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Assessment of Major Spring Systems in the Oolloo Dolostone, Daly River

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Cover photo: Small spring on the bank of the Katherine River, MGA52, 166147E, 8370297N, photo R. Farrow

Assessment of Major Spring Systems in the Oolloo Dolostone, Daly River

Steven Tickell
Editor

December 2011

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Glossary of abbreviations

ASRIS, Australian Soils Resource Information System
BFI, Base flow index
CDU, Charles Darwin University
CERP, Croplands Erosion Research Projects
CFC, Chlorofluorocarbons
CSIRO, Commonwealth Science and Industrial Research Organisation
ET, Evapotranspiration
MRC, Master recession curve
NRETAS, Department of Natural Resources, Environment The Arts and Sport
NT, Northern Territory
Oolloo Region, The area in which the Oolloo Dolostone occurs
PAAS, Post Archean Australian shale (Taylor and McLennan, 1985)
SVAT, Soil-vegetation-atmosphere transfer models
SWAT, Soil and Water Assessment Tool
TRaCK ,Tropical Rivers and Coastal Knowledge Research
USDA, United States Department of Agriculture
WAP, Water Allocation Plan
WAVES, A model that simulates the fluxes of mass and energy between the atmosphere, vegetation, and soil

Executive Summary

The Oolloo aquifer is an important karstic aquifer in the northern part of Australia's Northern Territory. Its groundwater discharges into the Daly River, providing the major portion of its baseflow with flow maintained throughout the Dry season supporting the associated riverine ecosystems. This groundwater is also increasingly being extracted for agriculture. A draft Water Allocation Plan for the aquifer is to be released during early 2012 and this study comprises research into various aspects of aquifer water balance and components of the associated water cycle. It was undertaken in order to provide the most up to date scientific knowledge to support the plan.

Geological investigations including reconnaissance mapping and drilling have better defined the extent of the aquifer and has confirmed a twofold subdivision into an upper, highly permeable, fractured and karstic aquifer and a lower, less permeable, mainly fractured rock aquifer. A new geological formation, the Florina Formation was also recognised and mapped. It is important because it acts as a confining layer to the Oolloo aquifer. Drilling through the Florina Formation into the top of the Oolloo aquifer has demonstrated that the Oolloo Dolostone was exposed to the atmosphere and underwent kastification prior to the deposition of the Florina Formation during the Early Palaeozoic. This explains the widespread development of the highly permeable karstic aquifer, even at depth in the central parts of the Daly Basin. The updated knowledge about the Oolloo aquifer has been used to compile a new hydrogeological map of the area.

Groundwater discharge from the aquifer is largely through springs in the Daly and Katherine Rivers. They occur in places where confining layers are not present. Three main groups of springs were recognised based on location and discharge. They have been named the Katherine River, Stray Creek and Daly River spring zones. Spring discharge from the Oolloo aquifer varies considerably with time on a scale of decades due to medium term (decadal) rainfall changes.

Hydrochemical investigations have indicated both upward and downward leakage of groundwaters between the Oolloo aquifer and overlying Cretaceous strata, depending on the local hydraulic gradient. Localised upward leakage from the underlying Jinduckin Formation into the Oolloo aquifer was also indicated. Nitrate concentrations in groundwater are very low. Broad trends in dissolved oxygen and iron(II) concentration, coupled with the fact that measured concentrations are so low, suggests there may be some capacity for denitrification to mitigate potential future nitrogen contamination of the groundwater.

A suite of environmental tracers (^{222}Rn, CFCs, SF_6, ^{14}C, and ^{4}He) was used to characterise groundwater interaction between the Oolloo aquifer and Daly River. Both modern (less than about 100 years) and older (hundreds to thousands of years) waters were differentiated in the groundwater and springs. Their distribution has led to a new conceptual model of groundwater flow. At the small scale, within 1 km of the river, the Oolloo aquifer is recharged by a combination of deep drainage through surface soils and, to a lesser degree, from annual flooding and lateral flow into the aquifer. In the subsequent Dry season, discrete point source seeps provide relatively young water to the river. However, at the large scale, on the order of the Daly Basin, regional scale groundwater flow supplies water to major spring zones and most likely to submerged (concealed) seepage zones that extend downstream of Stray Creek. Along the entire section of the Stray Creek and Daly River spring zones the older regional-scale groundwater makes up approximately 35 per cent of the baseflow. In the Stray Creek spring zone it represents approximately 90 per cent of baseflow. At Oolloo Crossing, groundwater levels exhibit a hydraulic damming effect that governs interaction between the Daly River and adjacent aquifer. At this location extensive bank-storage is probably not occurring during the annual flooding.

Groundwater recharge was estimated utilising environmental tracers, analysis of time-series hydraulic head data and cross-sectional numerical modelling. Vertical recharge was estimated to be 17 per cent of rainfall where the massive unit of the Oolloo aquifer is close to the ground surface and 7 per cent where overlain by Cretaceous sediments. When a dual-continua approach to modelling groundwater flow and apparent age is invoked, the unique transmission and storage properties (i.e. matrix and conduit flow) of the Oolloo aquifer can be replicated. Furthermore, qualitative comparison of apparent age appears to be useful for further constraining numerical models.

Recharge (and other water balance components) was also estimated using SVAT (soil-vapour-atmospheric transfer) models calibrated, where possible for soils, vegetation and land forms of the Daly River catchment. The SWAT model was tested over the Oolloo region, simulating surface runoff, soil profile water redistribution and evapotranspiration. Model outputs compared reasonably to observed data available. In addition, outputs from the WAVES model were extracted to generate a map of deep drainage (downward drainage beyond the root zone) and values of recharge ranged up to 150 mm/year with a mean of 67 mm/year (7 per cent of rainfall) in good agreement with geochemical based estimates. These models are limited by the paucity of soil data available to provide robust simulations, with soil hydraulics particularly import for the accurate partitioning of runoff and drainage.

An extensive set of soil hydraulic properties was obtained by field and laboratory measurements across the extent of the Oolloo aquifer to examine the degree of spatial variation and the departure from agricultural soil types for which there are some available data. Observations were made across the Oolloo region to examine variability in soil texture, bulk density, hydraulic conductivity and water release properties. Two distinct groups were identified based on water release characteristics that correspond to agricultural and non-agricultural soils. Data describing non-agricultural soils is sparse despite the area occupied across the Daly catchment, especially in headwaters landforms. A flume was established within one of these small headwater creek systems characterised by skeletal soils and runoff was three times that typically occurring from agricultural soils.

Spring dependant ecosystems will be broadly protected by the Water Allocation Plan as it sets minimum flows at various points in the river based on ecological studies. More localised impacts on spring flows caused by drawdowns from production bores located too close to the river need to be addressed. To do this buffer zones adjacent to the main spring zones are recommended. The karstic nature of the aquifer makes it difficult to set distance limits based on rigorous scientific methods. Observed groundwater levels and overall knowledge of the aquifer have been used to recommend limits of three km for the Stray Creek spring zone and 1.5km for the Daly and Katherine River spring zones.

1 Introduction

The project is a collaboration between the Territory Government Department of Natural Resources, Environment, The Arts and Sport (NRETAS), CSIRO Land and Water and Charles Darwin University. Funding was provided by the National Water Commission and the Territory Government.

1.1 *Aims*

The project has five aims. Most effort was directed to the first aim and all three collaborators worked on that aspect. The remaining aims are mainly dealt with by NRETAS. The aims are:

- Undertake research to fill key knowledge gaps concerning the water balance components of the system;
- Identify areas where development is likely to proceed and provide monitoring infrastructure to support future management needs;
- Identify adaptive management practices that are compatible with the maintenance of spring dependent communities with healthy endemic populations;
- Develop a robust workable system to identify, measure and manage the risks to springs and dependent ecosystems caused by the allocation of water and land use changes in the region; and
- Work collaboratively with water managers and industries that will depend on the water to ensure that the study outcomes are understood, relevant and applied.

The Oolloo aquifer is a major karstic aquifer. Its groundwater discharges into the Daly River, providing the major portion of its baseflow. The river flows throughout the Dry season and supports an important ecosystem. The groundwater is also increasingly being extracted for agriculture. A Water Allocation Plan (WAP) for the aquifer is currently being finalised. This will allocate the groundwater to defined uses, one of which is the natural environment. It sets the rules for future management of the resource. This study originated from a recommendation of the Daly River Management Advisory Committee, that more scientific research was needed to better inform water allocations. That committee is made up of stakeholders from the catchment and is designated to advise the government on water allocations in the Daly River.

