383	23/09/1994	5.53	14.63	9.10
RN029384	23/09/1994	8.96	18.52	9.56
RN029385	23/09/1994	12.08	23.60	11.52

Note: SWL data obtained from Hydstra February 2010
RL information has been obtained from the SRTM digital elevation model error ±4 metres

5.4.2 Time series groundwater levels

Time series groundwater levels data are available from the Northern Territory Government Hydstra database. SWL data for the 11 monitoring bores in the Berry Springs dolomite were obtained from Hydstra in February 2010. The details of these bores are presented in **Appendix A**. Plots of the groundwater level data are also presented in **Appendix A**.

5.5 River discharge data

5.5.1 Manual gauging data

River discharge data are available from the Northern Territory Government Hydstra database. The gauging site at March Fly Weir downstream of Berry Springs (G8150027) is assumed to represent the discharge from the Berry Springs spring complex and also includes any discharge upstream. 178 manual gaugings have been conducted since mid 1952. The gauged flow records at the site vary between 5 l/s to 9630 l/s. The minimum and maximum gauged flow for each month are presented in **Table 4**.

Table 4 Number of gaugings separated into each month with maximum and minimum flows recorded.

Month	Number of gaugings	Minimum	Maximum
Jan	22	0.0283	9.63
Feb	10	0.139	6.8
Mar	17	0.439	36
Apr	6	0.311	3.68
May	14	0.241	1.25
Jun	20	0.17	0.906
Jul	18	0.0425	0.861
Aug	20	0.098	0.551
Sep	16	0.058	0.401
Oct	14	0.0051	0.319
Nov	15	0.0425	0.268
Dec	6	0.0354	1.96
Total	**178**		

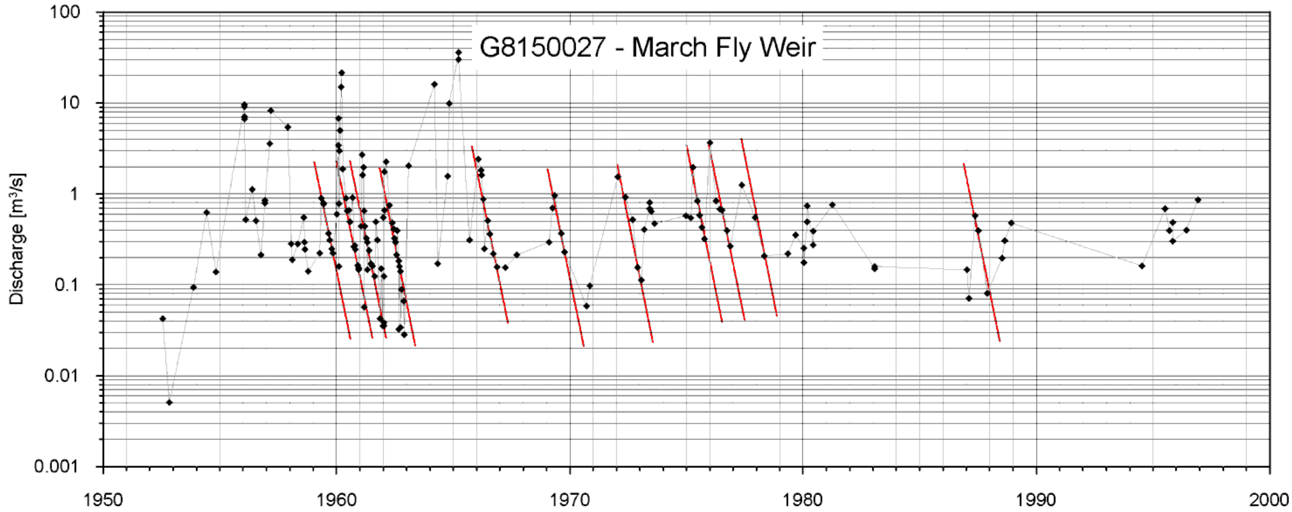


Figure 17 Manual gauged data for March Fly Weir (G8150027) with linear fits demonstrating the recession in dry season groundwater discharge.

There are no data available for the Parson Spring and Twin Farm Spring; it is assumed that the mechanism of the discharge in the vicinity of these springs is similar to the Berry Springs spring complex and the magnitude is proportional to the size of the groundwater sub-basin discharging to them.

5.5.2 Continuous recorder data

Continuous height data are also available at March Fly Weir (G8150027) from 1960 to 1982. A plot of this data converted using the rating table to flows compared to the manual gauged flow data is presented in **Figure 18**.

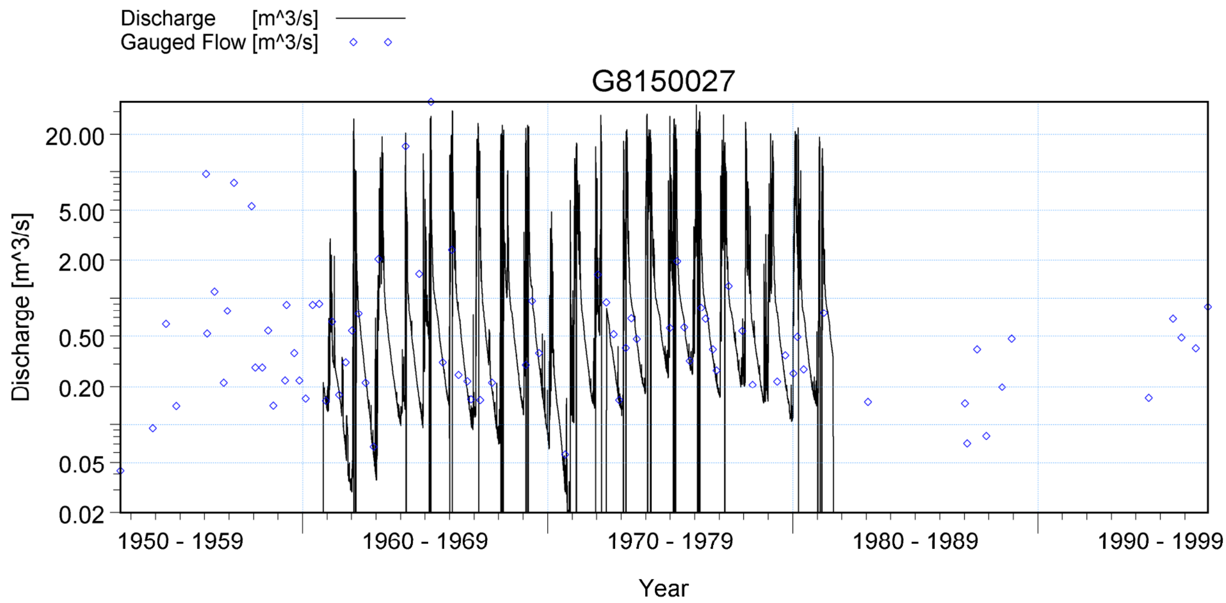


Figure 18 Historic discharge data at G8150027. Gauged flows have been conducted 27/07/1952 – 7/12/1996. Continuous record exists from 2/11/1960 – 24/08/1981.

5.6 Pumping data

No known flow meters are installed on bores extracting groundwater from the Berry Springs dolostone aquifer; therefore to estimate extraction the following methodology was employed.

1. The 2008 release of the Land Use Mapping Project (LUMP) data was used to identify which properties within the Berry Springs Planning Area (Berry Springs dolostone aquifer with a buffer

of 1km) were classified as “Production from Irrigated Agriculture and Plantations”. Each property that is completely or partially under this category was identified as an "Irrigated Property".

2. Bores on "Irrigated Properties" were identified as "Irrigation Bores" and assigned a portion of the irrigated land use (in Hectares) that the bore was assumed to be watering. If more than one bore was on the property each bore was either assigned a particular portion of irrigated land or the total area was divided between each bore.
3. Each bore now has a certain amount of land in hectares and assumed to have an average use of 6ML/ha/year use. Bores identified as being "Irrigation Bores" were also assigned a time series component with pumping only occurring over the 6 months of the dry season (assumed to be from 01 May thru to 01 November).
4. All bores not identified as "Irrigation Bores" within the Berry Springs dolostone aquifer were filtered to remove all “Not in Use” and “Monitoring” bores. All remaining bores not on "Irrigated Properties" were assumed to be Stock and Domestic and assigned a 3.5ML/year volume of use.

The results of this classification are summarised in Table 5.

Table 5 Summary of pumping bore extraction data.

Use	Area Irrigated (Ha)	Number of Bores	Annual extraction m^3/yr	
Irrigation	864.3	114	6.0 ML/ha	5,185.5
Stock & Domestic		198	3.5 ML/bore	693.0
Total		312		5,878.5

The bore registrations completion dates and applied extraction are presented in Appendix C.

5.7 Data gaps

Several data gaps have been identified during the study, these are:

- Limited overlap of groundwater discharge measurements and groundwater level measurements
- No discharge data for springs in the west of the study area ie Parson Spring and Twin Farm Springs
- Lack of actual groundwater extraction figures
- Bore measuring point RLs were obtained from SRTM data, this data has an error of ±5 metres. To improve the calibration of the model the measuring point of the observation bores in the Berry Springs dolomite require levelling using differential global positioning system (DGPS).

6 Groundwater flow model development

6.1 What is a groundwater flow model?

A model is a simplified representation of a physical system. Groundwater models are used to represent the natural groundwater flow in the environment. Groundwater models may also be used to predict the effects of hydrological changes (like groundwater abstraction or irrigation developments) on the behaviour of the aquifer and are often named groundwater simulation models. Also nowadays the groundwater models are used in various water management plans for urban areas.

Mathematical or numerical groundwater models are based on groundwater flow equations which are based on the real physics of groundwater flow.

Preceding and underlying the mathematical model is a largely qualitative description of the structure of the system under study and the physical, chemical, and biological processes to be included in the model. This qualitative description is called a conceptual model.

6.2 Conceptual model

A conceptual model provides a simplified overview of a complex natural system. The major geological units represented in the groundwater model are presented in **Table 6**.

Table 6 Hydrogeological units relevant to the groundwater modelling study.

Unit name	Age	Dominant Lithology	Hydrologic type	Comment
Berry Springs dolomite	Mesoproterozoic	Dolostone	Karstic aquifer	Aquifer with major discharge
		Metasediments	Hydrologic basement	Underlies the Berry Springs dolostone.
Mullaman Beds	Early Cretaceous	Claystone and basal sandstone		Overlies large portions of the Berry Springs dolostone and reduces the amount of recharge

- The groundwater system consists of two hydrogeological layers representing the Cretaceous sands and clays and the karstic Proterozoic dolostone;
- The weathered highly permeable portion of the aquifer is assumed to extend to 50 metres below the mean sea level;
- Conceptually, the groundwater system developed in the weathered dolostone aquifer is a dual continua consisting of karsts / fractures within a porous media, although at a regional scale it appears to behave as porous media;
- Continuum flow (often termed diffuse flow) processes are active in low permeability matrix blocks or slightly fissured limestone beds, while concentrated flow processes can be observed in a discrete conduit network in the karst features;
- The water level and discharges dynamics observed are characteristic of a highly permeable media with relatively limited storage;
- The groundwater flow within the Berry Springs dolostone is from the south to the north where it discharges to the bed of the rivers and creeks and via discrete springs such as the Berry Springs complex, Parson Spring and Twin Farm Springs;

- Berry Spring is thought to occur at the contact between the unnamed dolostone and the Burrell Creek Formation;
- Under natural conditions the spring discharge recession follow an exponential decay function;
- The level in the springs are assumed to be relatively constant and only discharging;
- The area can be divided into two smaller scale sub-basins where a groundwater divide occurs roughly coincident with surface water catchment divide of the Darwin River and Berry Creek;
- The groundwater flow within the two groundwater sub-catchments is towards the Berry Springs spring complex from the divide to the north east and Parson Spring and Twin Farm Spring to the north west;
- Discharge from the springs in the west of the study area ie Parson Spring and Twin Farm Springs are of a similar magnitude to discharge from the Berry Springs complex;
- Evapotranspiration rates are of the order of 1110 mm (Cook et al., 1998b);
- It is assumed that areas where the groundwater level approaches the ground surface the soil column becomes saturated and therefore no recharge is possible resulting in recharge being 'rejected' as runoff;
- Extraction of groundwater is estimated based on the area of landuse and water use of each landuse;

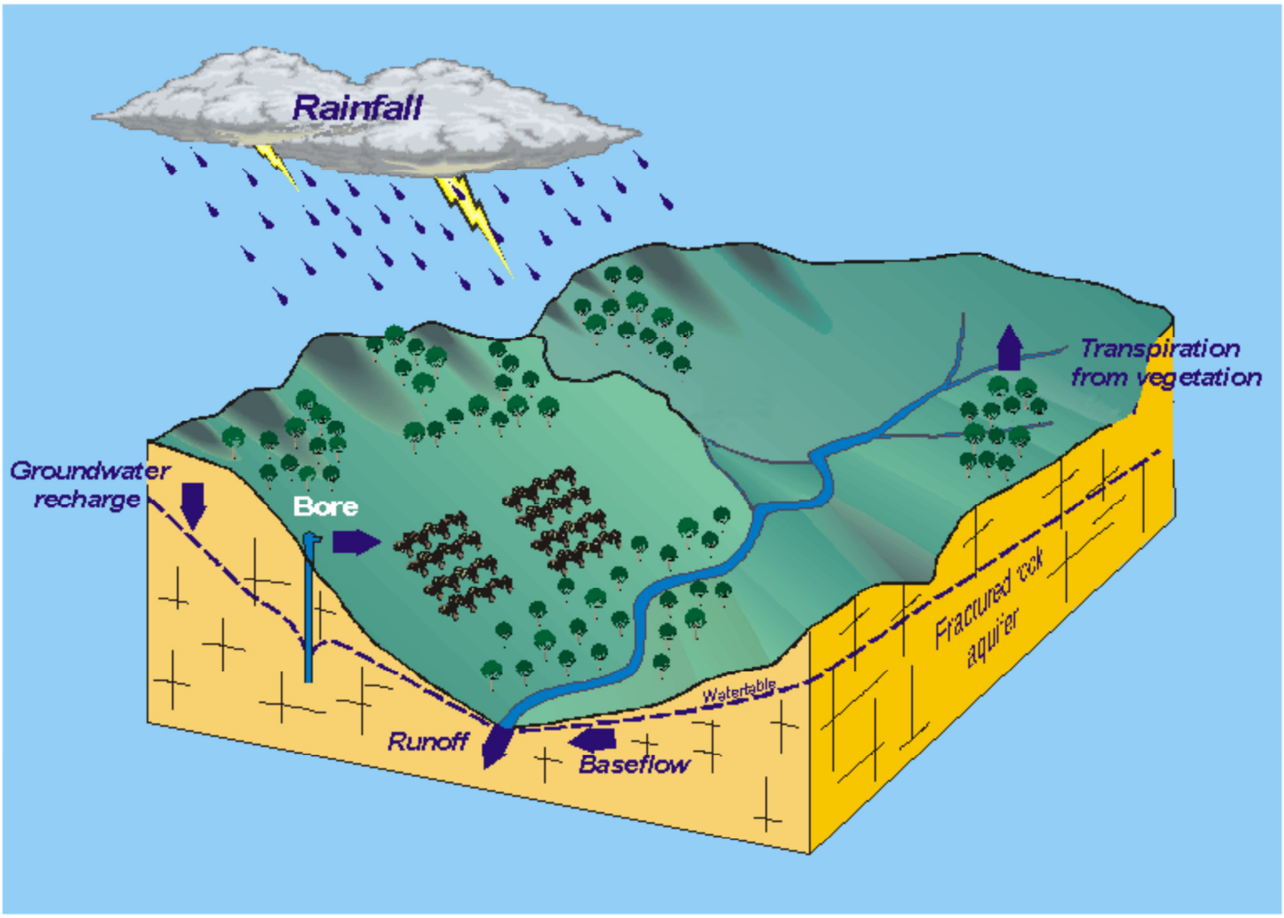


Figure 19 Conceptual model of the Berry Springs aquifer system.

6.3 Modelling approach

Following the determining a conceptual model of the Berry Springs aquifer system A steady state finite element saturated groundwater flow model was created to model the Berry Springs dolostone aquifer.

The steady state model was developed and calibrated to heads and flows for September 1994, which are considered to be representative of steady state conditions.

The steady state model was converted to a transient model. Recharge estimates were determined using the MIKESHE software refer to **Appendix C** for further details. Recharge was coarsely calibrated to match the water balance estimate calculated for the Howard East area .(Cook et al., 1998b).The transient model was then manually calibrated to coarsely match groundwater head variations and discharges.

Final parameter refinement was completed using PEST (Doherty, 2004) refer to Appendix .

6.4 Model package

The finite element package FEFLOW® v5.415 from DHI-WASY was used to simulate the saturated flow processes. FEFLOW® is a fully three dimensional finite-element package capable of simulating unsaturated and saturated flow and contaminant transport. FEFLOW® also has built-in mesh-design, problem editing and graphical post processing display modules that allow rapid model development, execution and analysis (Diersch, 2004). A 64-bit PC laptop under Windows XP was used as the platform for the numerical simulations (transient simulations over 111.9 years typical took 15-20 minutes).

The high-level graphical interface, the Geographic Information System (GIS) capabilities, and the capacity for detailed mesh generation built into FEFLOW are important features that have allowed the rapid development and testing of the models described in this report.

Finite elements provide greater flexibility in the mesh design than the rectilinear grids employed by finite difference code (eg ModFlow), allowing for the refinement of the mesh around points such as bores and linear features such as rivers. The finite difference codes have discretisation issues where both regional and local scaled features are required in the problem.

The code is proprietary and as such has limitations because the software requires a licence to run – unlike the core code for ModFlow which is “freeware” from the US Geological Survey. The requirement for a licence means that the developed models cannot be transferred to parties without a licence. Similarly the use of parameter optimisation code on parallel computers (ie Parallel PEST) requires a valid licence for each computer involved in the parallel optimisation process.

6.5 Model mesh geometry

6.5.1 Mesh design

The model mesh boundary was defined using the mapped extent of the dolomite basin (Verma, 1994).

The model was designed with two layers. The upper layer represents the Cretaceous sands, sandy clays and clays and the lower layer represents the weathered dolostone aquifer.

The mesh was refined along the major drainage crossing the dolostone basin. The mesh was further refinement in the areas where inundation is mapped on the 1:100000 topo map of the area. The resulting mesh is presented in **Figure 20**.

6.5.2 Mesh generation

The superelement, mesh and model were developed with the FEFLOW® package. The superelement mesh was designed using the polygon shapefile for the Berry Springs dolomite extent and the polyline shapefile of the two major drainage lines in the model domain.

The mesh was generated using the automatic Triangle option (Shewchuk, 2002). This feature offers the ability to define the local variation of mesh density by allowing for the refinement of the mesh around specified point and line features. The model mesh was also refined along the major drainage features previously identified, where significant discharge from the aquifers occurs.

The regional mesh was generated using the following settings for the Triangle generator in the Mesh Generator Options:

- Quality mesh, minimum angle <= 30 degrees
- Force all triangles to be Delaunay
- Fill all possible holes in mesh
- Divide-and-conquer meshing algorithm
- Refinement around line-addins – Gradation 2, Target element size = 1000 metres

An initial mesh density of 7000 elements was used in the Generate Automatically option to generate the mesh. The regional mesh was then refined in the areas mapped as 'subject to inundation' using the Mesh Geometry Editor. The resultant mesh used in the modelling is presented in **Figure 20** and comprises 34620 elements and 26316 nodes.

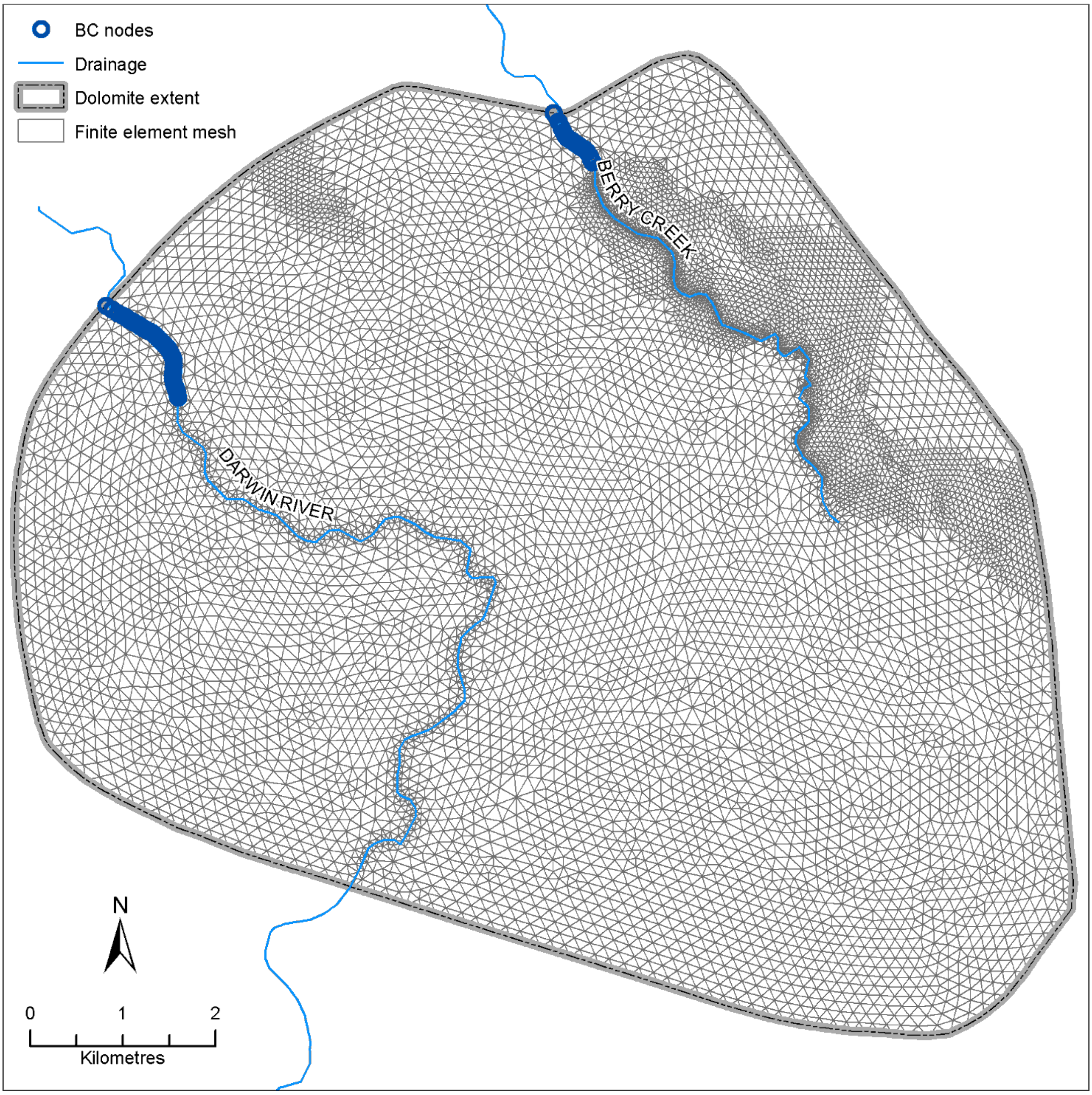


Figure 20 Finite element mesh geometry used in Berry Springs groundwater model.

6.6 Material properties

It was assumed that the vertical hydraulic conductivity for both layers was 10% of the horizontal hydraulic conductivity.

	Top [mAHD]	Bottom [mAHD]	Kxy [m/d]	Kz [m/d]	Sy
Layer 1	SRTM	0	0.01	0.001	0.022
Layer 2	0	-50	15	1.5	0.022

6.7 Fracture flow

The karstic aquifer system conceptually is dual permeability. To simulate this discrete features were employed. It has been assumed that the flow through the karsts and fractures may be idealised as occurring between two parallel plates with a uniform separation equivalent to the fracture aperture.

Formulation of the discrete feature fracture flow employed in FEFLOW is presented in **Appendix E**.

6.8 Boundary conditions

Boundary conditions used in the model were:

- recharge applied to the upper surface of the model using time series areal fluxes generated using a 1D MIKE SHE soil model;
- ‘seepage face’ condition at nodes on the upper surface of the model to remove water as it intersects the surface;
- spring features as constant head boundary conditions with a constraint of 0 m/d flux into the model domain (ie only flow out of the model domain, no flow into the model domain);
- Pumping bores for stock and domestic and horticultural use were implemented using Well BC’s. The Well BC describes the injection or withdrawal of water at a single node in kL/d (m^3/d).

6.8.1 Recharge and Areal ET Flux

The MIKESHE recharge power function (refer to Appendix C) was imported into the model using the Time–varying power function editor dialog as a constant curve type.

Evapotranspiration and “rejected recharge” were estimated using the ‘seepage face’ condition applied to the upper slice of the model.

It was assumed that when the groundwater level intersects the ground surface the water is removed from the model as evaporation or overland flow.

Evapotranspiration was estimated using a ramp function similar to that used in the ModFlow package EVT and is based on the following conditions:

- When the water table is at or above the ground surface (Slice 1), evapotranspiration loss from the water table occurs at the maximum rate specified.
- When the elevation of the water table is below the ‘extinction depth’ evapotranspiration from the water table is 0.
- Between these limits, evapotranspiration from the water table varies linearly with water table elevation.

The resulting recharge / evapotranspirational function is presented in **Equation 1**.

$$\text{Term A} = \begin{cases} 0.003 & \text{if} \quad \text{Head} \geq \text{REFDSTR.GndSurface} \\ 0.003 \cdot \left\langle 1 - \left\langle \dfrac{\text{REFDSTR.GndSurface} - \text{Head}}{2} \right\rangle \right\rangle & \text{if} \ \langle \text{REFDSTR.GndSurface} - \text{Head} < 2 \rangle \\ 0 & \text{otherwise} \end{cases}$$

$$Qp = 0.00161 * \text{POWER.SILO}_{Rech} - \text{Term A}$$

Equation 1 **Recharge / evapotranspiration function Qp is in m/d.**

where:

Qp is the recharge (or ET) applied to each element for a given timestep.

REFDSTR.GndSurface is the elevation of Slice 1 derived from the SRTM data.

Head is the calculated groundwater head.

POWER.SILO$_{Rech}$ is the time series recharge power function estimated using MIKESHE refer to Appendix C.

TermA determines the ET rate based on the groundwater head and the surface elevation.

6.8.2 Constant head BC values

The elevations of the constant head boundary conditions were determined from the SRTM data and corrected by adjusting the vertical offset.

6.9 Pumping data

As identified in **section 5.6** prior to 1980 there was little development of the groundwater resources in the catchment, therefore, pumping bores are only relevant to scenario modeling to examine future impacts. Pumping rates were applied during scenario modelling either as at a steady state value equal to the annual pumped volume for the bore converted to kL/d (m^3/d) or as a variable pumping rate using power functions to define the transient pumping schedule for each bore. The monthly pumping schedule, expressed in kL/d, as applied to the historic model are presented graphically in **Figure 21**.

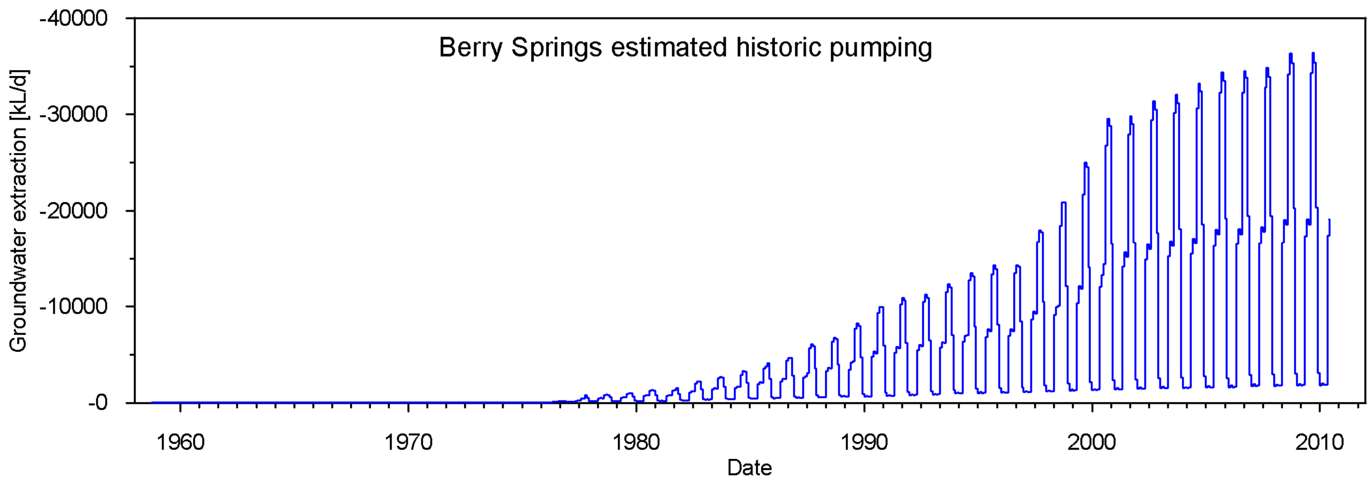


Figure 21 Estimated historic monthly pumping (expressed as kL/d) applied to the Berry Springs groundwater model

6.10 FEFLOW settings

6.10.1 Problem class

The model was defined as a saturated, flow only and unconfined problem with the following three dimensional slice settings:

- Slice 1 Free & movable
- Slice 2 Unspecified
- Slice 3 Fixed.

The free surface constraints were set for the water table:

- Falling Dry at Bottom was Constrained as water table.

- Touching the Top Surface was Constrained as seepage face.

The residual water depth for dry (phreatic) elements was set to 0.001 metres.

The remaining specific option settings were left at their default values.

6.10.2 Temporal and control data

During the parameter estimation process the time step control was set to automatic with an initial time of 0 days (equivalent to 01/01/1900) and a final time of 39692 days (equivalent to 01/09/2008). The step size upper bound, under the specific options for time step control schemes, was limited to 10 days.

7 Calibration

7.1 Steady state finite element model

The model was calibrated in steady state to obtain initial conditions for the transient model. Steady state conditions were assumed to be represented by groundwater levels from September 1994 (refer **Table 7**).

Table 7 Groundwater levels used for steady state calibration

Site	Date	Observed SWL	Simulated SWL	Diff
		[mAHD]	[mAHD]	metres
RN028855	23/09/1994	15.0	13.5	1.5
RN028856	23/09/1994	8.9	14.6	-5.7
RN028858	23/09/1994	14.0	15.9	-1.9
RN028859	23/09/1994	20.0	14.9	5.1
RN028864	23/09/1994	9.8	9.0	0.8
RN028961	23/09/1994	17.7	15.6	2.1
RN028962	23/09/1994	18.0	14.7	3.3
RN028964	23/09/1994	7.6	6.2	1.5
RN028965	23/09/1994	11.3	13.3	-1.9
RN029016	23/09/1994	10.3	13.5	-3.2
RN029019	23/09/1994	9.9	9.3	0.6
RN029382	23/09/1994	3.9	7.8	-3.9
RMSE				**2.99**

Note: Data obtained from Hydstra February 2010

7.1.1 Steady state model results

Using PEST resulted in a reasonable match to the groundwater levels and the observed discharge for each of the rivers used in the calibration process. A comparison of the assumed steady state heads and discharges and the modelled results are presented in **Figure 22**.

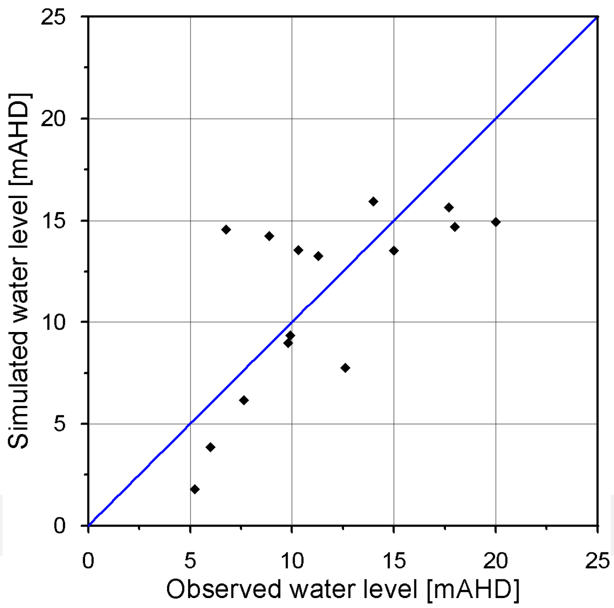


Figure 22 Steady state heads RMS error (2.99 m) is approximately the same order as the error associated with the SRTM elevation data.

7.2 Transient finite element model

Following the calibration of the groundwater model under steady state conditions the model was converted to transient and calibrated against the available observed data.

The available data for calibration included:

- 532 groundwater levels at 11 bores
- 93 dry season gaugings representing groundwater discharge at Berry Springs

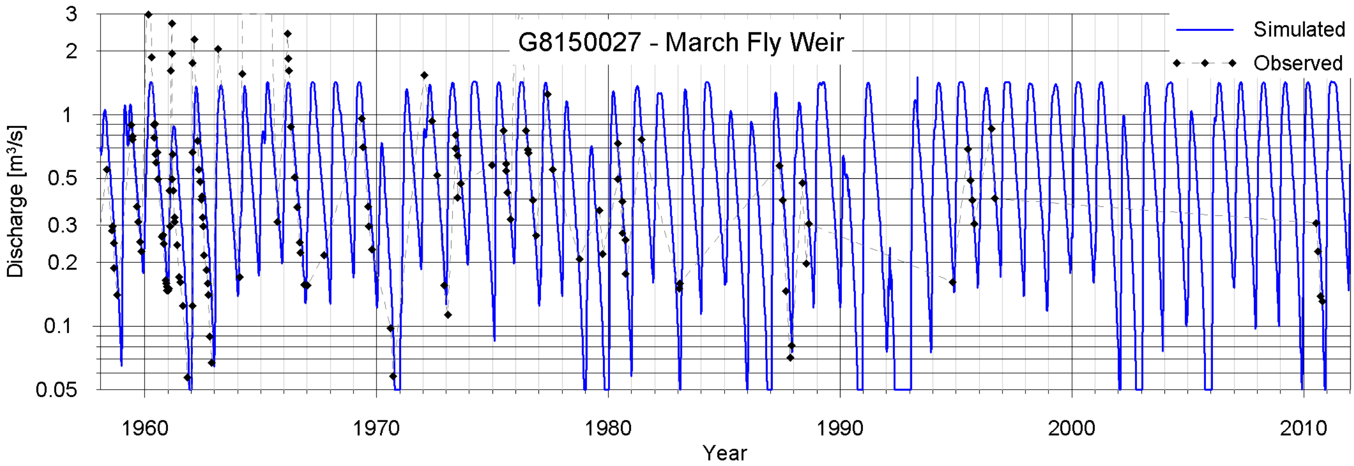


Table 8 Calibrated aquifer parameters

	Top	Bottom	Hyd Conductivity		Sy	Fracture	
			xy	z		Thickness	Aperture
	[mAHD]	[mAHD]	[m/d]	[m/d]	–	[m]	[m]
Layer 1	SRTM	0	0.1734	0.0173	0.02	–	–
Layer 2	0	-50	5.121	0.5121	0.02	0.003	0.0065

8 Scenarios

Two scenarios have been considered here based on available data:

- Scenario A – Historic climate under natural conditions
- Scenario B – Historic climate with current estimate of pumping

8.1 Water balance assessment

Essential a water balance describes the inflows and outflows from a groundwater system and the resulting changes in groundwater storage in the system;

Inflows - Outflows = Change in storage

If the change in storage is positive then inflows are greater than outflows and the system is gaining water; groundwater levels will be seen to trend upwards.

If the change in storage is negative then inflows are less than outflows and water is being lost from the system and groundwater levels will be seen to trend downwards.

8.2 Scenario A – Historic climate without pumping

8.2.1 Water balance under historic climate

The FEFLOW budget analyser was used to determine the applied recharge to the model from 01/01/1900 - 01/03/2012 a total of 5631 GL was applied to the model domain during this period or an average annual volume ≈51.3 GL/yr. The area of the groundwater model is 87,911,271 m^2, this means that equivalent to 584 mm/yr. Evapotranspiration and runoff in areas where the water table was at the surface is calculated at 1461 GL or 13312 mm for the same period, which is equivalent to 151 mm/yr. This value is expected to represent the rejected recharge from the system, therefore the actual amount of rainfall recharging the groundwater system is 4170 GL this is equivalent to 432 mm/yr.

The total groundwater discharge to springs and rivers is estimated at ≈38.1 GL/yr which equates to an equivalent height of 433 mm/yr. Discharge to Berry Springs for the period 1/1/1900 - 1/9/2009 is estimated at ≈13.8 GL/yr this is equivalent to 157 mm/yr. **Table 9** summarises the water balance information expressed in gigalitres (GL).