Water allocations will be guided by a combined surface water/groundwater model (Knapton et al. 2010). It is a computer model that performs a water balance on the catchment. It balances inputs of water against outputs. Groundwater levels and stream flows in the Daly River under different levels of extraction are predicted in order to assess how much water can be extracted from the aquifer without causing an unacceptable impact to the environment. The accuracy of the model is dependent on knowledge of the hydrogeological properties of the aquifer and of the mechanisms operating on the groundwater and surface water. The model can be adjusted to incorporate improved knowledge when it becomes available. The WAP itself must be reviewed every five years. This project is part of the process of gaining a better understanding of how the groundwater system works and then feeding that knowledge into the model so that its predictions will more accurately reflect the actual state of the aquifer and of Dry season river flows. Some of the current work is on parts of the water cycle that are not at present directly taken into account by the model. It could however be expanded in the future to incorporate aspects such as infiltration and runoff properties of different soil and land unit types.

1.2 *Project activities*

This project examines various aspects of the Oolloo aquifer and parts of the water cycle that act on it. NRETAS used drilling and reconnaissance geological mapping to better define the extent of the aquifer and its relationship to adjacent geological formations. Tools such as down-hole imaging, drill core reflectance spectroscopy logging and chemical analyses of the rock were utilised to learn more about the rock and how the aquifer was formed. Individual springs were mapped by field surveys, while spring discharge was quantified and geographically located by conducting detailed stream gaugings. Rapids were also mapped and a longitudinal survey of the Katherine/Daly River was made in February 2011 when the river was in flood using GPS and a depth sounder. The results of the latter survey are not presented here as the processing of the data was incomplete at the time of writing of this report.

CSIRO extensively sampled groundwater, springs and river water. Chemical parameters ranging from major ions, nutrients and environmental tracers were analysed. This was done to gain information on recharge, how the groundwater and surface water interact, the source of baseflow, the age distribution of groundwater within the aquifer and nutrient mobility in the aquifer.
Charles Darwin University focused on soil hydraulic properties. Field and laboratory determinations of soil hydraulic properties were done with a focus on soil types with little or no currently available soil physical data. They also developed rainfall-runoff functions for land units featuring skeletal soils, also a part of the landscape with little or no measured hydraulic properties.

Another aspect of the water cycle looking at the soil was a study done by NRETAS testing the applicability of the USDA SWAT model (Neitsch *et al*. 2004) for simulating surface runoff, soil profile water redistribution and evapotranspiration (ET). The study area was divided into 101 subcatchments. Each subcatchment was further divided into multiple hydrological response units (HRU) based on the combination of soil characteristics, slope and land use management. Modelling was undertaken at the individual HRU scale and expanded, through time and space, to the sub catchment and then ultimately to the catchment scale.

1.3 *Previous work*

This report builds on work of Wilson et al., (2006) who used a variety of techniques to determine some of the key parts of the water balance of the Oolloo aquifer. They compared drainage rates under native and cleared land using both a surface water balance and subsurface water chemistry. Several observations suggested that recharge beneath native vegetation is dominated by bypass flow rather than diffuse flow. Groundwater chemistry was used to make estimates of recharge as well as the proportions of bypass and diffuse recharge.

The earliest investigation of the Oolloo aquifer was included in a water balance of the whole Daly catchment (Jolly, 2000). Bore hydrographs were used to estimate recharge to the aquifer. A general hydrogeological study of the Oolloo aquifer was made by Tickell (2002). The regional flow paths and major discharge zones were defined. A subdivision of the Oolloo Dolostone into an upper “massive” unit and a lower “bedded” unit was recognised.

The USDA-SWAT modelling work built upon knowledge gained from hydrological studies undertaken in the 1980’s and 1990’s in the Daly River Catchment, particularly the Land Management Strategies for the Semi Arid Tropic (LAMSAT) and the Croplands Erosion Research (CERP) projects (refer: Dilshad and Peel (1994); Dilshad *et al*. (1994, 1995, 1996a, and 1996b; Motha *et al*. 1994, 1995a, 1995b, Motha and Dilshad 1996, 1997a and b; and Peel et al. 1994 and 1996). Knowledge gained from these past works provided a significant input into the parameterisation of the USDA SWAT model.

1.4 Location

The study area is defined by the extent of the Oolloo Dolostone, a geological formation. It is in the Katherine-Daly region of Australia’s Northern Territory (NT), some 200 kilometres south east of Darwin (Figure 1-1). The Daly River, a large perennial river, flows through the centre of the study area. The term “Oolloo region” used in this report refers to the area in which the Oolloo Dolostone occurs

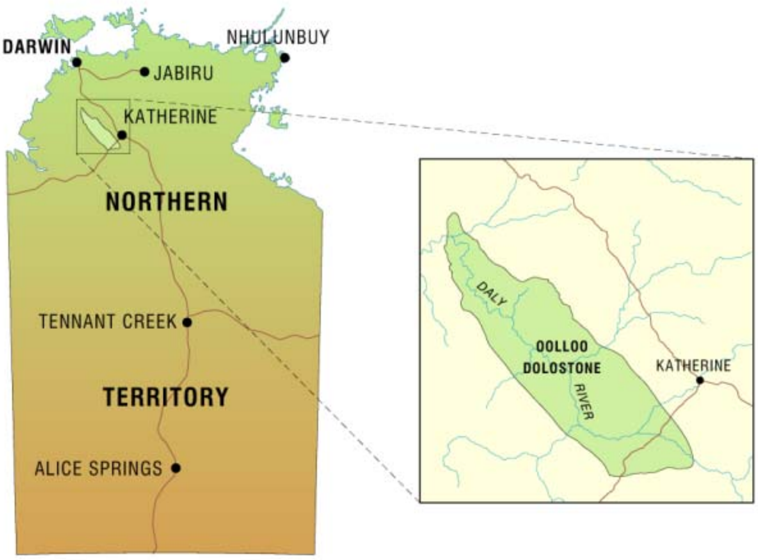


Figure 1-1 Locality map, Oolloo Dolostone

1.5 Climate

The study area is hot throughout the year and experiences a wet-dry monsoon climate with two distinct seasons. 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.

The variety of rainfall sources results in large annual variability. Annual rainfall (October-September) recorded at Katherine since 1887 varies from 364 mm (1952/53) to 1990 mm (1897/98). Rainfall is distinctly seasonal throughout the catchment. Typical annual rainfall in the region is 1200 mm; maximum rainfall is usually in February. Annual pan evaporation is approximately 2300 mm; solar influences are distributed relatively evenly over the year, yet both maximum pan evaporation and monthly temperature occur in October (Bureau of Meteorology), when daily maximum temperature is typically 38°C. Daily rainfall rarely exceeds 200 mm (Erskine et al., 2003).

Significant long-term variations are apparent in the Katherine rainfall record (1887 to present). It is notable that since 1996 annual rainfalls have mostly been above average (Figure 1-2). This has had a significant influence on the water balance of the Oolloo aquifer.

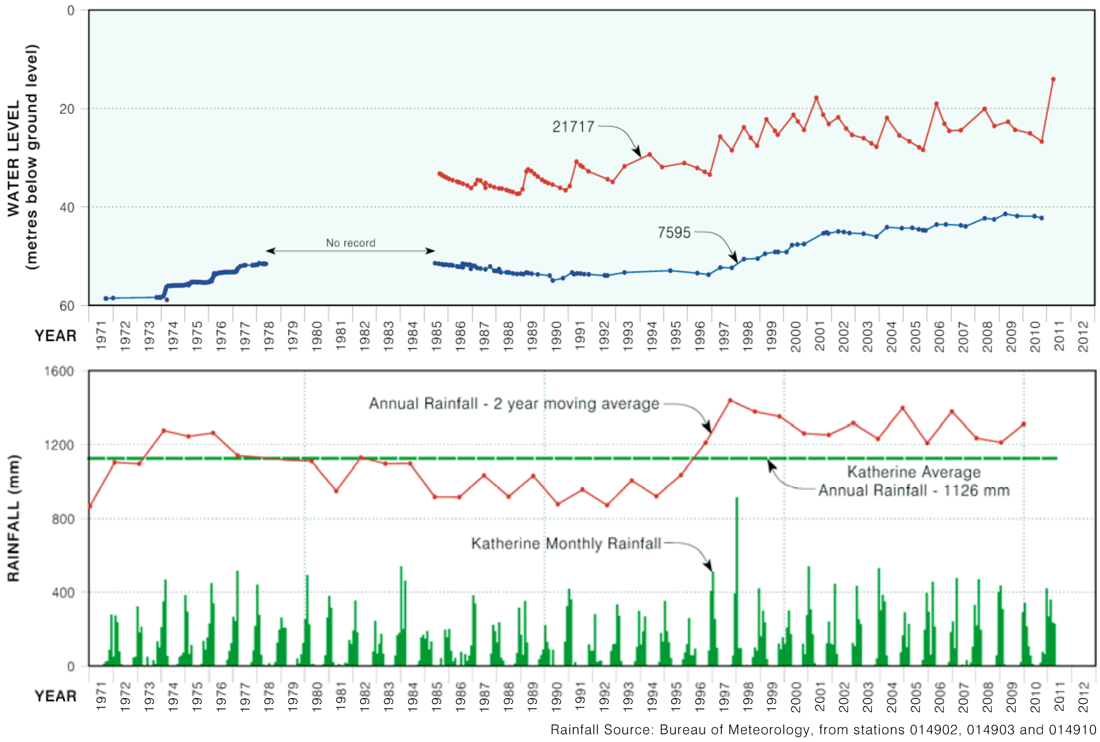


Figure 1-2 Katherine rainfall and typical bore hydrographs

2 Geology and Hydrogeology

Steven Tickell
Department of Natural Resources, Environment the Arts and Sport

Geological and groundwater information collected during this project has been combined with existing knowledge to produce two products that summarise the data. These include a hydrogeological map (Tickell, 2011a) and a GIS (geographic information system). The latter is available both as an unpublished ArcGis project and in Google Earth format, available on the internet (click here).