Median discharge from the Berry Springs spring complex is 0.4 m^3/s.

The water balance for the Berry Springs system over 109.75 years indicates that it is in dynamic equilibrium, with inputs very close to outputs 38.0 GL/yr cf 38.1 GL/yr with a difference of approximately 0.3% between recharge and discharge.

The model also identifies that there are significant discharges to the Darwin River in the vicinity of the Parson’s and Twin River Farm Springs.

Table 9 Water balance for 109.75 years of historic climate data for the Berry Springs groundwater model.

Component	Total Volume [GL]	Volume per annum [GL/yr]
Recharge (gains)		
Applied recharge	5630.8	51.3
ET / Rejected recharge	-1461.0	-13.3
Sub-total	**4169.8**	**38.0**
Discharge (loses)		
Pumping	0	0
Berry Springs complex	-1510.6	-13.8
Darwin River, Parson's and Twin River Farm Springs	-2670.5	-24.3
Sub-total	**-4181.1**	**-38.1**
Imbalance	**-11.3**	**-0.10 (0.3%)**

8.3 Scenario B – Historic climate with current pumping estimates

8.3.1 Pumping estimate methodology

Current pumping was estimated using the area under irrigation for each block associated with each licensed bore (refer to **section 5.6**). All other bores not indicated as abandoned or monitoring were assigned the nominal rate for stock & domestic usage (3.5 ML/yr).

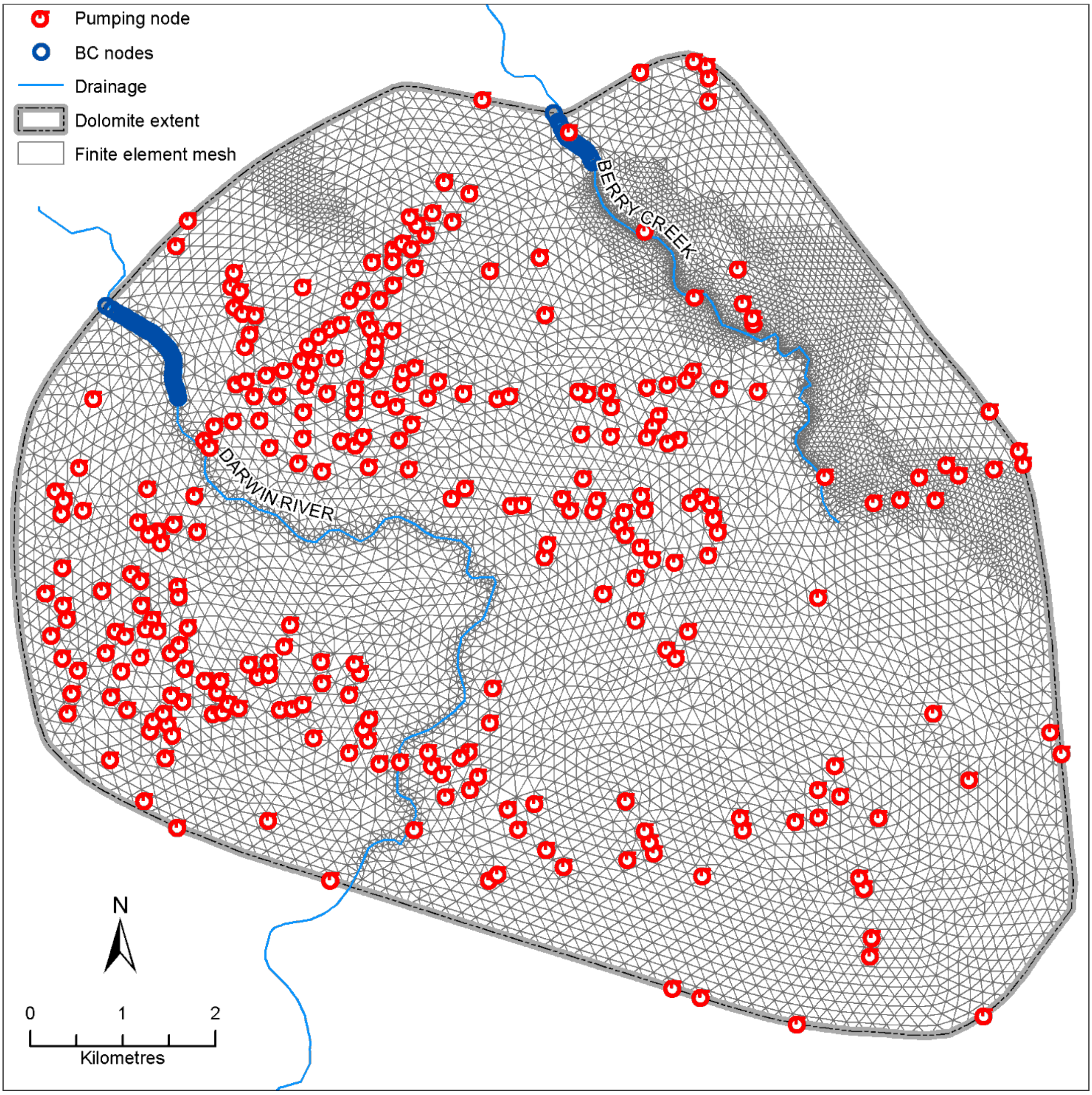


Figure 23 Location of pumping nodes applied to slice 3 of the FE model.

8.3.2 Water balance under historic climate and current pumping

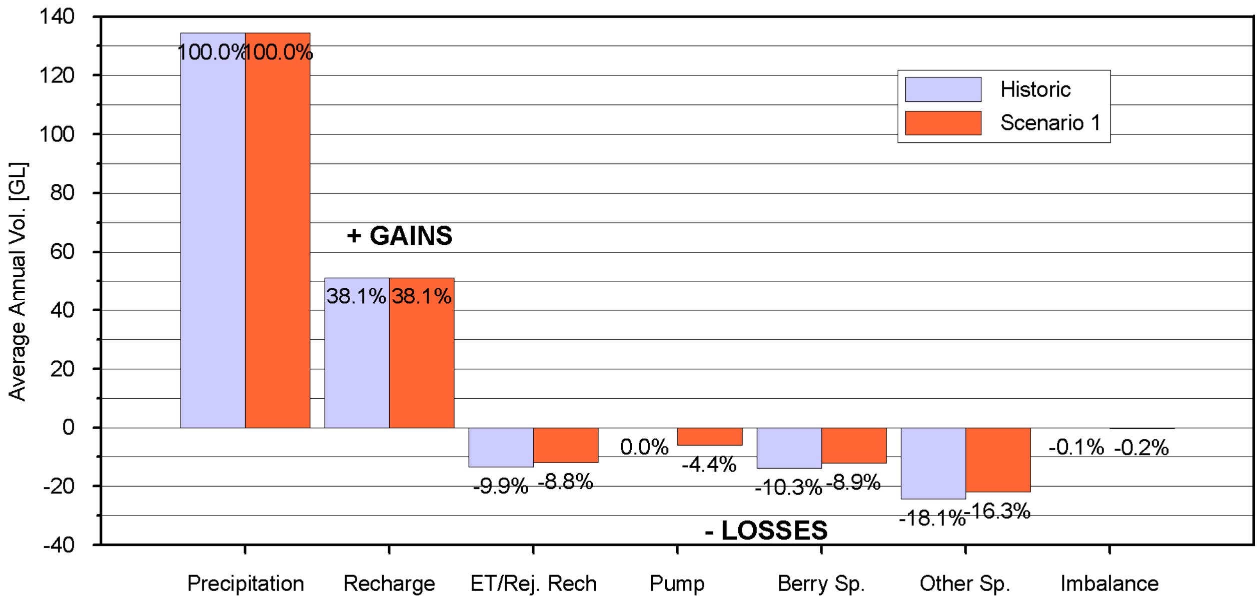
The calibrated model shows that the applied recharge to the model was 5631 GL from 1/1/1900 - 1/9/2009, which is equivalent to an average annual volume 51 GL/yr. Evapotranspiration and runoff in areas where the water table was at the surface is calculated at 1291.2 GL for the same period, which is equivalent to 13.3 GL/yr. This value is expected to represent the rejected recharge from the system, therefore the actual amount of rainfall recharging the groundwater system is 4339 GL this is equivalent to 38 GL/yr.

The total groundwater discharge to springs and rivers is estimated at ≈23.9 GL/yr. Discharge to Berry Springs for the period 1/1/1900 - 1/9/2009 is estimated at ≈12 GL/yr). **Table 10** summarises the water balance information expressed in gigalitres (GL).

Table 10 Berry Springs groundwater model water balance for 109.75 years of historic climate data and current pumping estimates.

Component	Total Volume [GL]	Volume per annum [GL/yr]
Recharge (gains)		
Applied recharge	5630.5	51.3
ET / Rejected recharge	-1291.2	-11.8
Sub-total	**4339.3**	**39.5**
Discharge (loses)		
Pumping	-645.9	-5.9
Berry Springs complex	-1319.2	-12.0
Darwin River, Parson's and Twin River Farm Springs	-2403.4	-21.9
Sub-total	**-4368.6**	**-39.8**
Imbalance	**-29.2**	**-0.30 (0.7%)**

To demonstrate the difference between the two scenarios the water budget components are presented as a proportion of the average annual rainfall.



8.3.3 Impacts of pumping on groundwater discharge at Berry Springs

Key finding

Currently groundwater extraction is approximately 15% of average annual recharge.

The water balance data indicates that approximately 1.55 GL/yr of recharge is induced from the rejected recharge due to pumping resulting in a 4% increase in recharge. The remaining 4.18 GL/yr is intercepted before discharging to the springs. On average the annual discharge to Berry Springs is reduced by 1.74 GL/yr a reduction of 13% from the no-pumping scenario.

To further investigate the effects of pumping on the discharge at the Berry Springs spring complex the results of the two models using historic climatic conditions with no-pumping and pumping were compared, the plot of this data can be seen in **Figure 24**. The discharge at Berry Springs under historic climatic conditions with no pumping shows only one year (1962-63) where Berry Springs ceased to flow. This is in contrast to the scenario with pumping where at least 9 years show cease to flow at Berry Springs.

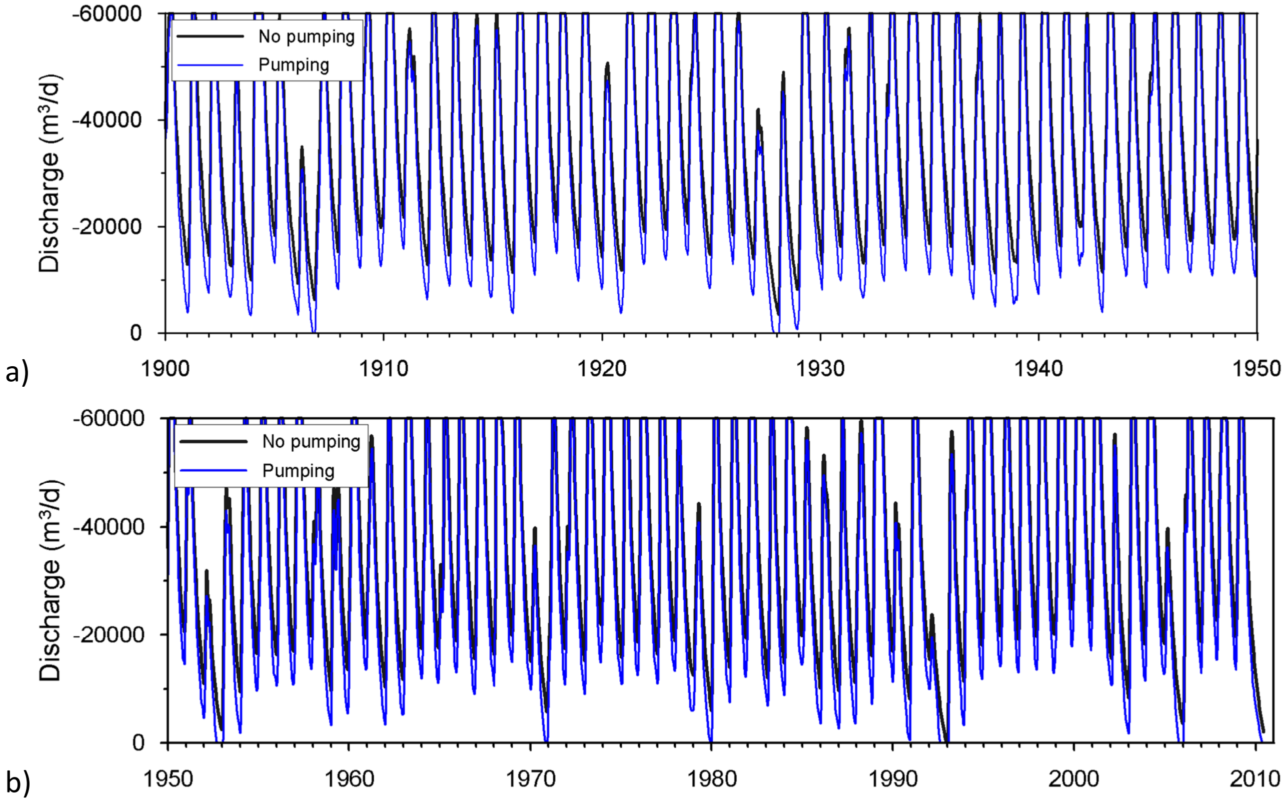


Figure 24 Comparison of simulated discharge (m^3/d) at Berry Springs spring complex under historic climatic conditions with no pumping and estimated current pumping for the period a) 1900-1950 and b) 1950-2010.

The difference between the historic flow regime and the pumping scenario was calculated to further describe the impacts from pumping. **Figure 25** demonstrates that the impact to late dry season discharge is always affected by more than 20%.

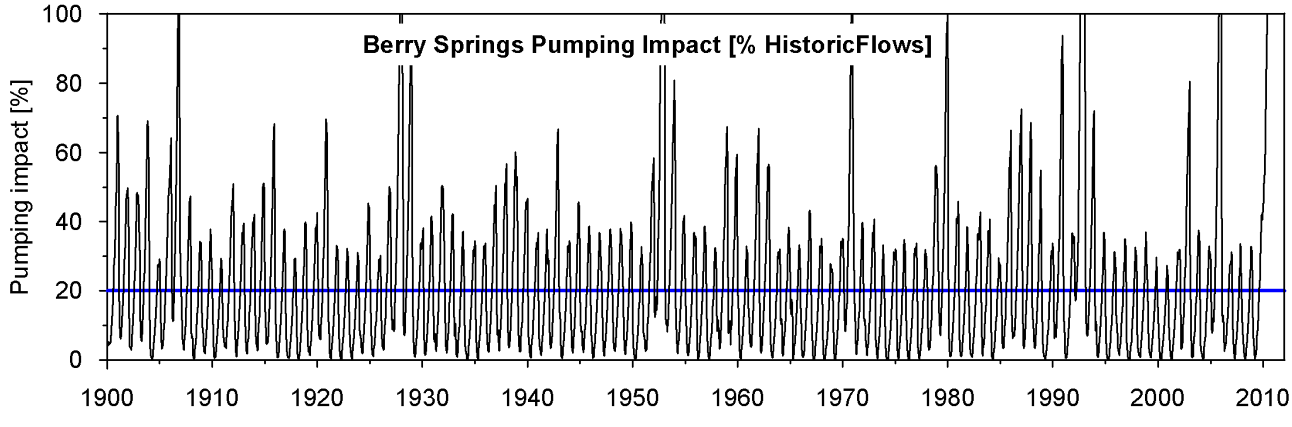


Figure 25 Impact of pumping expressed as the percentage decrease from the modelled historic flows.

8.3.4 Flow duration

To better demonstrate the effects of pumping on the flow regime of the spring complex a flow duration or flow exceedance curve has been developed for the two scenarios. The flow duration curve shows the percentage of time that flow in a stream is likely to equal or exceed some specified value of interest. The flow duration plots for the Berry Springs spring complex with no pumping and with pumping are presented in **Figure 26**. The plot shows that under historic climatic conditions with no-pumping the flow at the spring is above 0.2 m^3/s for 80-90% of the time, whilst under historic climatic conditions and current pumping estimates the flow is reduced to about half of this 0.1 m^3/s for 90% of the time.

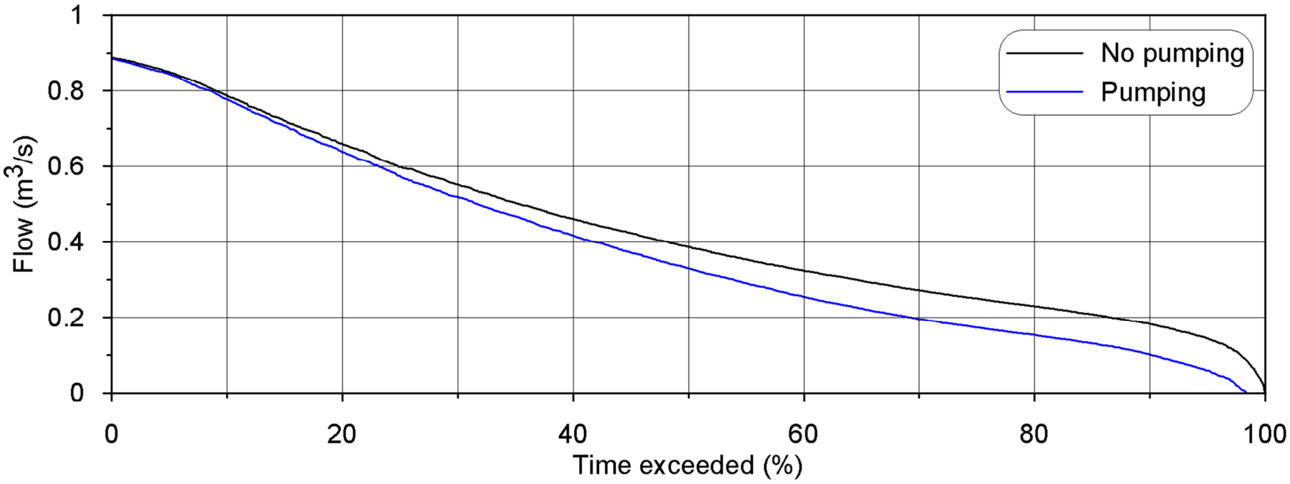


Figure 26 Flow duration curve demonstrating effects of pumping on the discharge to the Berry Springs spring complex.

The flow duration plot can also be interpreted in terms of the 80:20 rule, where it can be expected that the historic flows at Berry Springs will be impacted by more than 20% for 40% of the time.

9 Results and discussion

9.1 Measurable impacts

9.1.1 Reduced dry season flows

Key indicator

Dry season flows at Berry Springs are directly impacted by groundwater pumping.

Target -cease to flow should only occur due to climatic variability.

As identified in **section 8** the dry season flows at Berry Springs are directly impacted by groundwater extraction from the aquifer. Although the flows at Berry Springs are measureable the impacts of extraction are not easily quantifiable through measurements as the expected flows under natural conditions are not known. Use of a model to generate natural flow conditions enables an estimate of the impact due to extraction.

Dry season flows appear to have a direct impact on water quality in the pools at Berry Springs. A reduction in the dry season flow means that water quality will deteriorate earlier in the dry season.

9.1.2 Recession slope of dry season flows

Key indicator

The groundwater recession at Berry Spring indicate changes in the extraction regime. Recession constants less than -0.0136 will indicate groundwater abstraction greater than current usage

The available gaugings are plotted in **Figure 17** as a log-linear plot of time versus discharge. 'Linear' segments have been fitted to each dry season recession.

Each recession segment is interpreted to be the baseflow or groundwater discharge and fits a exponential decay function (hence the linear trend on a log-linear plot) and is expressed as:

$Q_t = Q_0e^{-at}$

or

$Q_t = Q_0e^{-1/Tc}$

where Q_t is the stream flow at time t, Q_0 is the initial stream flow at the start of the recession segment, a is the slope of the recession segment also known as the cut-off frequency (fc) and Tc is the residence time or turnover time of the groundwater system defined as the ratio of storage to flow.

The term e^{-at} in this equation can be replaced by k, called the recession constant or depletion factor, which is commonly used as an indicator of the extent of baseflow (Nathan and McMahon, 1990).

Converting flows to log10 produces:

$\ln Q_t = \ln Q_0 - at$

$-a = \ln (Q_0/Q_t) / t$

The slope of the recession prior to 1996 is about -0.0091 (minimum = -0.0108 and maximum = -0.0062). Available data for 1996 and 2010 give a recession slope of -0.0127 and -0.0136 both considerable lower than the average value. in 1996 the deviation may be due to measurement error, however, multiple gaugings were conducted in 2010 and suggest that the groundwater recession is greater than previously observed. This is probably due to the effects of pumping.

Annual changes in the recession slope at March Fly weir may therefore be used to identify when losses from the system have changed. Historically the recession slope was approximately-0.009 with recent recession slopes of around -0.013 reflecting the impacts of groundwater extraction from bores.

9.1.3 Groundwater levels

Key indicator

Groundwater levels near the springs should be maintained at their current minimum observed levels.

Figure 27 demonstrates the variation in head between the dry season and the wet season. The groundwater levels are presented for 2000/01 water year. It can be seen that the groundwater levels to the south vary by about 10 metres and in the north by about 6 metres.

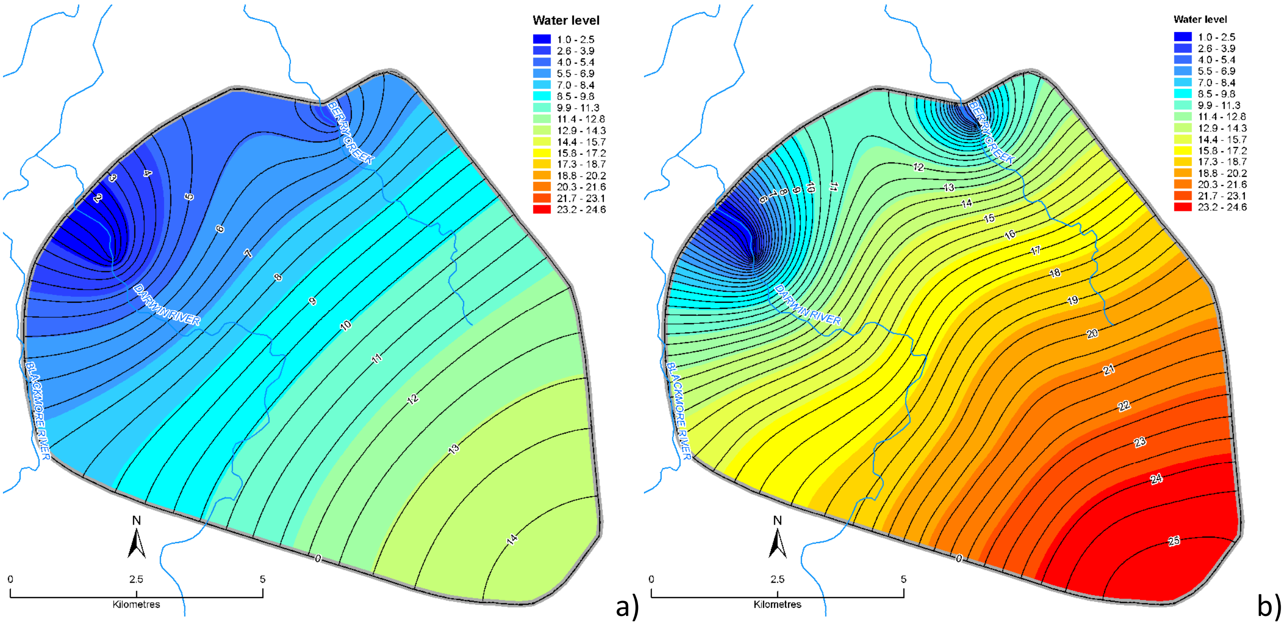


Figure 27 Predicted heads for a) dry season - 8/12/2000 (36868d) and b) wet season - 27/04/2001 (37008d)

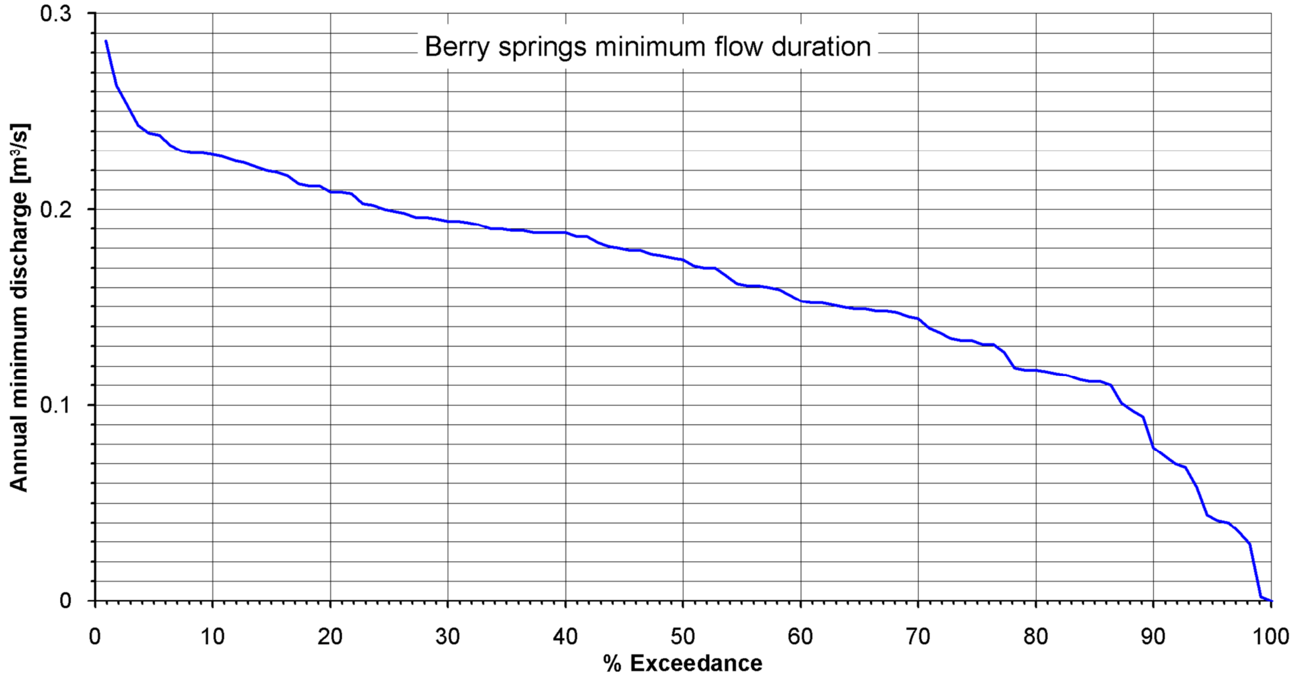
Comparison of the simulated discharge at Berry Springs to the simulated groundwater levels at RN028964 indicates a linear relationship.

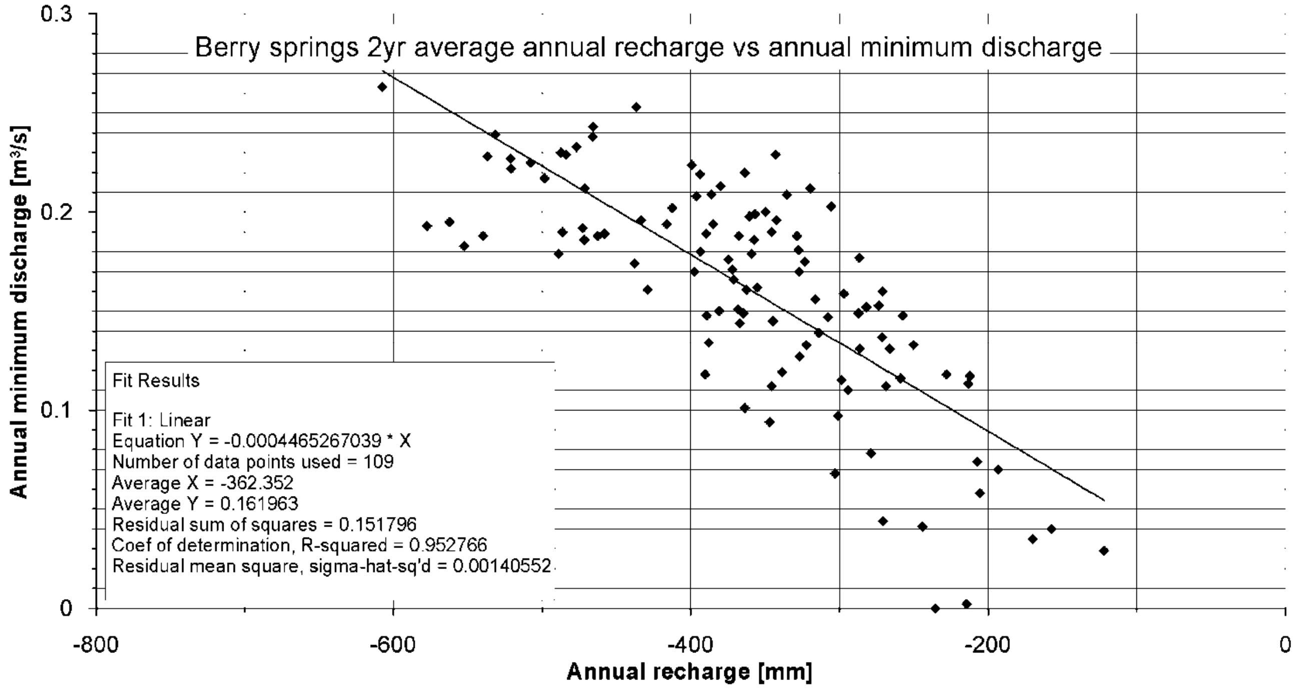
Currently there is a lack of data to determine a relationship between observed discharge and groundwater levels.

9.2 Rainfall, recharge & minimum flows analysis

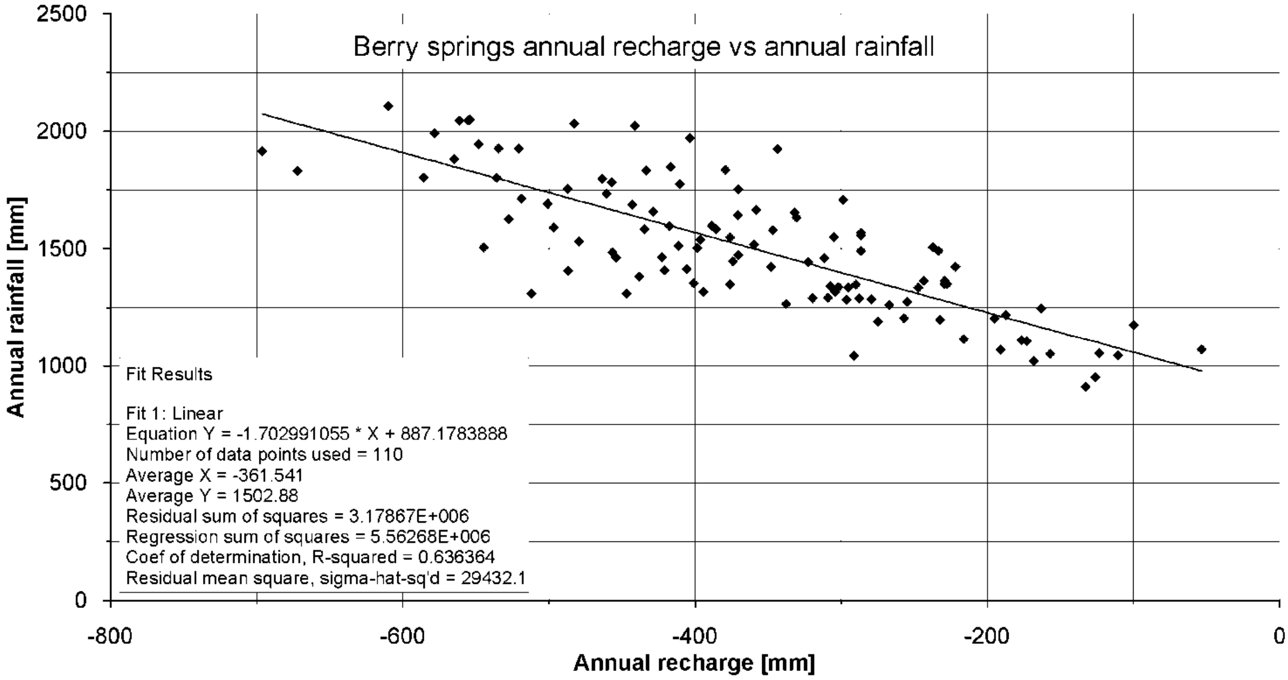
The rapid response of the groundwater system to annual recharge means that:

- the system can in years where annual rainfall is above a threshold fill to capacity
- in lower than a threshold annual rainfall have reduced minimum discharge at the springs





Annual recharge compared to annual minimum discharge for Berry Springs.



Recharge = (Annual Precipitation - ET losses and Runoff) / Proportional loss to ET and Runoff

where the Proportional loss to ET and Runoff is the amount of increase in ET and Runoff due to the increase in rainfall which doesn't result in recharge.

Based on the annual rainfall vs recharge Recharge ~ (Annual Precipitation - 890mm) / 1.70

Example:

Average annual precipitation = 1320 mm/yr

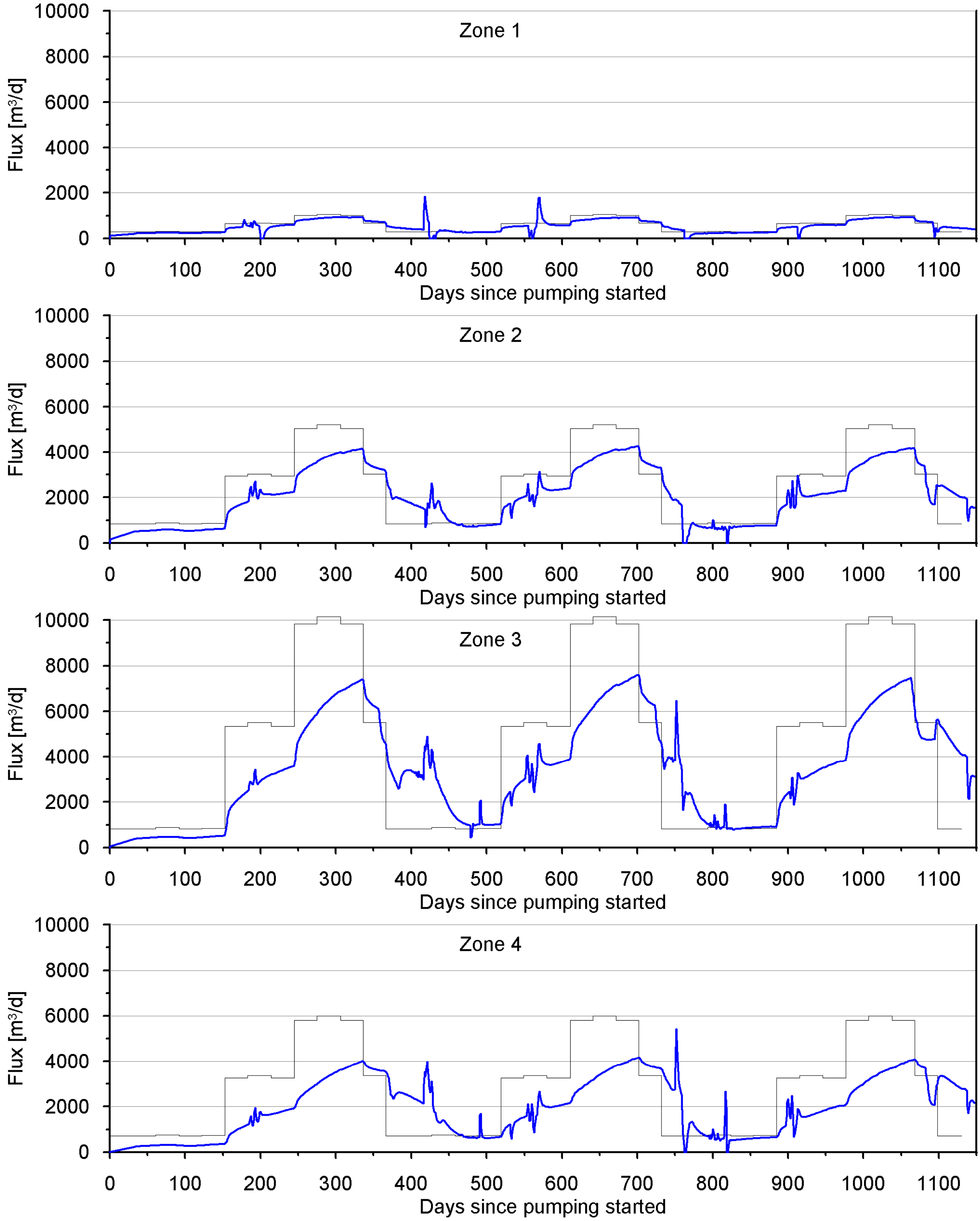
Average annual recharge = (1320mm - 890mm) /1.70