It includes spatial data such as boreholes, monitoring sites, springs, rapids, geology, groundwater quality and aquifers, as well as time series water levels. Parts of the ArcGis data will be incorporated into the NRETAS corporate spatial dataset which is available on request.

2.1 *Geology*

The Oolloo Dolostone is one of several geological formations which make up the Daly Basin, a largely undeformed sequence of carbonate rocks. Drilling and reconnaissance geological mapping carried out during the course of this study have considerably refined the extent of the Oolloo Dolostone and have confirmed the existence of a previously unrecognised formation that overlies it. The new unit, the Florina Formation is also part of the Daly Basin sequence.

The basin is elongated in a north west to south east direction with an elliptical shape, 170 km long and 30 km wide (Figure 2-1). The formations dip basin-wards at shallow angles, generally less than one degree. From oldest to youngest the layers which make up the basin comprise: the Tindall Limestone, the Jinduckin Formation, the Oolloo Dolostone and the Florina Formation. The maximum recorded thickness of the basin is just over 700m. Individual formations reach maximum recorded thicknesses of: Tindall Limestone 204m, Jinduckin Formation 356m, Oolloo Dolostone 250m and Florina Formation 167m. A simplified surface geological map of the study area is shown in Figure 2-2. The Oolloo Dolostone and the geological units which directly underlie and overly it are now described.

2.1.1 Jinduckin Formation

The Jinduckin Formation comprises interbedded siltstone, shale, dolostone , limestone and sandstone. It is commonly very well bedded to laminated (Plate 2-1a). It underlies and grades up into the Oolloo Dolostone.

2.1.2 Oolloo Dolostone

The Oolloo Dolostone is situated in the central part of the basin. Its outcrop is restricted by an extensive cover of both the Florina Formation and Cretaceous rocks. Areas where it is exposed have low undulating topography with sparse outcrops. The formation is reasonably well exposed along the Katherine and Daly Rivers. Karstic features are restricted to occasional pavements, pinnacles and dolines.

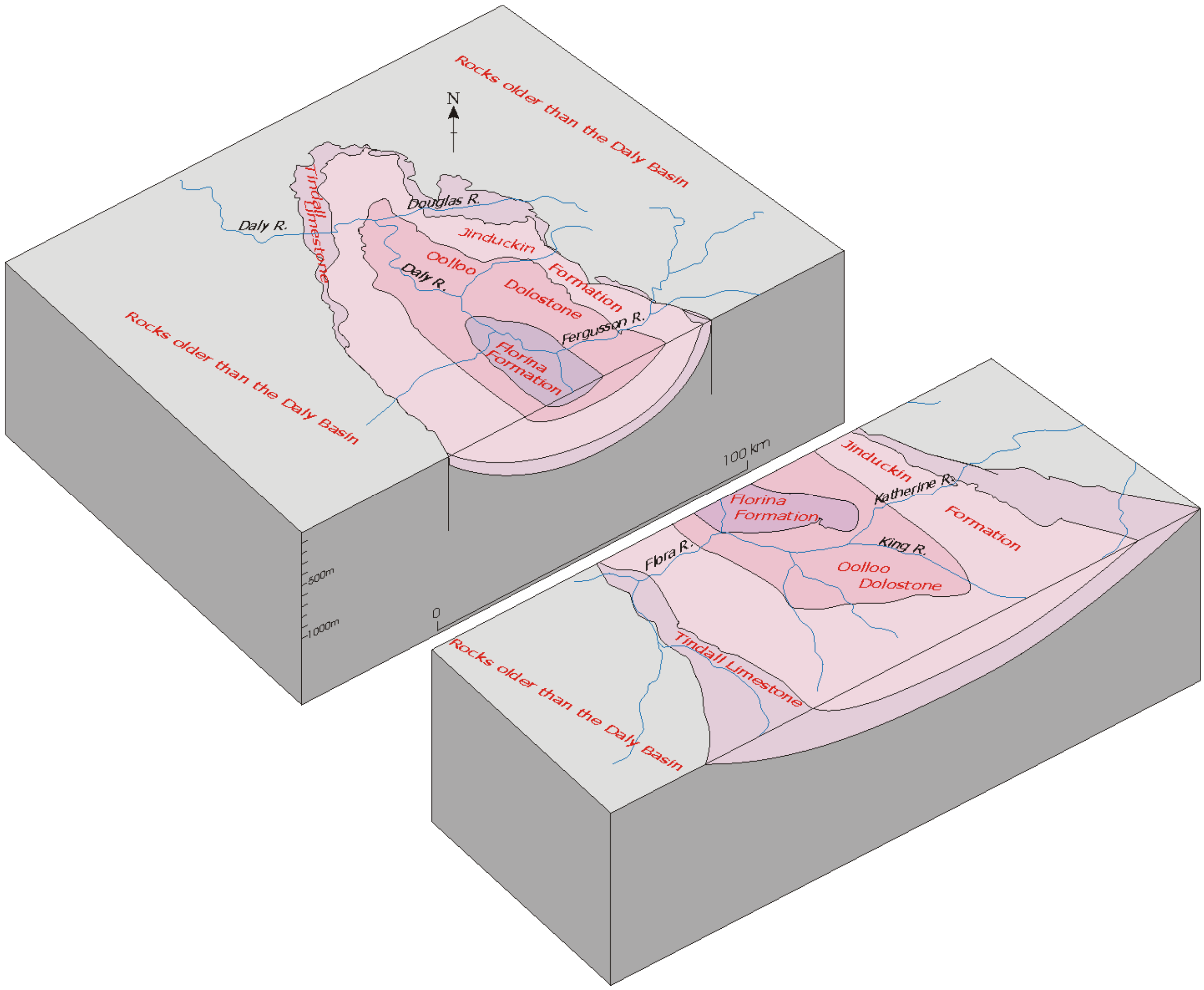


Figure 2-1 – The Daly Basin, note that Cretaceous rocks are not shown.

A twofold subdivision of the Oolloo Dolostone was made by Tickell (2002a), comprising an upper "massive" unit and a lower "bedded" unit. During the present study these have been mapped both in boreholes and by reconnaissance geological mapping. They are yet to be formalised with stratigraphic names and definitions. Examples of downhole images of the units are shown in Plate 2-1 a & b and outcrops are shown in Plate 2-2a, b & c.

The "bedded" unit, the older of the two grades upwards from the Jinduckin Formation and reaches a maximum thickness of 148m in the borehole KRVH1. It is recognisable in outcrop as well bedded dolostone, ooid dolograinstone, stromatolitic doloboundstone, quartzic dolostone and dolomitic sandstone. Beds range from 10 to 50 cm thick. Sparse silty laminae and silty and shaly dolostone beds are more apparent in drill cores and in down-hole imagery, as is finer scale bedding. Borehole gamma ray logs show that the silty/shaley intervals are moderately continuous across the region and are useful marker horizons.

The "massive" unit overlies the "bedded" unit and consists of coarse to medium crystalline dolostone. It has a maximum recorded thickness of 96 m. Sedimentary structures have been largely destroyed by recrystallisation but coarse bedding and stromatilitic horizons are rarely visible. Thin shaley beds are sparsely distributed through the section. Quartz sand is only present in trace amounts.