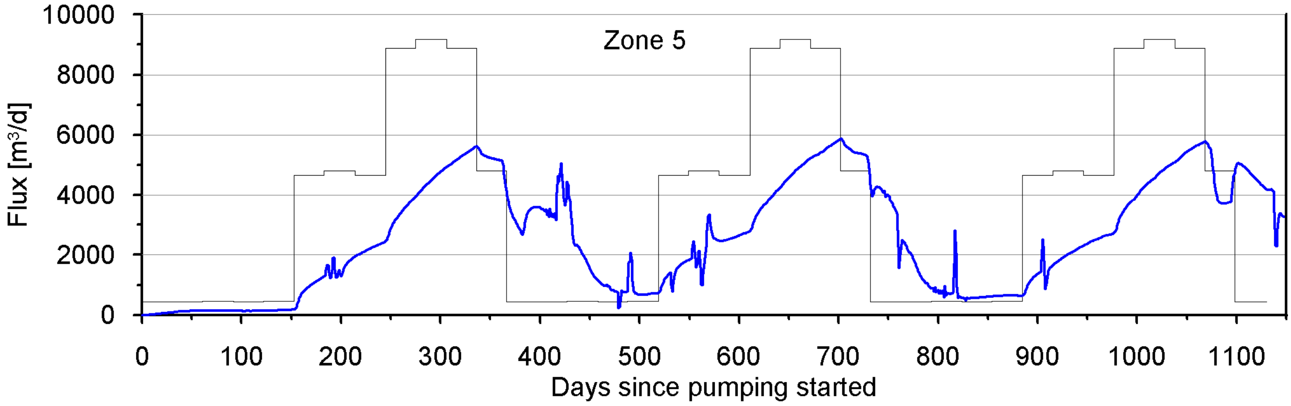
Average annual recharge = 255mm

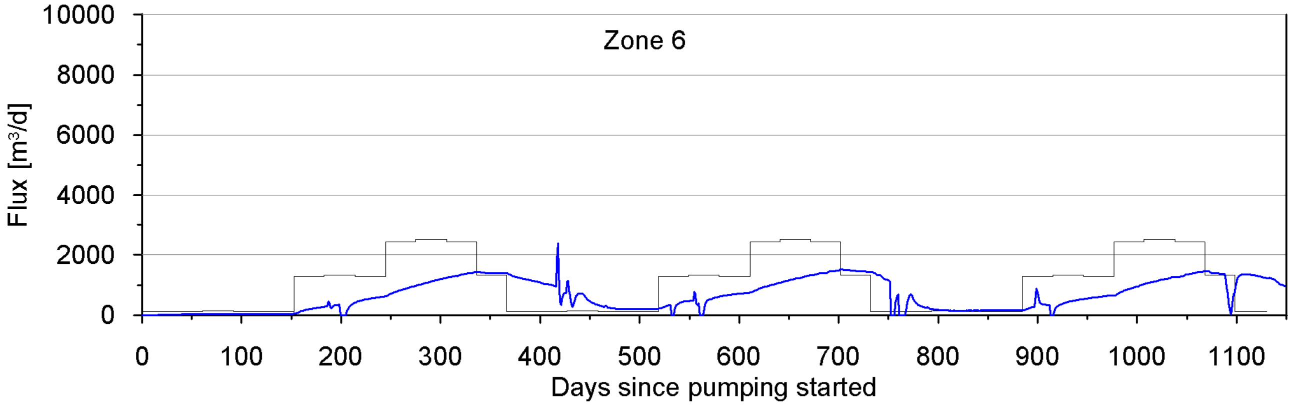
9.3 Impacts of pumping based on zones

To examine the worth of determining allocations based on distance from Berry Springs the impact of bores at different distance from the springs was assessed. Six (6) zones were determined and the bores situated in each of the zones were used to examine the timing and percentage impact at the spring. The results for approximately 3 years of simulation are presented in .

	1	2	3	4	5	6
Observed impact volume	386141.9	1532549.9	2477793.5	1399610.7	1819117.1	467013.5
Pumped volume	446222.5	1926828	3406964	2111587	2942155	809925.5
% Impact	86.5	79.5	72.7	66.3	61.8	57.7


Zone 1
Zone 2
Zone 3
Zone 4
Flux [m³/d]
Days since pumping started
0
2000
4000
6000
8000
10000
0
100
200
300
400
500
600
700
800
900
1000
1100


Zone 5
Flux [m³/d]
10000
8000
6000
4000
2000
0
0
100
200
300
400
500
600
700
800
900
1000
1100
Days since pumping started


Zone 6
Flux [m³/d]
10000
8000
6000
4000
2000
0
0
100
200
300
400
500
600
700
800
900
1000
1100
Days since pumping started

10 Conclusions

The flow at Berry Springs reduced – ceasing to flow under extreme seasonal conditions.

Groundwater levels show no declining trends under the current extraction regime.

Target outcomes determine the methodology for management:

1. instantaneous flows in rivers impacted by no more than 20%:

Minimum flows are reduced by 30-40% and at times up to 100%. To achieve this outcome it would be required that extraction is reduced during the dry season. Currently 187 l/s is being extracted.

2. extraction is less than 20% of average annual recharge:

This is the current situation.

The increase of ecoli using the threshold of 400 l/s can be expected to occur on average 1 month earlier under this regime compared to the natural state, and is probably occurring now.

Reinstate gauging station G8150027 to enable comparison with expected flows ie monitor if extraction is impacting flows.

Estimate lag times for bores at different distances to enable reduced impacts over a year and provide a buffer till the following years recharge event.

10.1 Key performance indicators

Cease to flow exceedance

Groundwater levels at end of wet season

Water quality changes

11 References

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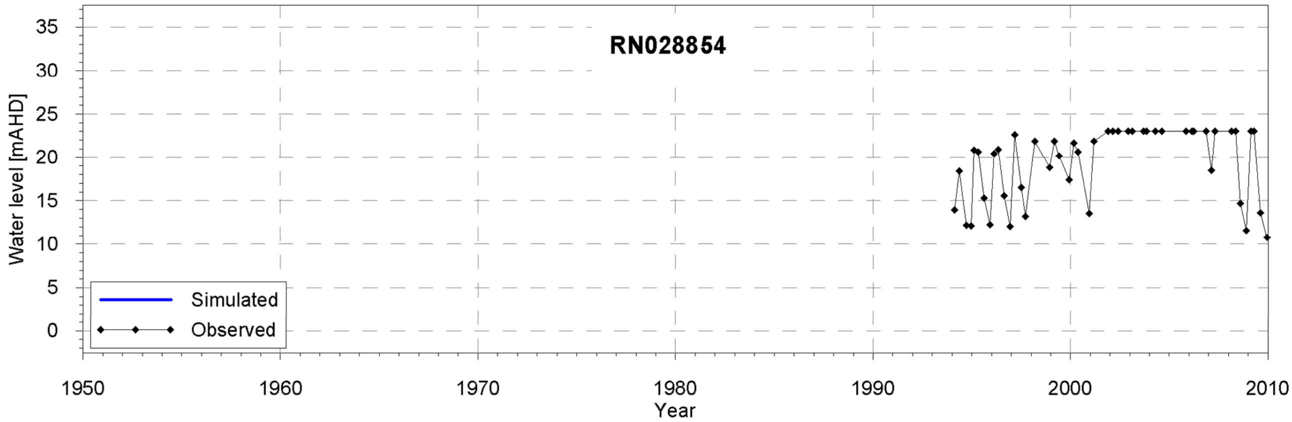
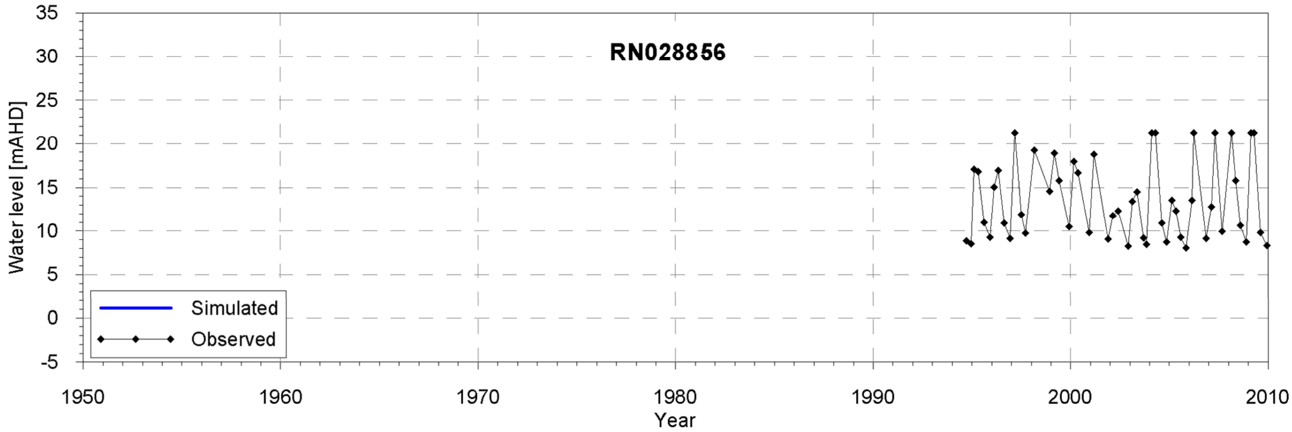
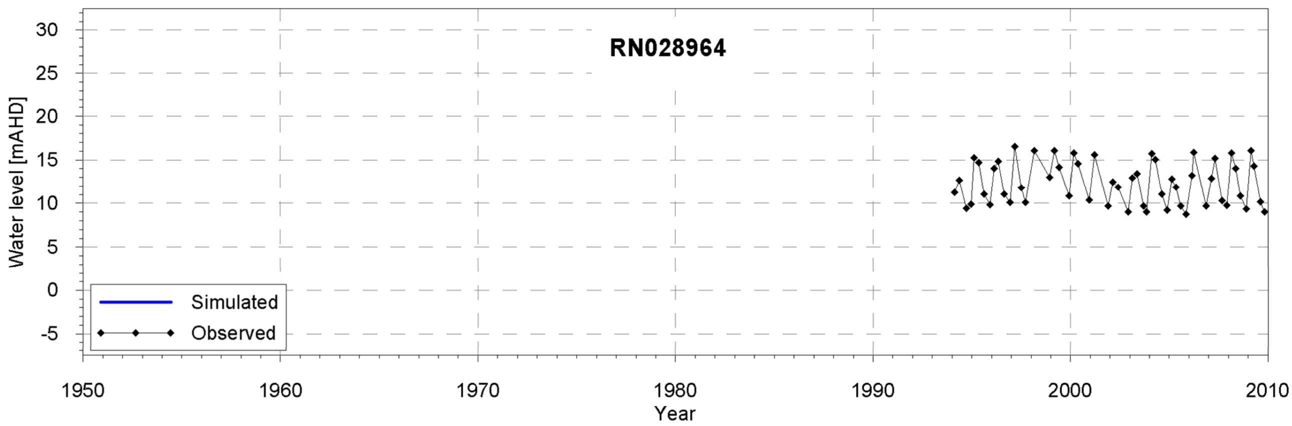
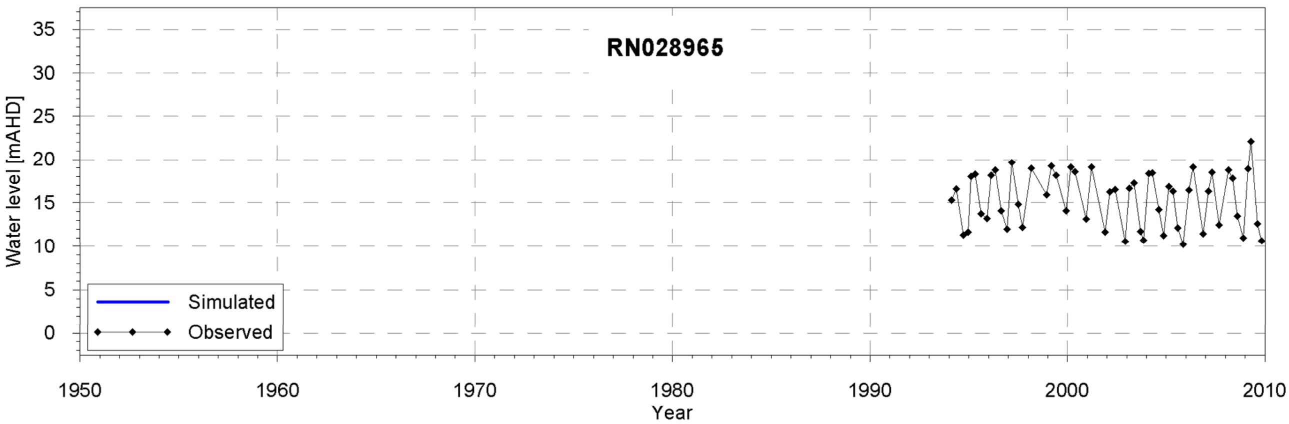
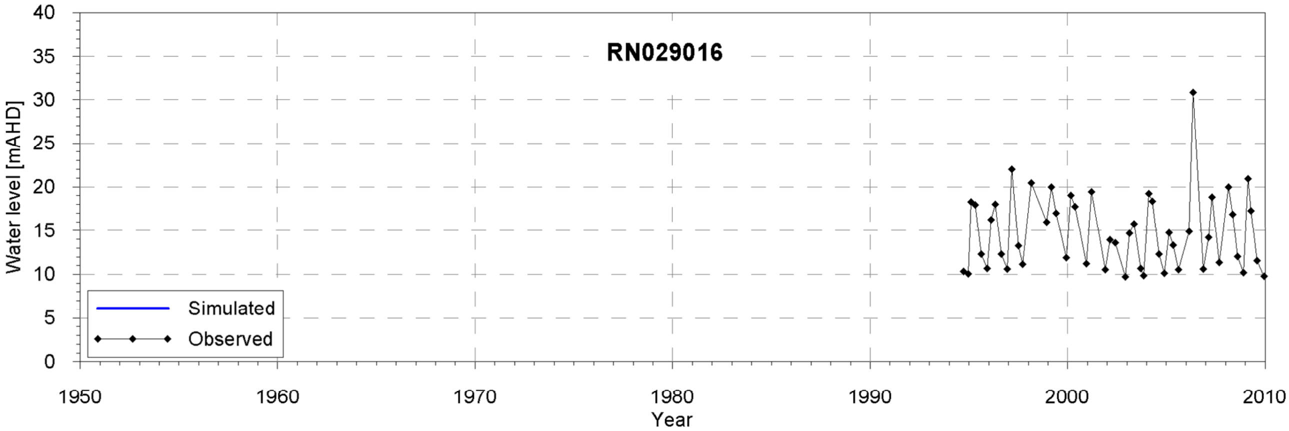
Appendix A - Groundwater level hydrographs