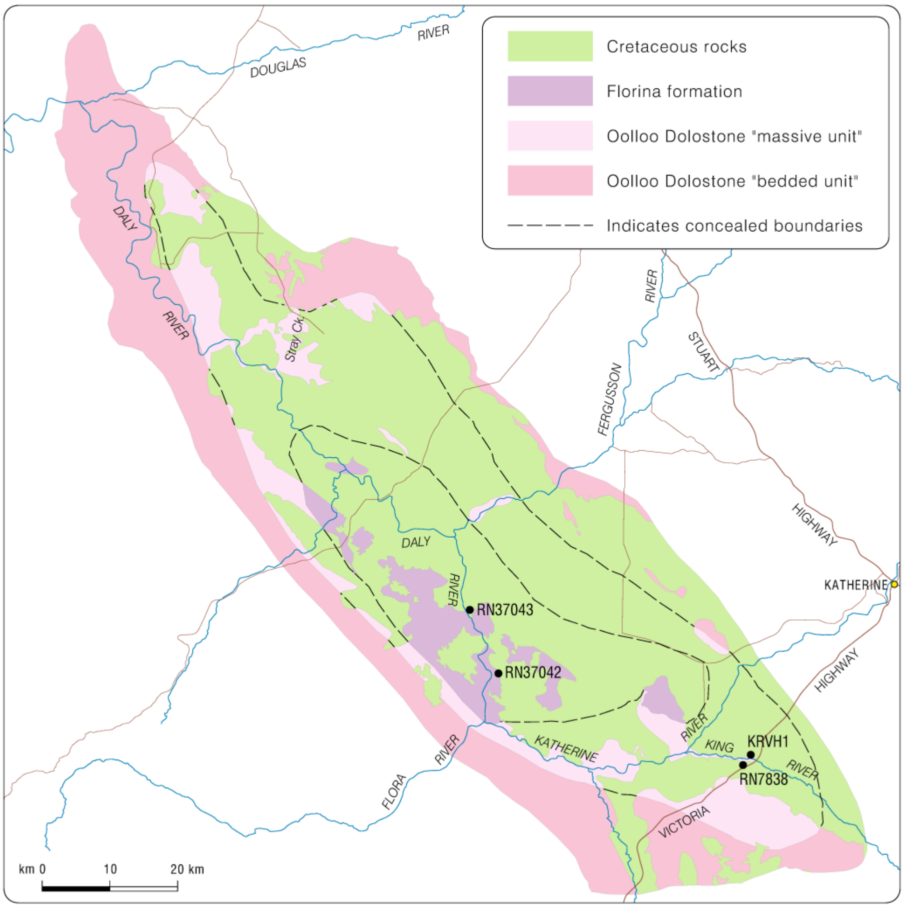


Figure 2-2 Surface geology

The uppermost sections are strongly iron stained to a dark red-pink, lightening in colour with depth. They are also permeated by solution cavities ranging from pervasive fine vugs, often aligned along bedding planes, to metre-scale cavities. This was interpreted as a palaeo-kast zone formed when the formation was exposed to the atmosphere (Tickell, 2002a). Recent drilling has shown that the weathering event occurred prior to the deposition of the Florina Formation during the early Palaeozoic (Tickell, 2010).

In order to learn more about the nature of the Oolloo Dolostone and its twofold subdivision, a detailed study was conducted on cores from the Northern Territory Geological Surveys diamond drillhole KRVH1. That drillhole was chosen because it has a complete set of cores through the Oolloo Dolostone and because it is close to a water bore RN7838 that has a down-hole gamma log for comparison to the cores. Lau (1981) geologically logged the cores and included descriptions of eight thin sections from the Oolloo Dolostone. The current project requested that the core be scanned with the Geological Survey's HYLOGGER, a reflectance spectroscopy logging instrument. It gives a semi-quantative determination of the mineralogy and at the same time captures detailed digital images of the drill cores. The results are described in Tickell (2011b) and are summarised here in (Figure 2-3). The main findings are that the carbonate minerals present are almost exclusively dolomite (calcium-magnesium carbonate). Traces of calcite (calcium carbonate) and ankerite (iron carbonate) are found in the "bedded" unit. The homogeneous distribution of dolomite throughout the formation suggests that dolomitisation pre-dates the palaeo-karst event and is likely to have occurred soon after sedimentation as a diagenetic process.

Another feature seen on the HYLOGGER data is that there is distinct mineralogical difference between the two units. The “massive” unit is largely dolomite with traces of montmorillionite (a clay mineral) and muscovite (a mica mineral) associated with minor shaley horizons. The “bedded” unit by contrast contains abundant muscovite in addition to dolomite. This is due to abundance of shale partings, shaley dolostone and thin shale beds. The lower contact of the “bedded” unit with the Jinduckin Formation is also clearly shown by the HYLOGGER. It is marked by the gradual appearance of ankerite and gypsum (calcium sulphate). The contact appears to be gradational and is taken to be at 251m as identified by Kruse et al. (1994). Note that the HYLOGGER is unable to detect quartz.

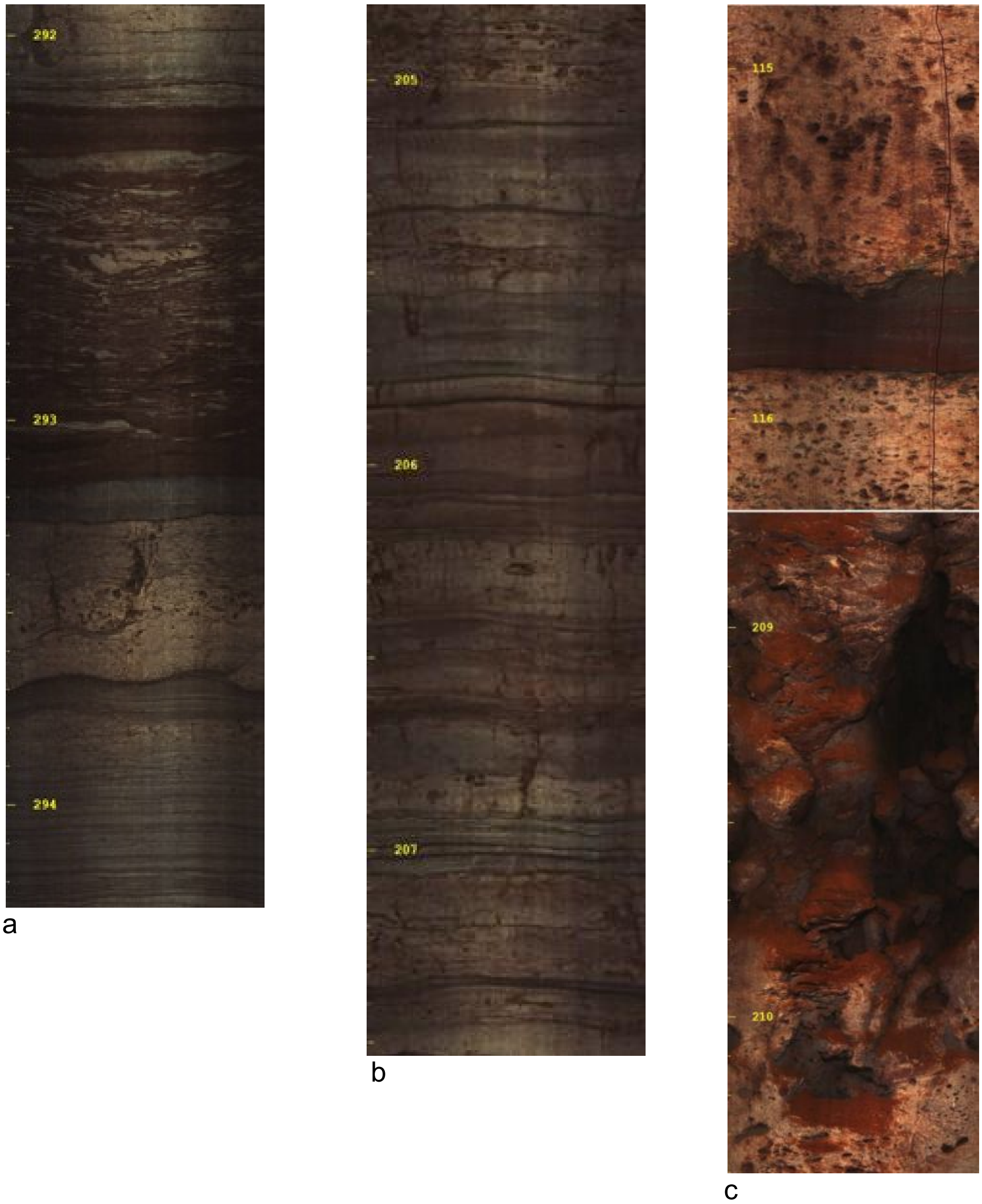


Plate 2-1 Down hole imagery, the depth scale marks are in metres. . a, Jinduckin Formation, RN7838, Laminated siltstone and dolostone. b, “bedded” unit of the Oolloo Dolostone, RN7838, bedded oolitic dolostone. c, “massive” unit of the Oolloo Dolostone, RN37042

a

b

c

d

e

f

Plate 2-2 Outcrops. **a**, ”bedded” unit, Oolloo Dolostone, note soil filled doline, old road quarry, Manbulloo Station. **b**, “massive” unit, Oolloo Dolostone, King River. **c**, Cave in the “massive” unit, NT Por.1349. **d**, Karstic outcrop in the “massive” unit, NT Por.1349. **e**, Glauconitic sandstone with minor shale, Daly River. **f**, Uppermost limestone unit, Florina Formation, Daly River, photos S. Tickell