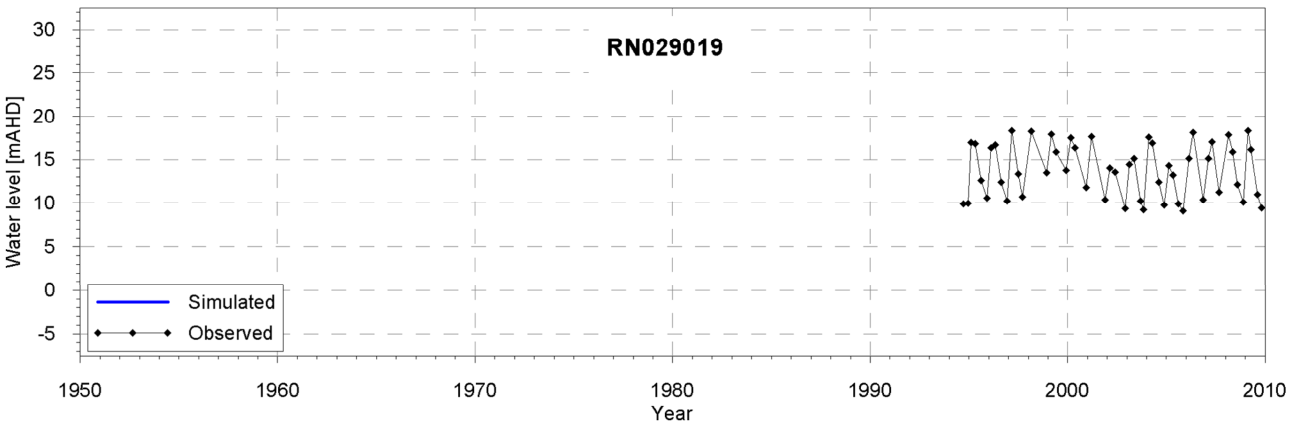


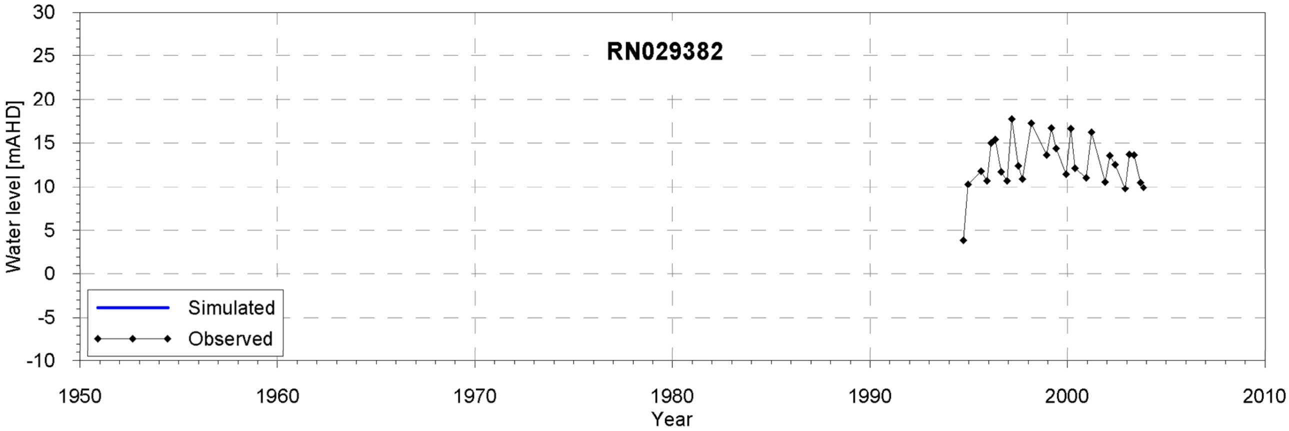


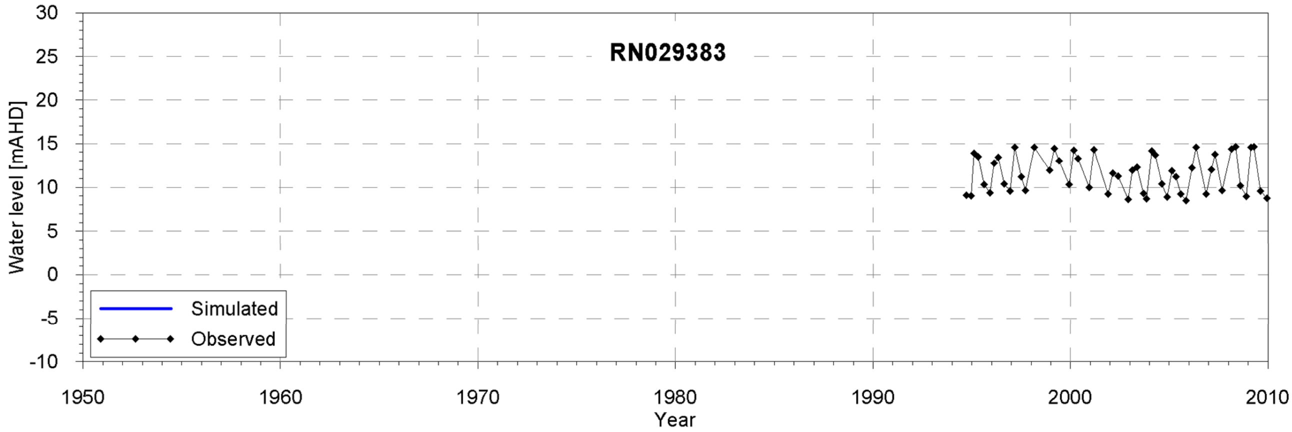


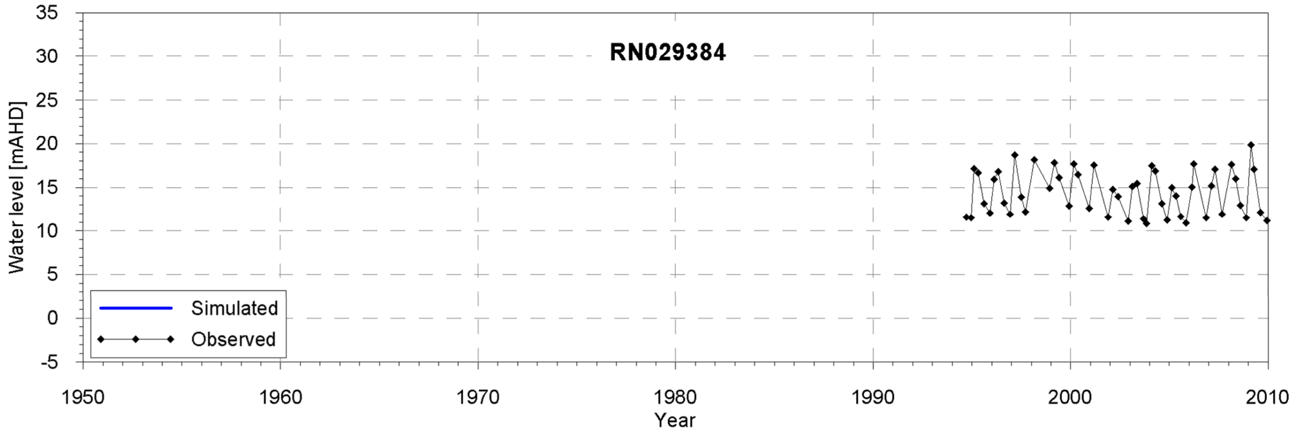

RN028965
Water level [mAHD]
Year
Simulated
Observed


RN029016
Water level [mAHD]
Year
Simulated
Observed


RN029019
Water level [mAHD]
Year
Simulated
Observed


RN029382
Water level [mAHD]
Year
Simulated
Observed


RN029383
Water level [mAHD]
Year
Simulated
Observed
30
25
20
15
10
5
0
-5
-10
1950
1960
1970
1980
1990
2000
2010


RN029384
Water level [mAHD]
Year
Simulated
Observed
35
30
25
20
15
10
5
0
-5
1950
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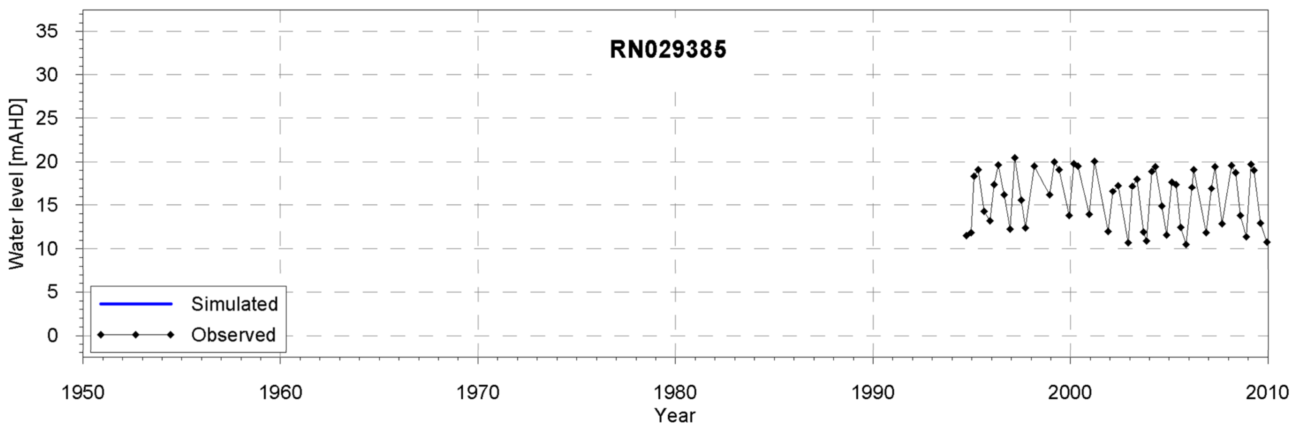
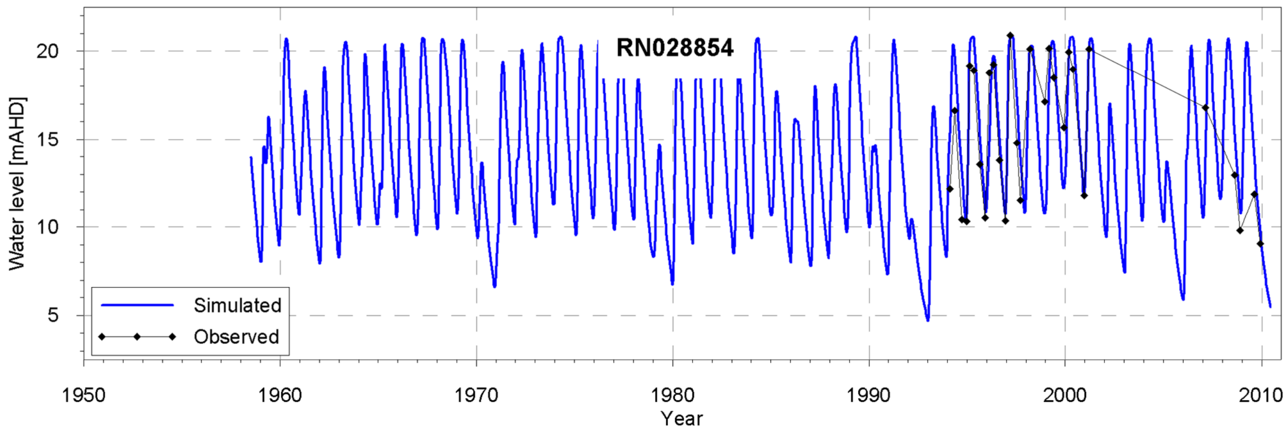
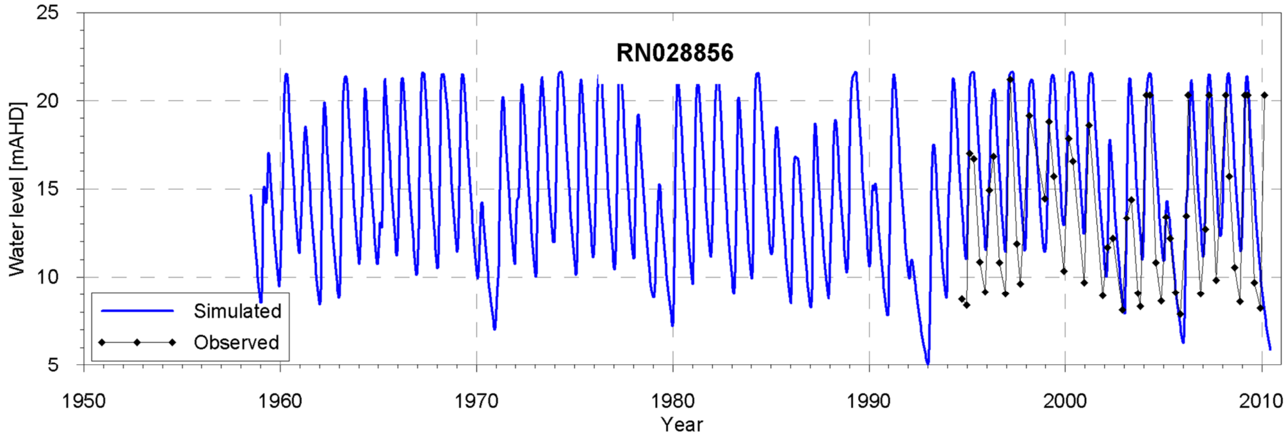
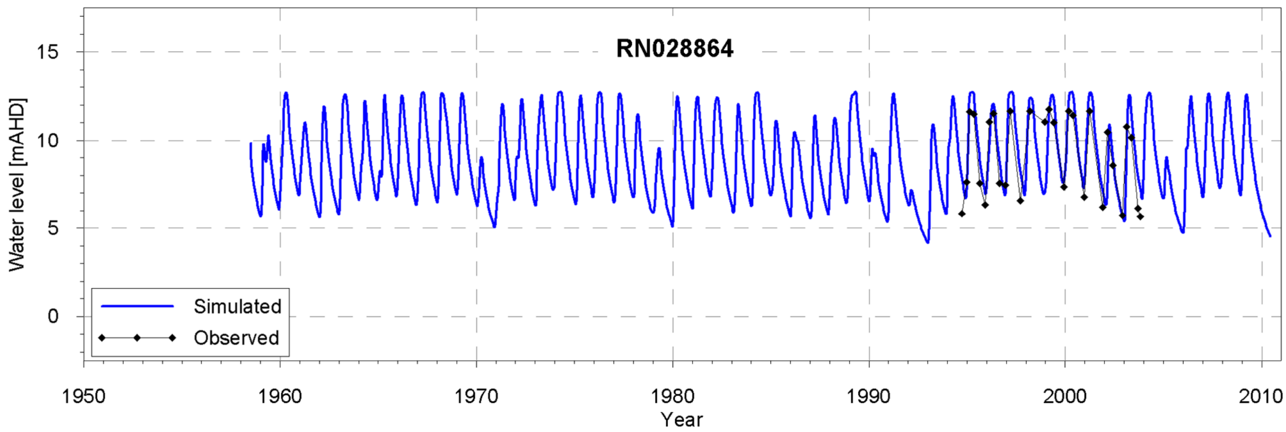
1970
1980
1990
2000
2010

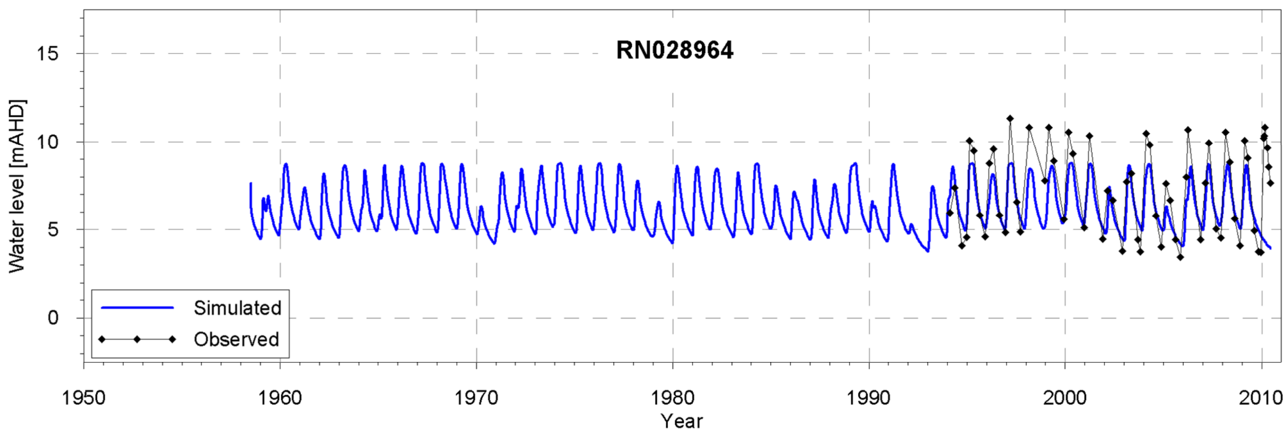

RN029385
Water level [mAHD]
Year
Simulated
Observed
35
30
25
20
15
10
5
0
1950
1960
1970
1980
1990
2000
2010

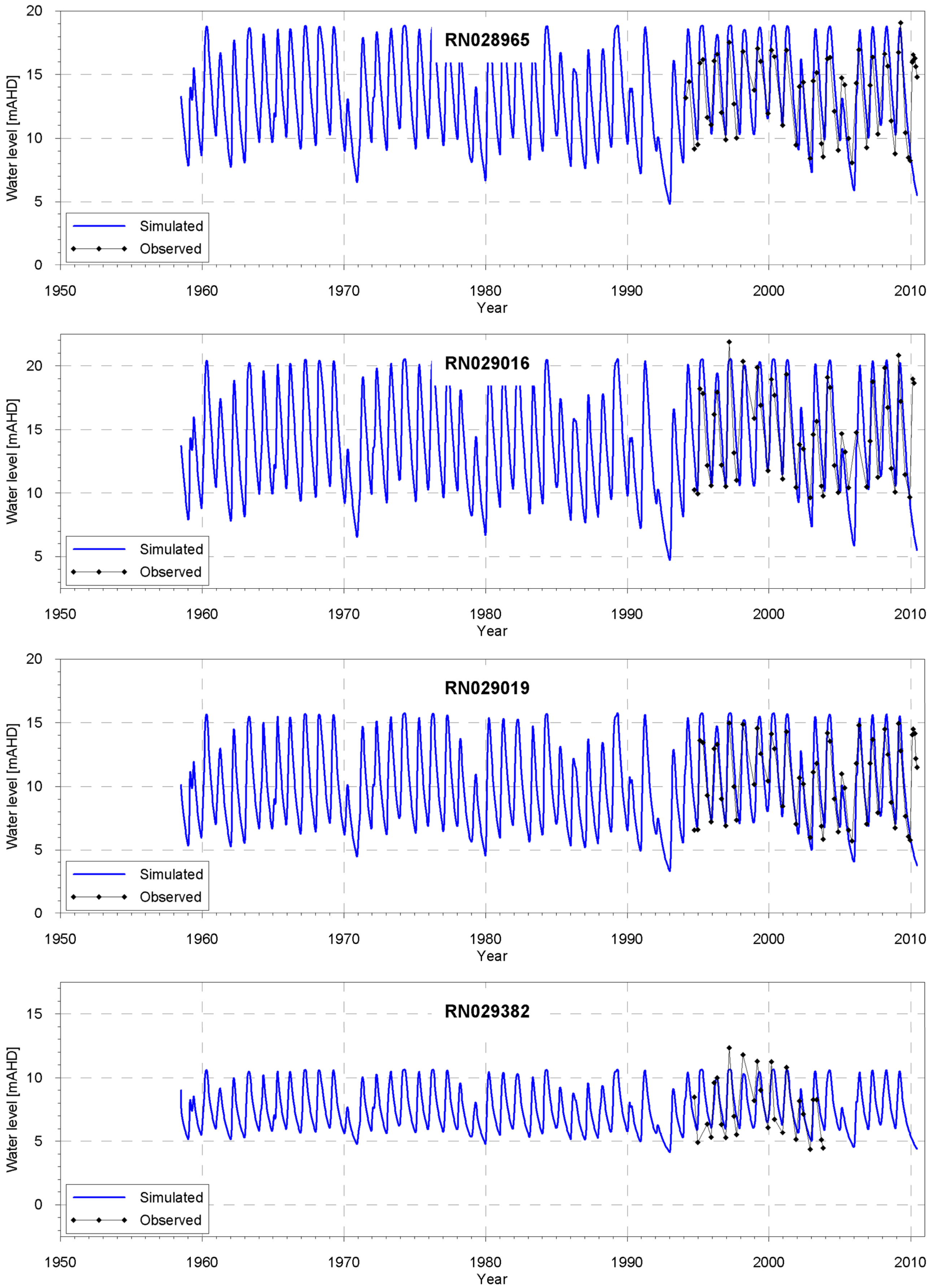
Appendix B - Calibrated transient model results