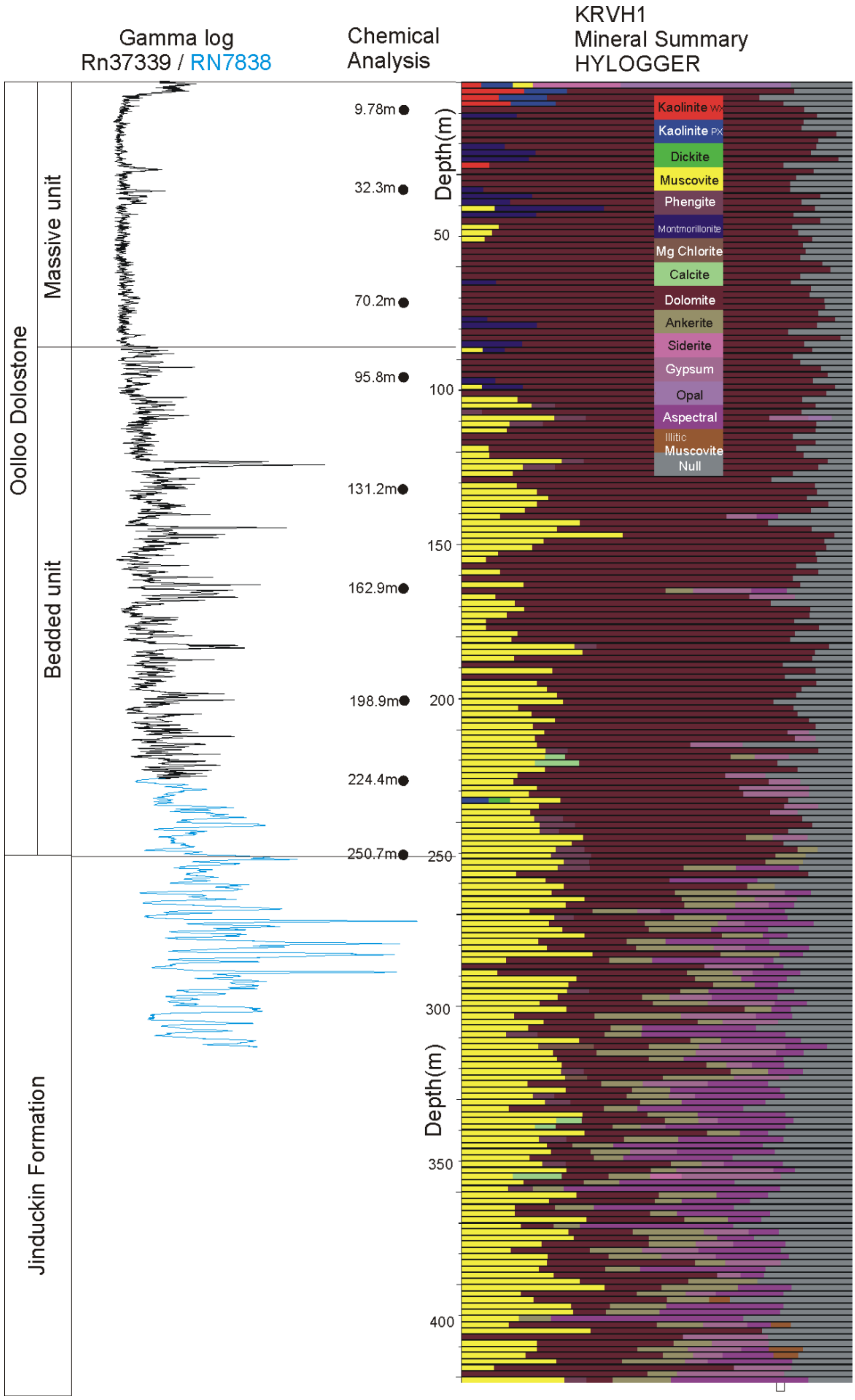


Figure 2-3 Graphic log of KRVH1

Nine cores from KRVH1 taken at depth intervals of around 30 m were assayed for major elements and trace elements. Calcium and magnesium are the dominant elements in all of the samples. The proportions of calcium to magnesium confirms the HYLOGGER result that dolomite is the main mineral present in the Oolloo Dolostone. There is little variation in the calcium to magnesium ratio with depth. Below 95.8 m there is a notable increase in silica, aluminium, potassium, zirconium and lithium.

The rare earth elements indicate three distinct types related to depth. The four shallowest samples plot as a group showing the lowest normalized abundances (Figure 2-4). These are all from the “massive” unit. The next four deeper samples are from the “bedded” unit and also form a distinct group but with higher normalized abundances. The deepest sample is from the base of the Oolloo Dolostone and has distinctly higher normalized abundances compared to all of the other samples. The patterns observed correlate well with the stratigraphic units and are probably a reflection of the increased shale content of the “bedded” unit. The thin section descriptions of Lau (1981) also indicate that the bedded unit also has more detrital grains, including quartz, feldspar, muscovite and heavy minerals. Some of these could also be responsible for the higher abundances of rare earth elements as well as the five elements mentioned above.

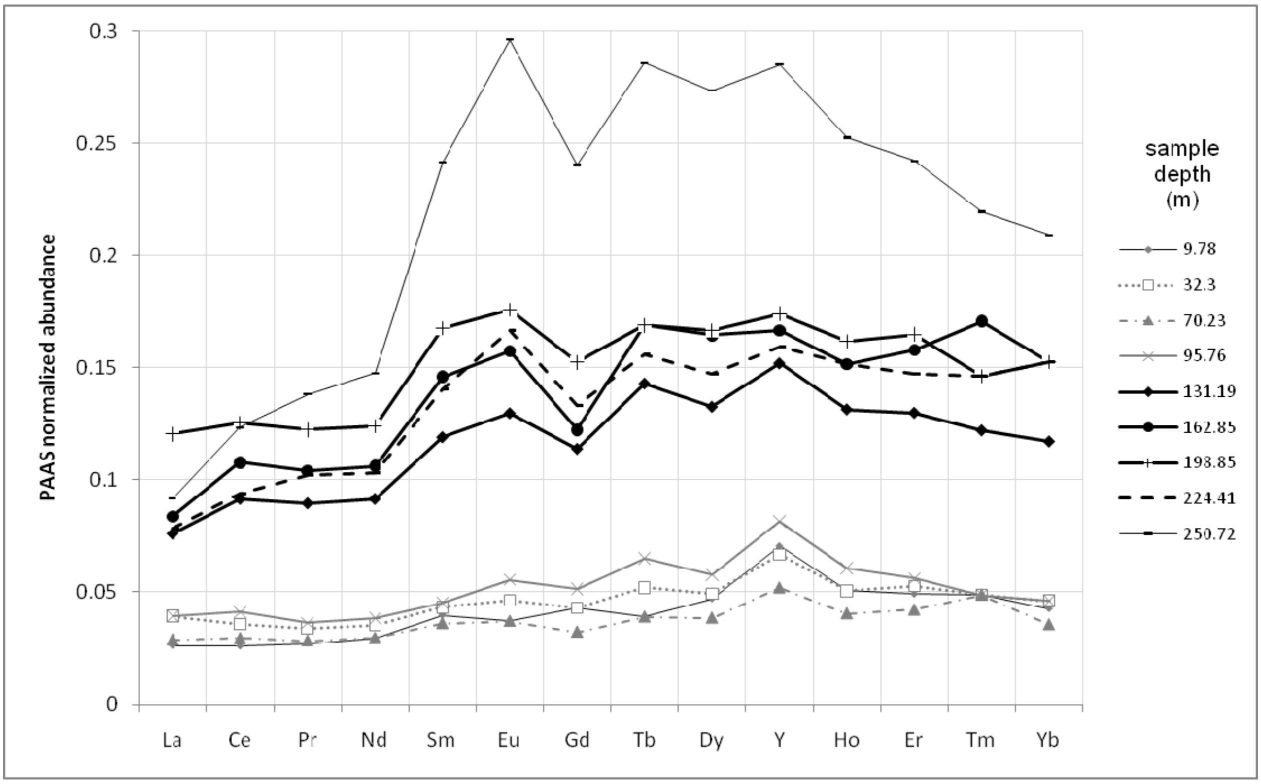


Figure 2-4 PAAS normalized abundances of Rare Earth Elements + Y in KRVH1 cores. sample locations shown in Figure 2-3 Graphic log of KRVH1 Figure 2-3.