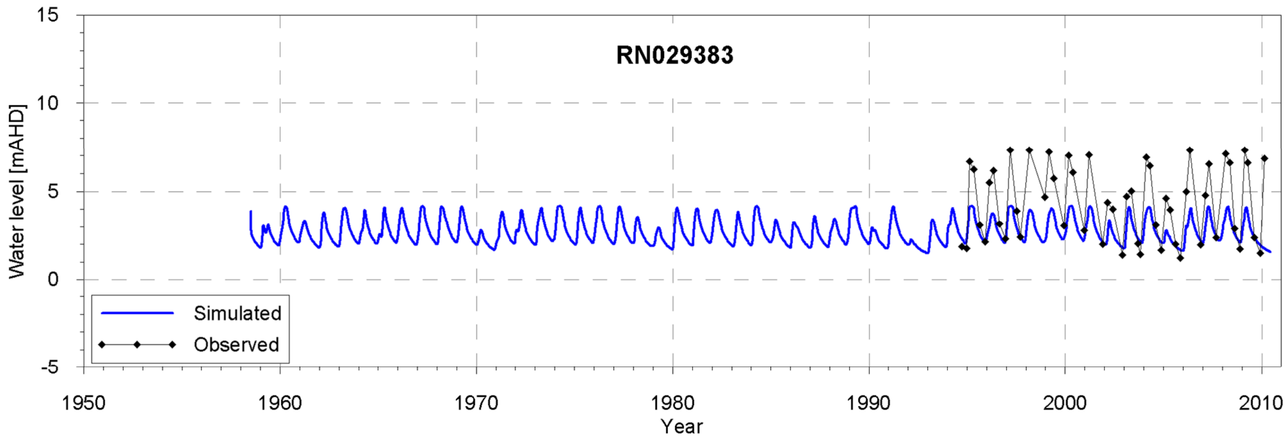


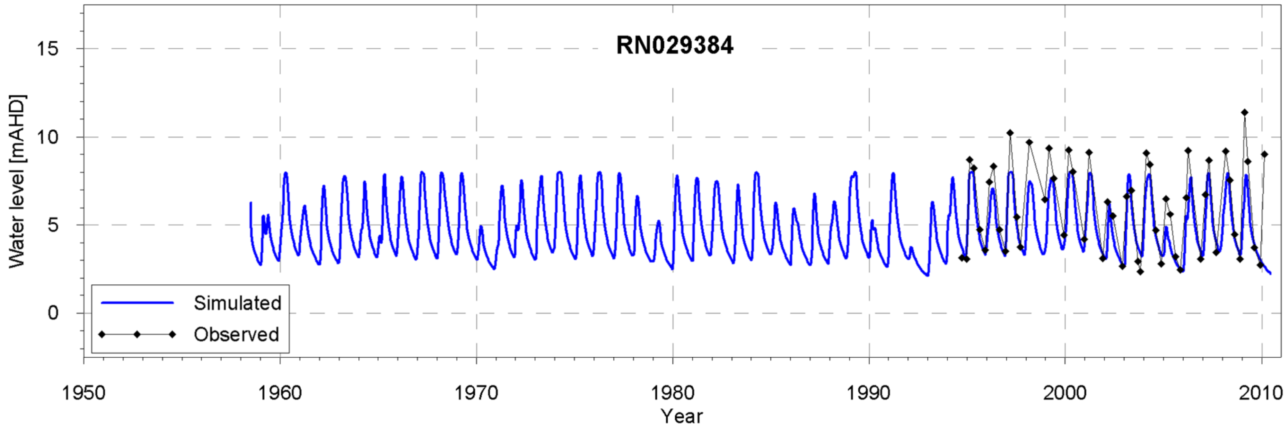


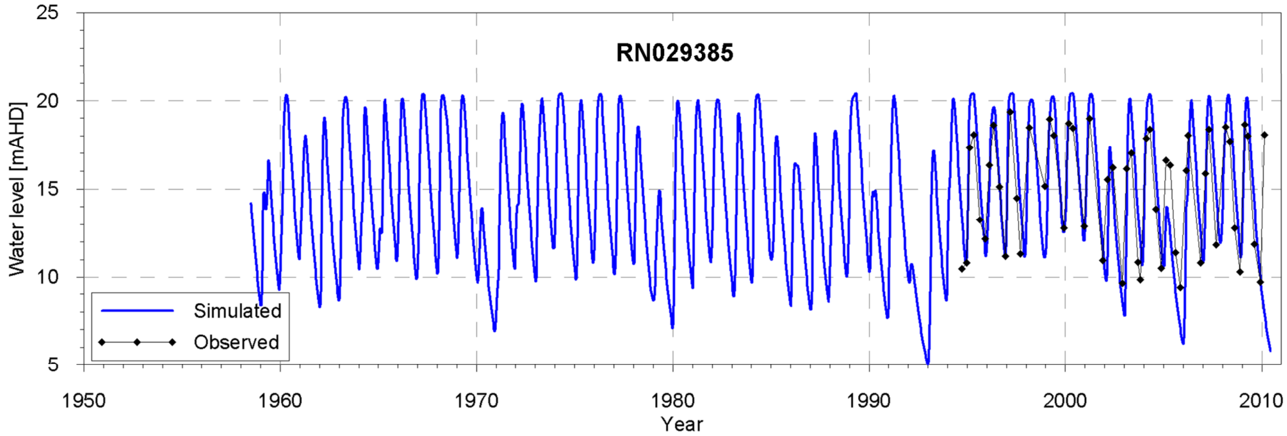


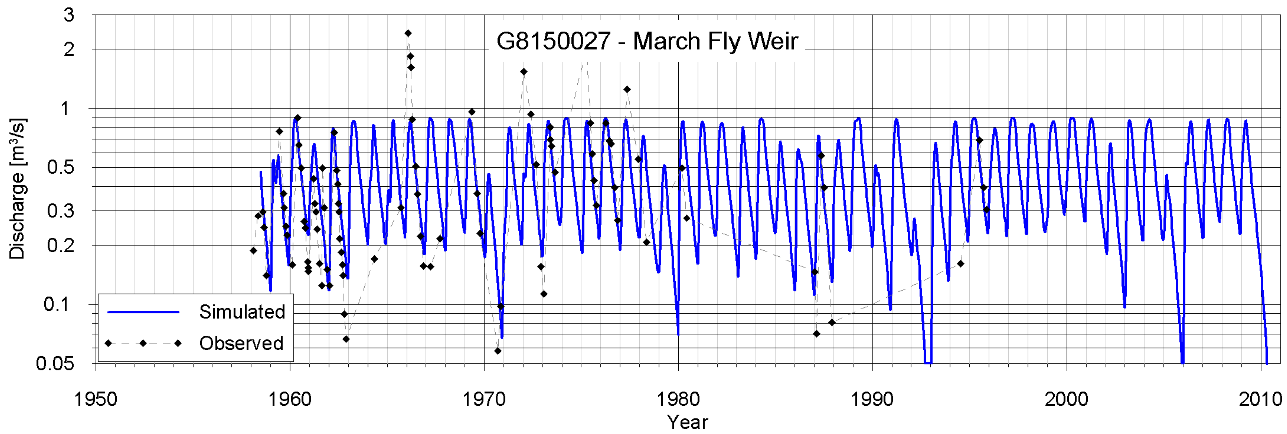



RN028965
Water level [mAHD]
20
15
10
5
0
Simulated
Observed
1950
1960
1970
1980
1990
2000
2010
Year
RN029016
Water level [mAHD]
20
15
10
5
Simulated
Observed
1950
1960
1970
1980
1990
2000
2010
Year
RN029019
Water level [mAHD]
20
15
10
5
0
Simulated
Observed
1950
1960
1970
1980
1990
2000
2010
Year
RN029382
Water level [mAHD]
15
10
5
0
Simulated
Observed
1950
1960
1970
1980
1990
2000
2010
Year


RN029383
Water level [mAHD]
15
10
5
0
-5
1950
1960
1970
1980
1990
2000
2010
Year
Simulated
Observed


RN029384
Water level [mAHD]
15
10
5
0
1950
1960
1970
1980
1990
2000
2010
Year
Simulated
Observed


RN029385
Water level [mAHD]
25
20
15
10
5
1950
1960
1970
1980
1990
2000
2010
Year
Simulated
Observed


G8150027 - March Fly Weir
Discharge [m³/s]
3
2
1
0.5
0.3
0.2
0.1
0.05
1950
1960
1970
1980
1990
2000
2010
Year
Simulated
Observed

Appendix C MIKE SHE 1D recharge modelling

Recharge is the major driver for flow in the groundwater system of the Berry Springs area. Previous modelling of the limestone / dolostone aquifers of the Northern Territory have employed a simple but effective soil moisture deficit model to determine recharge based on rainfall developed by NRETAS (Jolly et al., 2000). To improve on this method a more process based model was used to estimate recharge time series suitable for use in the FEFLOW groundwater model.

The water balance above the saturated zone was modelled using MIKE SHE (Système Hydrologique Européen) (Graham and Butts, 2005). MIKE SHE covers the major processes in the hydrologic cycle and includes process models for evapotranspiration, overland flow, unsaturated flow, groundwater flow, and channel flow and their interactions. Each of these processes can be represented at different levels of spatial distribution and complexity, according to the goals of the modelling study, the availability of field data and the modeller's choices, (Butts et al. 2004).

MIKE SHE was employed because it has the scope to model processes in the soil and incorporate direct recharge due to macro pores, which are considered an important recharge mechanism.

The simplified ET module includes the processes of interception, ponding and evapotranspiration. While MIKE SHEs unsaturated flow module using either the Richards Flow or simplified Gravity Flow solutions requires a detailed vertical discretization of the soil profile, the Two-Layer Water Balance module considers the entire unsaturated zone to be consist of two layers representing average conditions in the unsaturated zone. This results in a quicker computational time and requires much fewer parameters to be estimated.

MIKE SHE uses a simplified ET model that is used in the Two-Layer unsaturated flow (UZ) / evapotranspiration (ET) model. The Two-Layer UZ/ET model divides the unsaturated zone into a root zone, from which ET can occur and a zone below the root zone, where ET does not occur. The Two-Layer UZ/ET module is based on a formulation presented in Yan and Smith (1994). Its main purpose is to provide an estimate of the actual evapotranspiration and the amount of water that recharges the saturated zone.

The input for the model includes the characterisation of the vegetation cover and basic physical soil properties. The vegetation is described in terms of leaf area index (LAI) and root depth. The soil properties include a constant infiltration capacity and the soil moisture contents at the wilting point, field capacity and saturation.

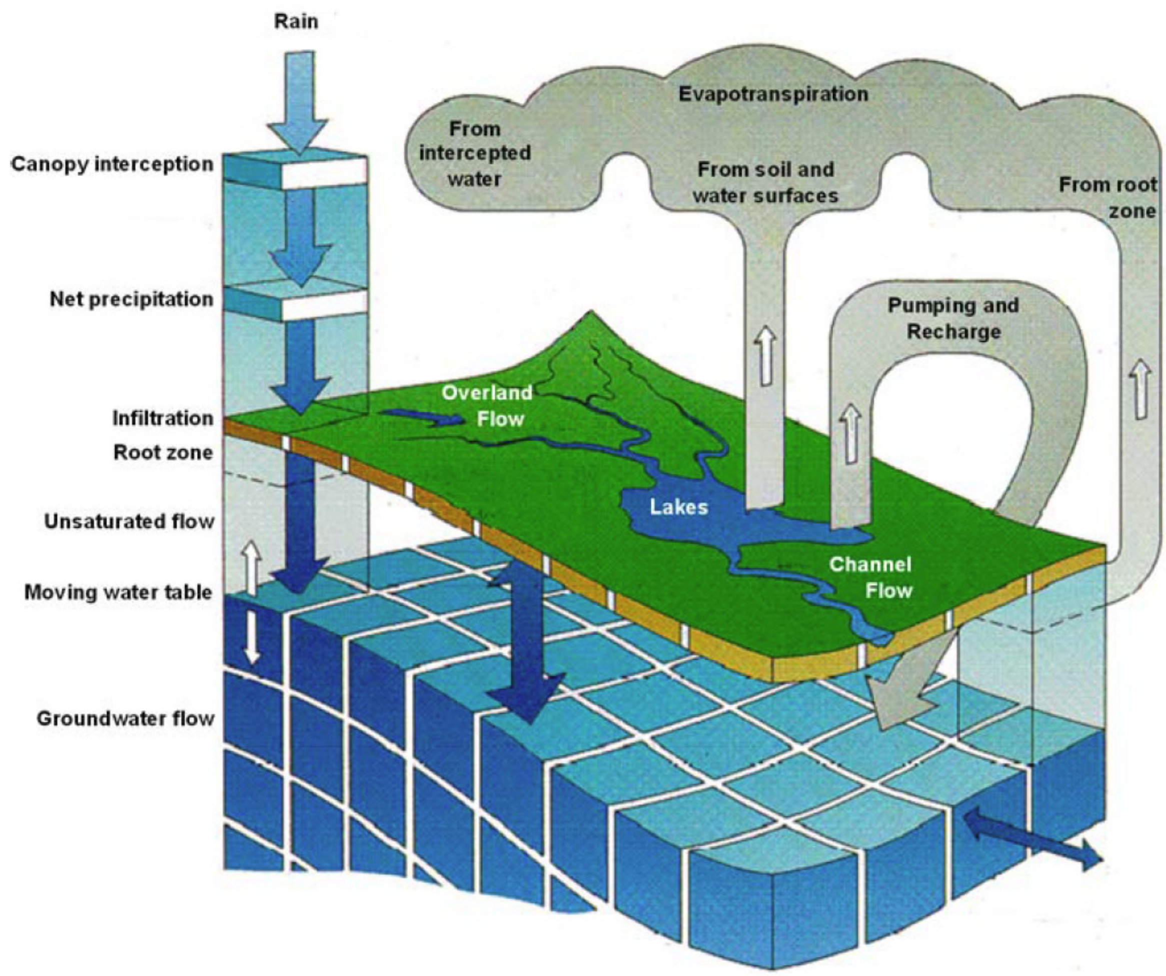


Figure 28 Conceptualisation of Mike SHE modelling components. In this case the groundwater flow was modelled using FEFLOW.

1.2 Simplified Macro-pore Flow (bypass flow)

Flow through macro-pores in unsaturated soil is important for many soil types. In the Two Layer Water Balance module, a simple empirical function is used to describe this process. The infiltration water is divided into one part that flows through the soil matrix and another part, which is routed directly to the groundwater table (bypass flow).

The bypass flow is calculated as a fraction of the net rainfall for each UZ time step. The actual bypass fraction is a function of a user-specified maximum fraction and the actual water content of the unsaturated zone, assuming that macro-pore flow occurs primarily in wet conditions.

Typically, macro-pore flow is highest in wet conditions when water is flowing freely in the soil (e.g. moisture content above the field capacity, θ_{FC}) and zero when the soil is dry (e.g. moisture content at the wilting point, θ_{WP}).

1.3 Model Inputs

1.3.1 Climatic data

The two climatic inputs to the model are the daily rainfall and daily evaporation data taken from the SILO data drill database record for Berry Springs. The input rainfall and evaporation data for the period 01/01/1900 – 01/09/2012 are presented graphically in **Figure 29** and **Figure 30** respectively.

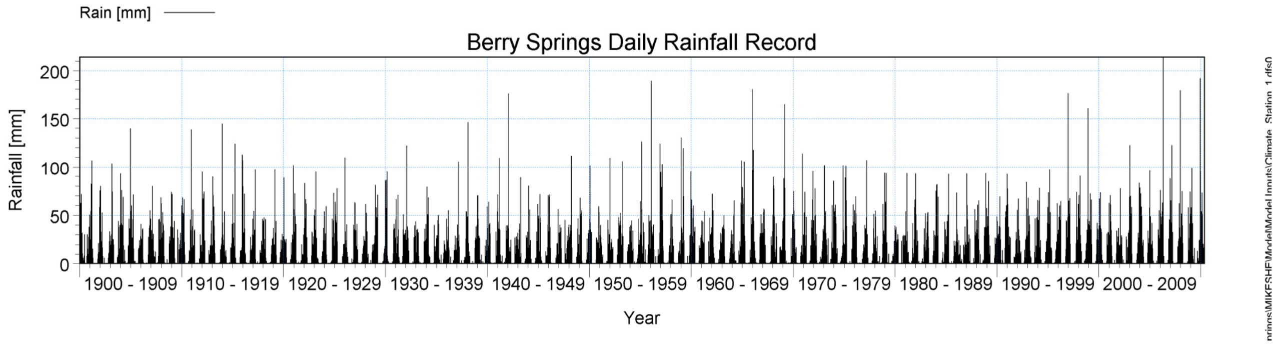


Figure 29 Input rainfall data to the MIKE SHE recharge model.

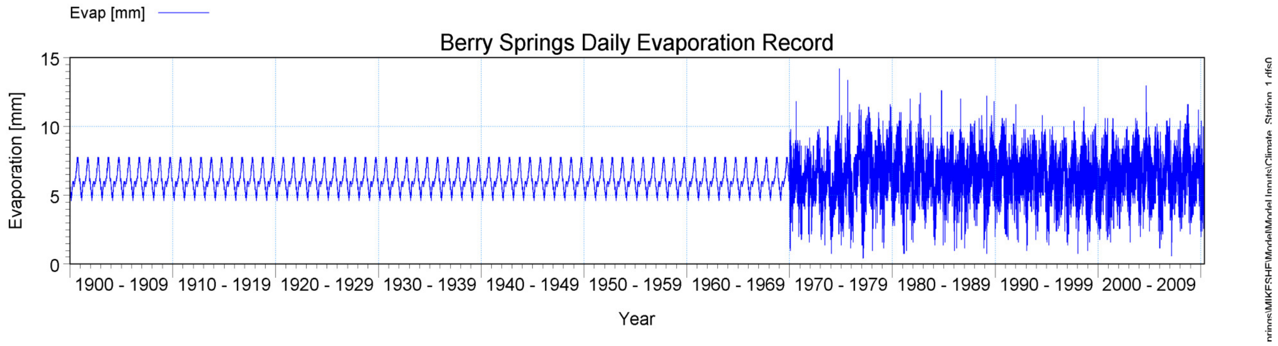


Figure 30 Input evaporation data (proxy for actual ET) to the MIKE SHE recharge model.

1.3.2 Soil data

There are four principle parameters that must be defined for each soil type in the Two-Layer Water Balance method:

Soil water content at saturation (θ_{sat}) - this is the maximum water content of the soil, which is usually approximately equal to the porosity.

Soil water content at field capacity (θ_{FC}) - this is the water content at which vertical flow becomes negligible. In practice, this is the water content that is reached when the soil can freely drain. It is generally higher than the residual saturation, which is usually defined as the minimum saturation that can be achieved in a laboratory test.

Soil water content at the field wilting point (θ_{WP}) - this is the lowest water content that plants can extract water from the soil.

The average moisture content of the upper ET layer can range between the field capacity, θ_{FC}, and the wilting point, θ_{WP}.

Infiltration rate (K_{inf}**)** - this is the saturated hydraulic conductivity of the soil.

Bypass Constants The bypass parameters include:

byp - the maximum bypass fraction (between 0 and 1.0) of the net rainfall,

thr1 - the threshold water content below which the bypass fraction is reduced, and

thr2 - the minimum water content at which bypass occurs.

1.3.3 Vegetation data

Leaf area index (LAI) is the amount of leaf area directly above a square metre of ground. The LAI of open woodland is likely to be in the range of 1.2 - 0.6 m^2 leaf per m^2 ground, while that of a closed forest is likely to be 2 – 4 m^2 leaf per m^2 ground (Eamus et al., 2006). Given that much of the study area is savannah the leaf area index (LAI) was assumed to vary from between 1.29 during the wet season when ET from grasses dominate and 0.47 during the dry season when the ET is dominated by transpiration from trees. These assumptions are based on savannah water use in the Howard East region (Hatton et al., 1997; O'Grady et al., 2000; Hutley et al., 2001). The temporal distribution of the LAI was generated using a simple soil moisture deficit (SMD) model to determine available soil water for shallow rooted (<1500 mm) annual vegetation such as grasses. During the wet season the soil moisture deficit is less than 130 mm and the grasses and deep rooted vegetation are expected to be able to access the soil water and a corresponding leaf area index of 1.29 is assigned. As the year moves into the dry season the soil moisture deficit becomes greater than 130 mm and the soil in the upper 1500 mm water is unavailable to grasses and only deeper rooted vegetation continue to transpire with a corresponding LAI of 0.5. The time series plot of LAI for the period 01/01/1900 – 01/09/2008 is presented in **Figure 31** along with root depth employed in the model. It was assumed that the total root depth of was 4000 mm.

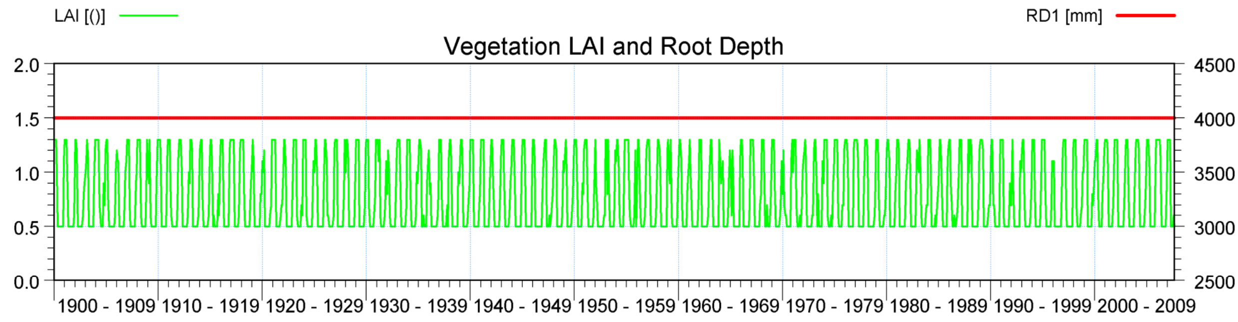


Figure 31 Time series leaf area index (green line) determined from typical wet and dry season values of LAI (Hutley et al., 2001) and the soil moisture deficit model. Included is the root depth (red line).

1.3.4 Calibration

Recharge estimates were based on the results determined for Howard East (Cook et al., 1998a)

Estimates of soil properties were taken from (Kelley, 2002) and (Wilson et al., 2006). Estimates of the infiltrations rates were taken for Tippera loamy red earths when bare and initially dry have infiltration rates of around 180 mm/h (Day, 1977). After 20 minutes of flooding, infiltration rates ranged from 9 – 18 mm/hr. However, values for Blain sandy red earths were initially about 425 mm/hr and 115 mm/h after 20 minutes (Dilshad et al., 1996).

Table 11 Soil parameters used in the recharge model.

Parameter	Unit	Documented Range	Calibrated Value
θ_{sat}	cm^3/cm^3		0.4
θ_{FC}	cm^3/cm^3	0.18 - 0.27	0.25
θ_{WP}	cm^3/cm^3	0.12 - 0.15	0.15
K_{inf}	mm/hr	425 – 180 & 9 – 115	3.6
Soil suction at wetting front	m		-0.25
byp			0.75
thr1	cm^3/cm^3		0.3
thr2	cm^3/cm^3		0.2

The proportion of overland flow and recharge identified in the Daly River modelling (URS, 2008) were also used to constrain the model

The cumulative recharge determined by the SMD model and the MIKE SHE model for the period 01/01/1900 – 01/01/2006 are presented in **Figure 32** and are expressed as depth in millimetres and are negative reflecting the loss of water from the soil profile as recharge to the groundwater. Trends in the accumulated recharge are similar for both models prior to the water year 1972/73, however, after 1973 the accumulated recharge calculated by the two models diverge. The MIKE SHE model shows increased recharge relative to the SMD model. Prior to 1972/73 the average daily recharge is approximately 0.2 mm/d for both models. After 1972/73 the average daily recharge increases to approximately 0.3 mm/d for the SMD model and 0.4 mm/d for the MIKE SHE model. The increase is assumed to be due to the macro-pore component of flow in the MIKE SHE model.

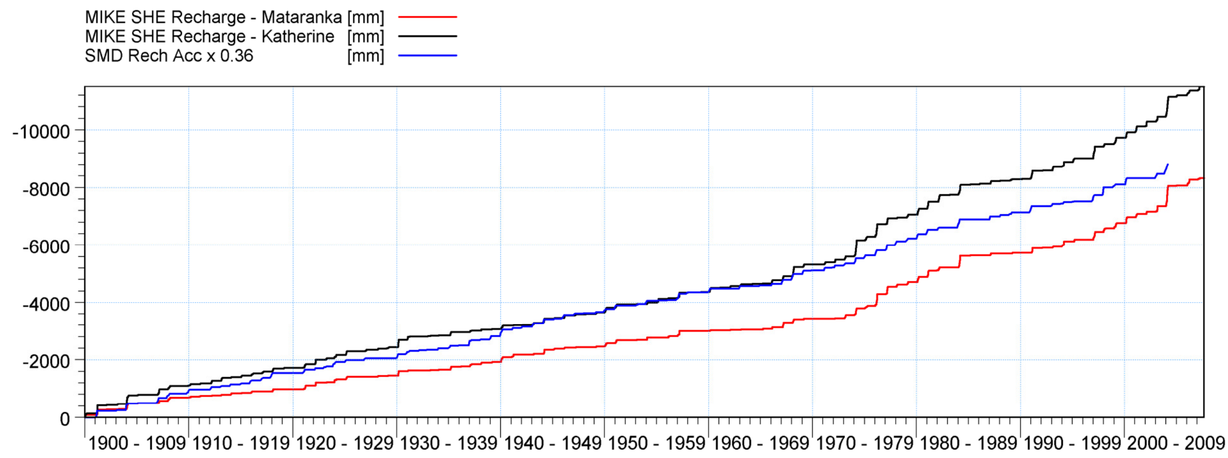


Figure 32 Comparison of cumulative recharge for 01/01/1900 to 1/01/2006 as determined by the SMD model (black line) and the Mike SHE model incorporating macro pore bypass (blue line).

1.3.5 Nash Sutcliffe efficiency coefficient

Nash–Sutcliffe efficiencies can range from −∞ to 1. An efficiency of 1 (E = 1) corresponds to a perfect match of modelled data to the observed data. An efficiency of 0 (E = 0) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero (E < 0) occurs when the observed mean is a better predictor than the model or, in other words, when the residual variance (described by the nominator in the expression above), is larger than the data variance (described by the denominator). Essentially, the closer the model efficiency is to 1, the more accurate the model is.

The NS can range from −∞ to 1; improved model performance is indicated as the NS approaches 1, while a value of zero indicates that simulated values are no better than the mean of observed values. While there is no consensus on specific Nash-Sutcliffe coefficient values that must be obtained for SWAT predictions to be considered good, a value greater than 0.5 is considered acceptable [38-40], and in particular considering monthly simulations. Based on other documentation, NS values greater than 0.75 signify good model performance, while those between 0.36 and 0.75 signify acceptable model performance. Values of NS greater than 0.4 have also been considered to indicate acceptable model performance. Other criteria presented include 0.65–0.75 (fair) and 0.75–0.85 (good) with values above 0.85 representing very good model performance.

Appendix D FEFLOW Model Optimisation Using Parameter ESTimation (PEST)

1.4 Introduction

The hydraulic parameters used in the calibrated model were generated using the PEST (Parameter ESTimation software (Doherty, 2004).

PEST is a model independent parameter optimizer that uses the Gauss – Marquardt – Levenberg non-linear estimation technique. It is adapted to run the existing model. The purpose of PEST (which is an acronym for Parameter ESTimation) is to assist in data interpretation, model calibration and predictive analysis. PEST will adjust model parameters and/or excitations until the fit between model outputs and laboratory or field observations is optimised in the weighted least squares sense. Where parameter values inferred through this process are nonunique, PEST will analyse the repercussions of this nonuniqueness on predictions made by the model. The universal applicability of PEST lies in its ability to perform these tasks for *any* model that reads its input data from one or a number of ASCII (ie. text) input files and writes the outcomes of its calculations to one or more ASCII output files.

It should be noted that the parameter estimation process does not provide an estimate of systematic error, ie that error associated with an oversimplified conceptual model and model design. If, however, measured values cannot be matched, it is a sign of a wrong conceptual model.

For the model calibration, PEST program was used in this study. PEST is a nonlinear parameter estimation and optimization package, and is one of the most recently developed systems offering model independent optimization routines (Doherty and Johnston, 2003). It applies a robust Gauss–Marquardt–Levenberg algorithm, which combines the advantages of the inverse Hessian method and the steep descent method and therefore provides faster and more efficient convergence towards the objective function minimum. The best set of parameters is selected from within reasonable ranges by adjusting the values until the discrepancies between the model generated values and those measured in the field is reduced to a minimum in the weighted least squares sense. Due to its model independent characteristic, PEST can be used easily to estimate parameters in an existing computer model, and can estimate parameters for one or a series of models simultaneously. Since its development, PEST has gained extensive use in many different fields.

The specifications of the calibration algorithm include model parameterization, the selection of calibration parameters, defining feasible parameter variation range, assigning prior information to a parameter group, assigning weights to members of the observation groups.

1.5 Parameter estimation process

The inputs to PEST are the observed and simulated groundwater levels and discharges and the outputs are the new model parameters. To achieve integration between Parallel PEST and FEFLOW several utility programs were required.

Discharge was exported from the model by an IFM DLL module using grouped flux from specified observation point groups along each of the rivers. It should be noted that to correctly report the flux all the nodes on each of the slices with constant head BCs need to be defined in the same observation group.

The PEST parallellisation was accomplished using 5 computers. A “master” PC with 2 xeon 3.0 GHz OS windows xp, 2 “slave” 2.66 GHz quad-core windows xp x64 OS based PCs and 2 “slave” 2.4 GHz quad-core windows xp x86 OS based PCs. The computers were connected via a TP-LINK fast Ethernet switch. Model runs generally took 120-150 minutes to complete.

Initially the measured flow data was used to generate the objective function, however, this produced marginal results due to the large dynamic range in the data and the nonlinear nature of the flow recessions. Given that the dry season flow data exhibits a linear recession when plotted on a semi-log graph the flow data was then transformed to logarithmic base 10 to create a more linear objective function.

1.6 Estimated parameters

The parameters estimated using PEST are the recharge scaling factor, storage coefficient, the hydraulic conductivity of layers 1 and 2, the .

Initial estimation of parameters indicated that the model output was relatively insensitive to the horizontal hydraulic conductivity of layer 1. Further parameter estimation was constrained by tieing the horizontal hydraulic conductivity to the vertical hydraulic conductivity of layer 1 using a ratio of 10.

1.7 Objective function

PEST uses the sum of squared residuals to determine the objective function or "goodness of fit" between the simulated response and the observed response. The dolomite aquifer was calibrated against discharge flow recessions calculated at each flow measurement for the 1 available gauging site for the period 1958 – 1995 and groundwater levels at 11 observation bores for the period 1994 - 2009.

Prior to calculating the flow recession data the gauged flow record was adjusted by removing data that were not representative of the dry season groundwater discharge refer to **section 5.5.1**.

To improve the linearity of the problem and to ensure that high flows did not dominate the parameter estimation process the gauged dry season discharges and simulated discharges were transformed to log 10.

The objective function scale factors used by PEST to provide equal weighting of 0.5 to groundwater levels and 3000 to discharge recession values.

1.8 Parameter ESTimation results

The resulting estimates of parameters in the model are presented in **Table 12**. An assessment of the sensitivity of the parameters can be established from the upper and lower limits determined for 95% confidence limits. The recharge and hydraulic conductivity of layer 2 are most sensitive the hydraulic The modelled groundwater levels and discharges are presented in Appendix B.

Table 12 Estimated parameter values determined from PEST process

Parameter	Estimated value	95% confidence limits		Percent variation
		lower limit	upper limit	
rech1				
stor1				
condxy1				
condxy2				

A scatter plot comparison of all the observed and simulated groundwater levels are presented in **Figure 33** a scatter plot comparison of the log transformed observed and simulated groundwater discharge is presented in **Figure 34**.

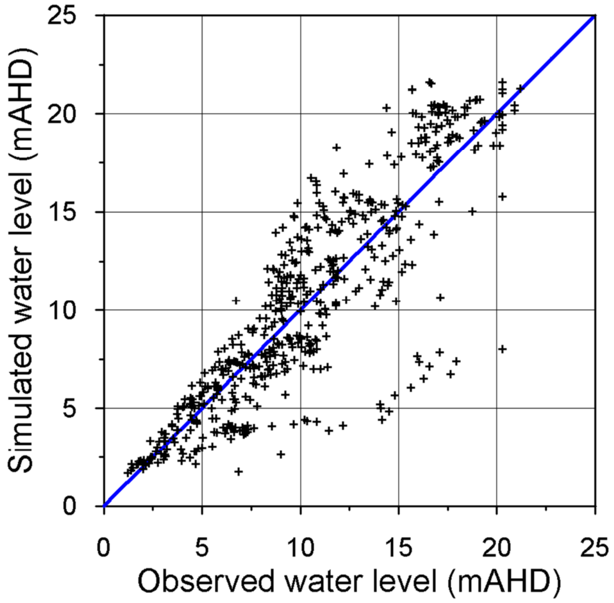


Figure 33 Comparison between observed and simulated heads of the calibrated Berry Springs groundwater model. The simulated heads are evenly distribution either side of the 1:1 fit suggesting that errors are relatively random, although there appears to be an overestimation of heads greater than 15 mAHD.

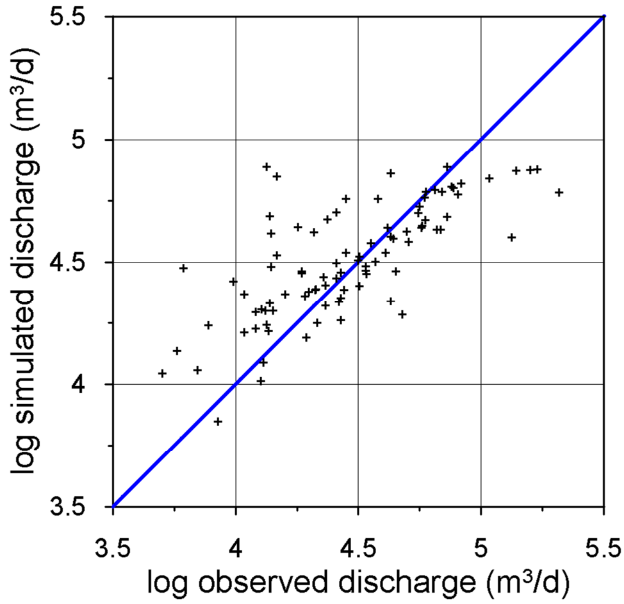


Figure 34 Comparison between log transformed observed and simulated discharge for G8150027.

1.9 Sensitivity Analysis

PEST is capable of providing the relative sensitivity of the model results to changes in the model parameters.

The parameters estimated for the calibrated groundwater model were adjusted to assess the sensitivity of the output. Each of the parameters used in the parameter estimation process were adjusted by ±1%, ±5% and ±10%, PEST determined objective function was used to determine the resulting change to the model.

A total of 6 runs per parameter were completed resulting in a total of 25 model runs including the baseline parameters. The parameters used are presented in .

Table 13 Parameter values used in the sensitivity analysis of the Berry Springs groundwater model

Rech Scaling	Storage Coef	Horizontal K (m/d)		Vertical K (m/d)	
		Layer 1	Layer 2	Layer 1	Layer 2

Note: the vertical hydraulic conductivity of each layer was tied to the horizontal hydraulic conductivity by a factor of 0.1.

The sensitivity analysis runs were completed using the SENSAN utility (Doherty, 2004). The SENSAN utility enables multiple runs of a model with changed parameter values for each run and records the resulting objective function which can be used to assess changes in the model output. The sensitivity show that the model is most sensitive to the hydraulic conductivity of layer 2 and the recharge scaling value. The model is less sensitive to changes in storage coefficient. The model is relatively insensitive to the hydraulic conductivity of layer 1, with very little change in the objective function for the different parameter values.

1.9.1 Pumping data

Appendix E Formulation of discrete feature fracture flow

Fracture flow is a major component of karstic aquifers. The discrete fracture approach is typically applied to fractured media with low primary permeability. Flow through a single fracture may be idealised as occuring between two parallel plates with a uniform separation equivalent to the fracture aperture.

It is evident that substituting for K_{frac} that Q_{frac} is proportional to the cube of the fracture aperture. These results for tubes and cracks are known as the *Hagen-Poisseuille* Law after two separate discovers. These formulae are only valid for laminar flow so always calculate the Reynolds Number in any particular numerical case.

Implementing the *Hagen-Poiseuille* cubic law the hydraulic conductivity of the fracture elements is related to the hydraulic radius (r_{hydr}) of the fracture which is determined from the aperture (b).

$$\boldsymbol{Q}_{frac} = 2bw\boldsymbol{K}_{frac}\left(\frac{dh}{dl}\right)$$

$$\boldsymbol{K}_{frac} = \frac{r_{hydr}^2}{a}\frac{\rho_0 g}{\mu_0} = \frac{b^2}{12}\frac{\rho_0 g}{\mu_0} = 6.3 \cdot 10^5\, b^2$$

where:

ρ_0 = 1000 [kg m^{-3}]

μ_0 = 1.3 [Pa s]

g = 9.81 [m^2 s^{-1}]

w is the fracture width [metres]

b is the fracture aperture [metres]

r_{hydr} = $b/2$

a = 3 for a planar geometry

FEFLOW provides 1D and 2D discrete feature elements which can be mixed with the porous matrix elements in two and three dimensions. Different laws of fluid motion can be defined within such discrete features, e.g., *Darcy*, *Hagen-Poiseuille* or *Manning-Strickler* laws. Both the geometric and physical characteristics of the discrete feature elements provide a large flexibility in modeling complex situations.

Although the overall water balance remains relatively consistent, the discharge response at the spring shows an improved match with the observed record.