2.1.3 Florina Formation

The Florina Formation (Kruse et al. 2012) is the youngest unit of the Daly Basin. Its outcrop is restricted to the upper reaches of the Daly River and to a few isolated localities away from the river. Elsewhere it is mostly concealed by overlying Cretaceous rocks. Prior to this study it was unnamed and unmapped. The NRETAS investigation drilling, specifically RN37042 and RN37043 confirmed that it overlies the karstified surface of the Oolloo Dolostone (Tickell, 2010).

The formation is up to167 m thick and consists of a sequence of alternating glauconitic sandstone and limestone with minor shale and dolostone. Three distinct limestone units and two intervening glauconitic sandstone units were recognised in outcrops and subsurface. The limestone is characteristically very well bedded (Plate 2-2f) and outcrops more prominently than the softer sandstone (Plate 2-2e).

2.1.4 Cretaceous rocks

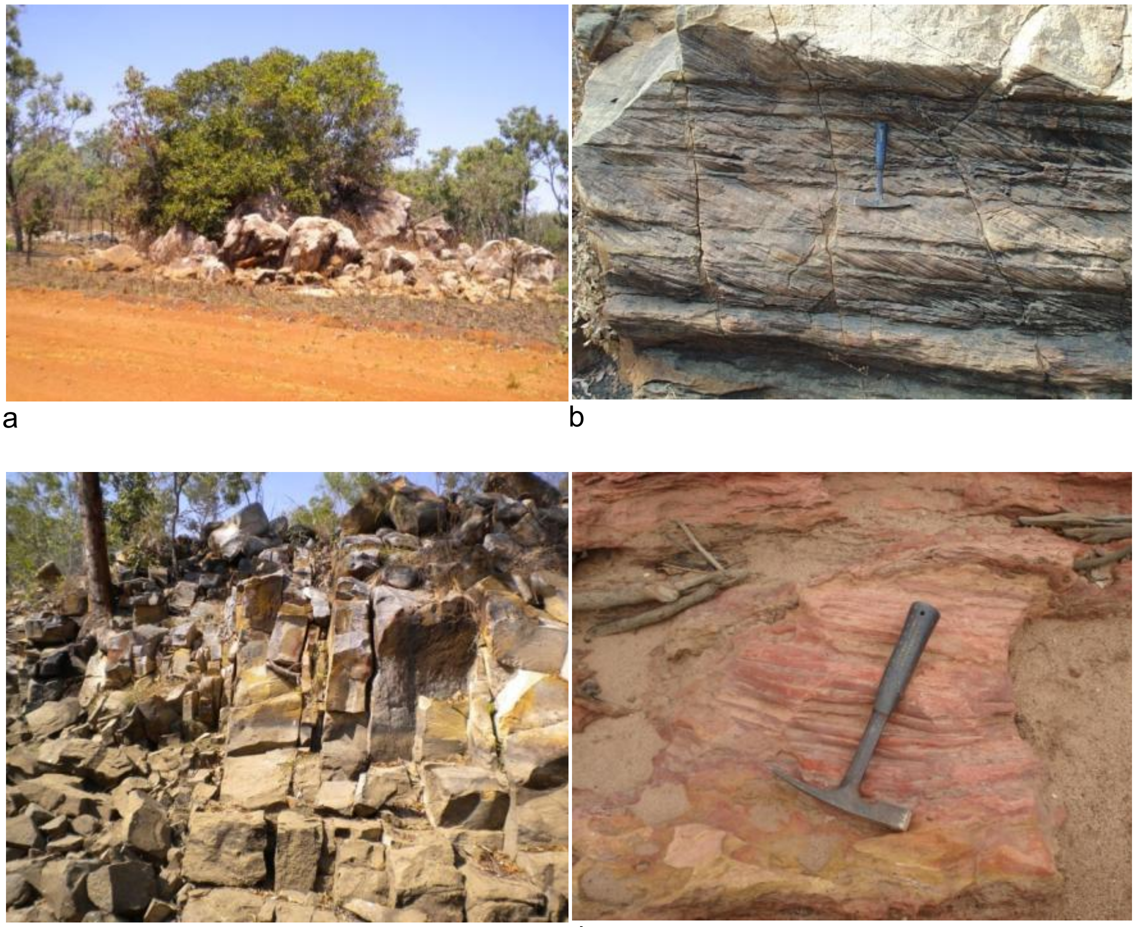
Cretaceous rocks form a covering over at least half of the extent of the Oolloo Dolostone (Figure 2-2). They outcrop sparsely with only local occurrences of silicified sandstone and claystone (Plate 2-3). Hard rocks found in outcrop and near surface result from silicification due to weathering. In the subsurface the formations are much softer comprising clay, sandy clay and sand. Clay is the dominant lithology. The rocks are deeply weathered, typically down to 70 m. Carbonaceous and glauconitic clays can be found below that depth. Sands are up to ten metres thick but tend to be laterally discontinuous. An exception is a sand/sandstone which is widespread either at or near the base of the sequence (Plate 2-2a & b). A bioturbated, brick red shale/clay is also commonly encountered near the base of the sequence (Plate 2-3d). It may represent the oxidized equivalent of the carbonaceous clay described above. The maximum thickness of Cretaceous strata intersected is 105 m in the borehole RN37337 on Florina Station.

2.2 *Hydrogeology*

2.2.1 Aquifers

Each of the geological units hosts aquifers to varying degrees. The Jinduckin Formation immediately below the Oolloo Dolostone is dominantly siltstone with only localised, fractured rock aquifers, typically yielding less than 2 L/s. On a regional scale it can be considered as an aquiclude because it confines the Tindall aquifer.

Aquifers in the two units of the Oolloo Dolostone (Figure 2-5) have contrasting properties. The “bedded” unit is a fractured rock aquifer with yields generally less than 5 L/s. Fractures are locally enlarged by solution effects. The rock is locally cavernous and where this occurs bores are capable of yields of between 20 and 100 L/s. This is particularly the case in the Douglas/Daly area north of Cadell Rd. No high yields have been encountered south of there but large areas are untested by drilling. The degree of fracturing is sufficient to ensure that the formation acts as a single aquifer over most of its extent. It is also in direct hydraulic connection to the overlying “massive” unit aquifer.



a b

c d

*Plate 2-3 Cretaceous rocks **a**, Basal sandstone/quartzite, Dorisvale Rd. **b**, Cross bedded sandstone. **c**,Silicified claystone, old Victoria Hwy. **d**, Shale at the base of the Cretaceous sequence, Daly River, photos S. Tickell*

The "massive" unit forms a widespread fractured and cavernous aquifer. It owes its existence to the weathering event that occurred prior to the deposition of the overlying Florina Formation. A network of solution cavities is present, ranging in size from less than a millimetre up to a metre across. Existing fractures are also enlarged by the weathering. The solution effects are greatest at the top of the unit and gradually diminish with depth. Apart from enlarged fractures there is also a more pervasive network of sub-millimetre to centimetre scale solution cavities (Plate 2-1c). The total thickness of the highly permeable zone ranges up to a maximum of about 90m. Pumping tests on irrigation bores in the Florina Road. area yield transmissivities ranging from 5,000 to 28,000m^2/d. Hydraulic conductivities derived from these range from 80 to 500m/d.

Although the aquifers in the two units of the Oolloo Dolostone have contrasting properties, they are in direct hydraulic connection with each other and on a regional scale can be considered as a single aquifer. The basal limestone unit of the overlying Florina Formation is also a fractured and locally kastic aquifer, with similar properties to the aquifer in the "bedded" unit of the Oolloo Dolostone. It is also in direct hydraulic connection to the "massive" unit of the Oolloo aquifer.

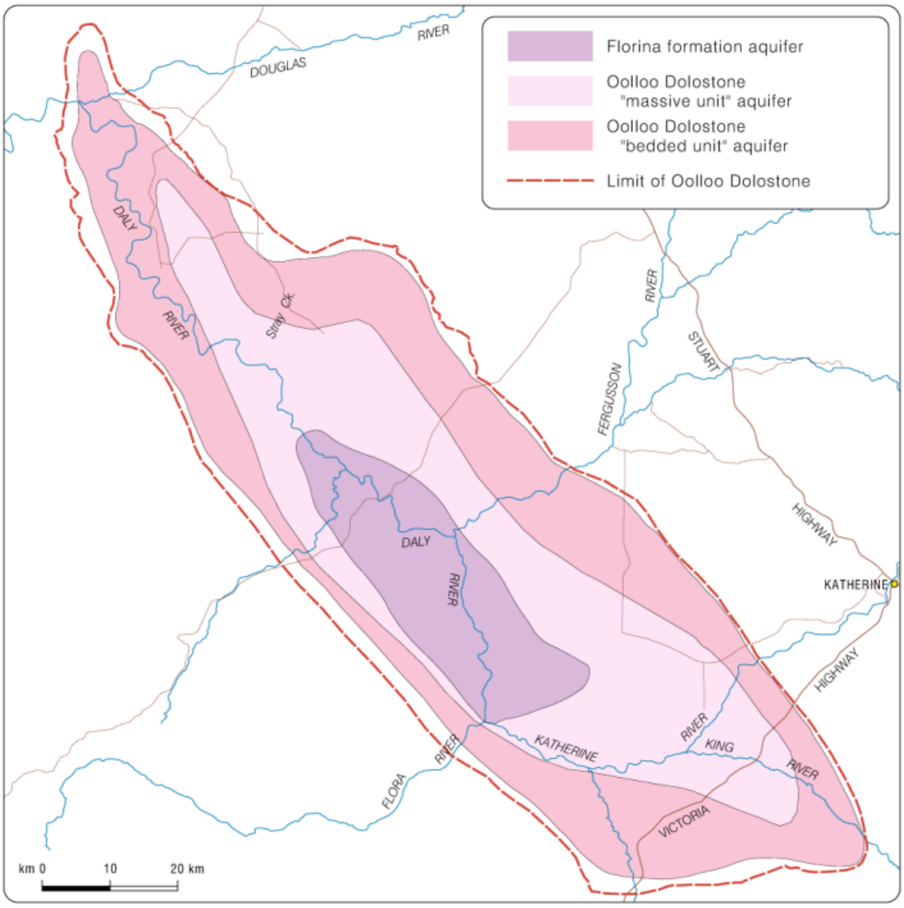


Figure 2-5 Oolloo and Florina aquifers

2.2.2 Recharge

Recharge to the Oolloo aquifer varies across its extent according to the nature of overlying material. Surface geology was used to classify recharge into four zones (Figure 2-6). The zone with the highest potential for recharge is where the “massive” unit is at or near ground surface. In this zone recharge is enhanced by thin soils and occasional open sinkholes and caves providing a direct pathway to the watertable. The highly permeable aquifer can readily accept recharge. Where the “bedded” unit is at or near to the surface, soils are also thin and some karstic channels are also found however the aquifer is generally less permeable and so recharge cannot be accepted at such a high rate. At the other extreme are parts of the aquifer overlain by the Florina Formation where recharge is likely to be negligible. Shaley horizons within the sandstone units make vertical water movement difficult. Cretaceous rocks similarly restrict recharge to the Oolloo aquifer because they are predominantly clay. In places where that unit is thin recharge through the basal sandstone is likely to be higher. These zones only show relative potential for recharge. Recharge is dealt with in more detail in Chapter 5.

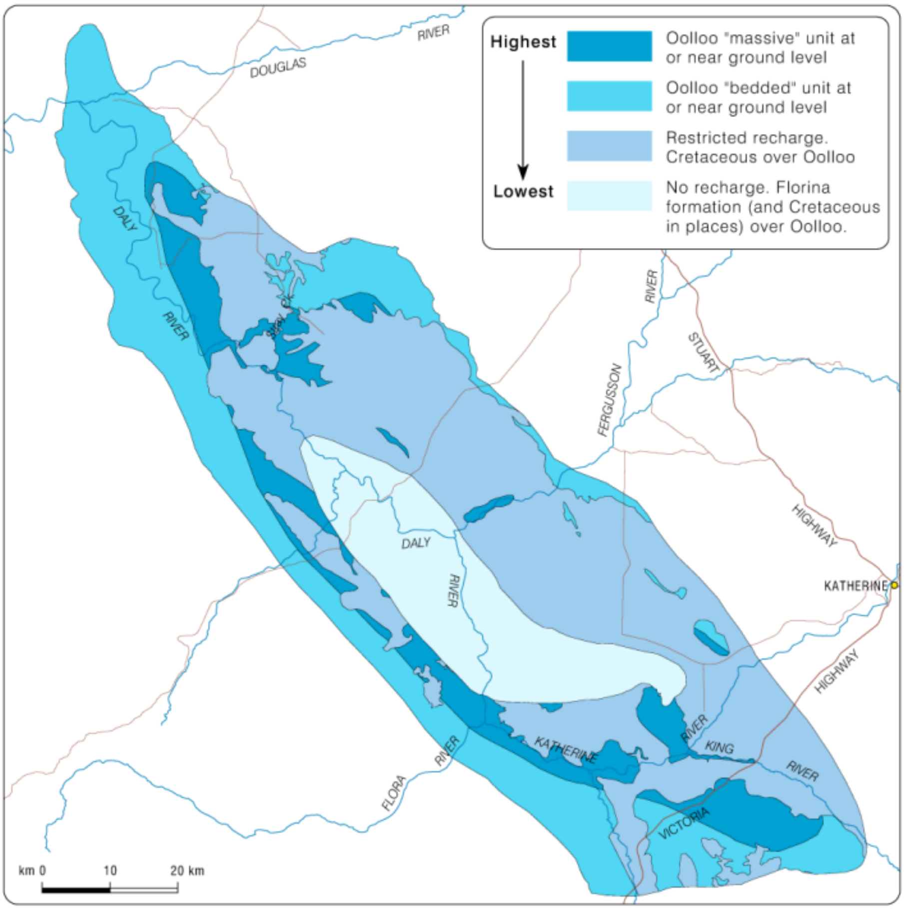


Figure 2-6 Recharge zones

2.2.3 Groundwater Flow

A recent potentiometric surface of the aquifer is shown in Figure 2-7. The regional flow direction is from south east to north west, with contributions coming from higher areas on either side from the basin to the north east and south west. Downstream of the Stray Creek area the flow lines converge on the Daly River. Although the Oolloo aquifer is made up of two main layers with contrasting hydraulic properties, they are interconnected.

2.2.4 Springs

The Daly River upstream of the Douglas River is located along the axis of the Daly Basin, so groundwater naturally drains to the river. Springs occur where the watertable is higher than the ground or river level and where there is a pathway for it to reach the surface.

There are two distinct discharge areas (Figure 2-7), one along the Katherine River and another along the Daly River extending from the Douglas junction upstream for about 60 km. No discharge from the Oolloo aquifer is observed upstream of that point through to the Flora River junction, because it is confined by the Florina Formation. Where Cretaceous strata are present, springs associated with the Oolloo aquifer only occur where the cover is thin and groundwater can pass up through it. The upstream extents of the Katherine, King and Ferguson Rivers also receive no discharge because overlying Cretaceous strata are too thick.

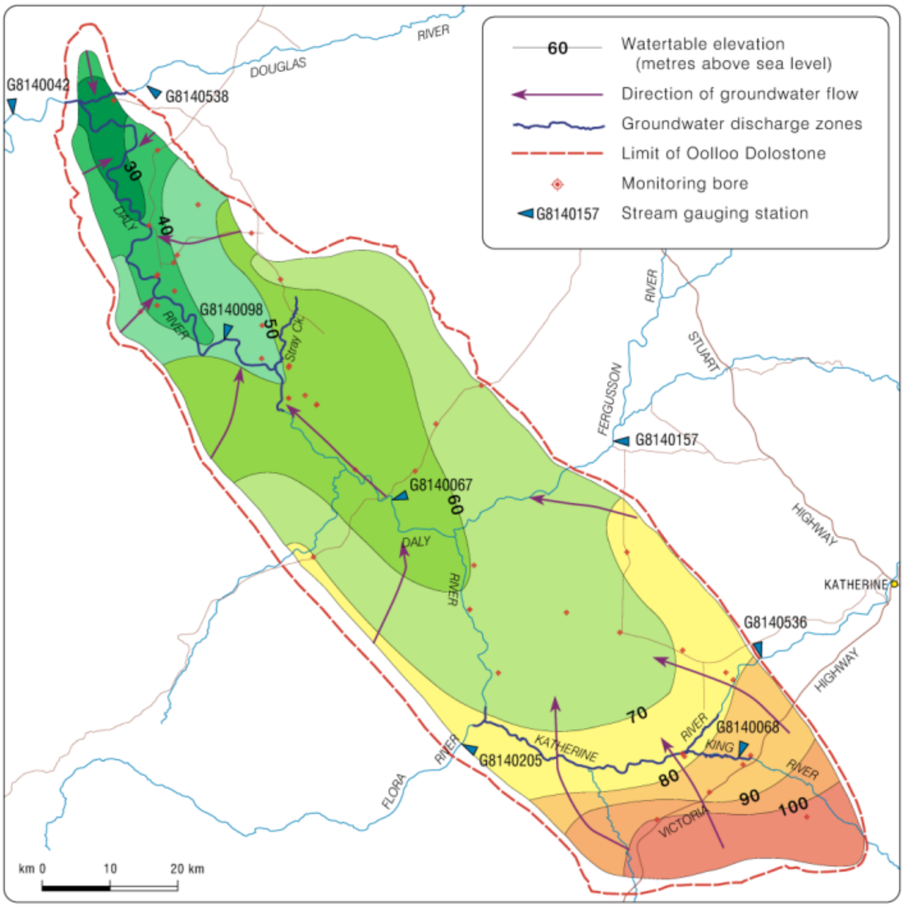


Figure 2-7 Potentiometric surface, Oolloo aquifer, November 2010

Upstream from the Stray Creek junction as far south as the Flora River, there is commonly a brick red soft shale at or close to the base of the Cretaceous (Plate 2-3d). The first springs appear some 8 km upstream of the Stray Creek junction and these coincide with the last outcrop of that shale, almost certainly an important local confining bed. During the Wet season the springs are covered by the river for varying periods of time and are exposed again as the river recedes.

Discharge to the river occurs as distinct point source springs, as broad zones of seepage along the river banks and as concealed springs and seepage zones in the river bed. The first two types were mapped during field surveys (White, 2001 and Tickell, 2002b and 2008). The concealed discharges have been detected by doing stream gaugings and noting progressive downstream increases (or decreases) in flow. Six flow gauging surveys have been conducted in the late Dry season in the Daly Basin since 2002 (Tickell, 2002b, Tickell et al. , 2002, Russ et al. , 2005, Tickell, 2008, Wagenaar et al. , 2009 and Russ et al. , 2011).

Only a few springs which discharge directly from dolostone have been observed (Plate 2-4a). The great majority discharge out of sandy alluvial deposits, Cretaceous sandstone or to a lesser extent from Cretaceous claystone (Plate 2-4b, c and f). In most cases dolostone is thought to be present beneath a thin cover of the younger formations. Field measurements of the water quality can easily distinguish between springs sourced from dolostone and those from Cretaceous rocks. The former have significantly higher electrical conductivities and the pHs are slightly alkaline. The latter have very low electrical conductivities and the pHs are slightly acidic. There are no examples of springs issuing directly from open solution cavities in rock, as is the case with the Tindall Limestone, such as Katherine Hot Spring and Rainbow Spring at Mataranka. The springs with significant discharges are most likely sourced from major solution cavities at shallow depths. Overlying material such as sand or sandstone is permeable enough to transmit the spring water to the surface. In the case of springs in claystone, the rock has collapsed above sinkholes creating fractures and rubble through which groundwater can move. Small basin like structures up to 50m in diameter observed in Cretaceous rocks are also a reflection of karstic collapse beneath.

Several prominent springs located just upstream from Stray Creek have been given names during the course of this project. All have relatively large discharges and are probably formed over karstic collapse features. Each is now briefly described:

- Hill Spring is the southernmost spring in the Daly River that is sourced from the Oolloo aquifer. It has the largest individual discharge, estimated in 2002 to be around 1200 L/s. It is situated on the top of a point bar at a height of about seven metres above the Dry season river level. The spring itself consists of a small swampy lagoon on loose river sand (Plate 2-5a). It is fed through the base of the lagoon and drains to the river via a small creek (Plate 2-5b). On a visit in 2002 the spring only had one outlet but several years later another creek had formed draining in the opposite direction;

- Gravel Bank Spring emerges from a low-lying pebbly sandbar (Plate 2-5c). The sandbar changes its shape with each Wet season flood. At times it is in the centre of the river and at others it is joined to a river bank. Shallow waterholes sometimes develop on the top of the sandbar and these drain to the river via small channels. It is difficult to estimate the discharge as there are usually many outlets but is probably of the order of several hundred litres per second;

- Island Spring is a small rubbly outcrop of Cretaceous claystone in the middle of the river. Water emerges through the rubble and pours into the river (Plate 2-5d). It is also difficult to measure its discharge but it is sufficient to be audible from the bank against the background noise of the river; and

- Black Cockatoo Spring is one of the few springs recorded that is not located in or alongside a stream bed. It consists of an oval shaped swamp on the edge of the floodplain of Stray Creek ((Plate 2-5e). Most of it is tree covered except for the central portion which is reedy with a small area of open water. The outlet is an ill defined creek which joins Stray Creek, not far from its junction with the Daly River. Cretaceous sandstone outcrops on the eastern margin of the swamp but a nearby borehole (RN36817) struck Oolloo Dolostone at a depth of six metres. It is notable that many of the trees have died due to waterlogging since the mid 1990s. An old track is reputed to have run through what is now a permanent swamp (D. Howe, pers. comm.).

Hundreds of individual springs and seepages can be seen along the Katherine and Daly Rivers. The majority have discharges less than a few litres per second. A few exceptional ones have discharges of the order of several hundred litres per second. In most cases it is either not physically possible or is impractical to measure individual discharges. Rough estimates of the visible spring flow account for less than half of the increase in river flow over the same stretch. The majority of groundwater discharge remains unseen through the river bed. To overcome that problem, stream gauging of the rivers and main tributaries have been used to quantify discharges and to locate them geographically. The two most detailed surveys (Tickell, 2002b and Wagenaar et al. 2009) have defined the broad pattern of discharge (Figure 2-8 & Figure 2-9). In October 2009 the Katherine River gained 1 m^3/s with only minor input from the King River. It is the “massive” unit of the Oolloo aquifer that contributes this water. Groundwater levels immediately next to the river in the vicinity of the King River junction were of the order of ten metres above the river level at the time of the survey. Heading downstream into the Daly River the first main input of groundwater begins about 8 km upstream of Stray Creek from which the flow increases from 10.6 to 20.1 m^3/s over a distance of about 10 km. This section is the main discharge zone from the “massive” unit of the Oolloo aquifer and it also has the highest concentrations of visible springs. Downstream from there the river passes over the “bedded” unit and progressively gains a further 4.7 m^3/s over 40km. Groundwater levels immediately next to the river at Oolloo Crossing were also of the order of ten metres above the river level at the time of the survey.

The spring flows also vary seasonally and are highly dependent on rainfall. Figure 2-10 shows the end of Dry season flows at the Mount Nancar (G8140040) and Dorisvale Crossing (G8140067) gauging stations on the Daly River. The former is located downstream of the Daly Basin and the latter is located 20km upstream of the major Stray Creek spring area. Over 80 per cent of the increase in flow between the two stations is due to discharge from the Oolloo aquifer. The remainder is sourced mainly from the Tindall Limestone. Note that the lowest recorded increase in flow between the two stations was 4 m^3/s in 1966 and the largest was 34 m^3/s in 2011. This is directly related to medium term rainfall variations of the order of decades. Higher rainfalls lead to increased recharge, higher groundwater levels (Figure 1-2) and then to increased discharge (spring flows). Individual spring flows have increased and the number of springs is probably greater. When rainfalls revert to pre-1970s levels the reverse situation will apply, i.e. less total spring flow, reduced flow from individual springs and fewer springs. The springs are therefore dynamic features that change geographically and over time.

Another consequence of the above average rainfalls is that groundwater levels have been very high since the mid-1990s (Figure 1-2). Springs currently occur in the river banks up to ten metres above the late Dry season river level. Saturation of the banks has led to widespread slumping since that time (Plate 2-4d, e). The amount of sand carried by the river is anecdotally reported to have increased in recent years. If this is correct then the widespread bank slumping is an obvious source of sediment. The observation that the river is generally flanked by steep banks suggests that slumping was nowhere near as common in the recent past, say the past one hundred years. Steep banks could not be maintained if slumping on the present occurred had occurred over a long period.

*Plate 2-4 Springs, **a** Spring emerging from fractures and bedding planes in the "bedded" unit of the Oolloo Dolostone. **b**, Spring in alluvial sands, note "boiling" sand. **c**, Spring in river bank, emerging from alluvium. **d**, Springs at the base of a landslip. **e**, Spring emerging from alluvial gravels. The fault marks the base of a landslip to its left. **f**, Spring in alluvial sands, photos S. Tickell*

Plate 2-5 Major springs. a, Pool at the source of “Hill” Spring. b, Outlet of “Hill” Spring. c, “Gravel Bank” Spring. d, “Island” Spring. e, “Black Cockatoo” Spring, note the dead trees, photos S. Tickell

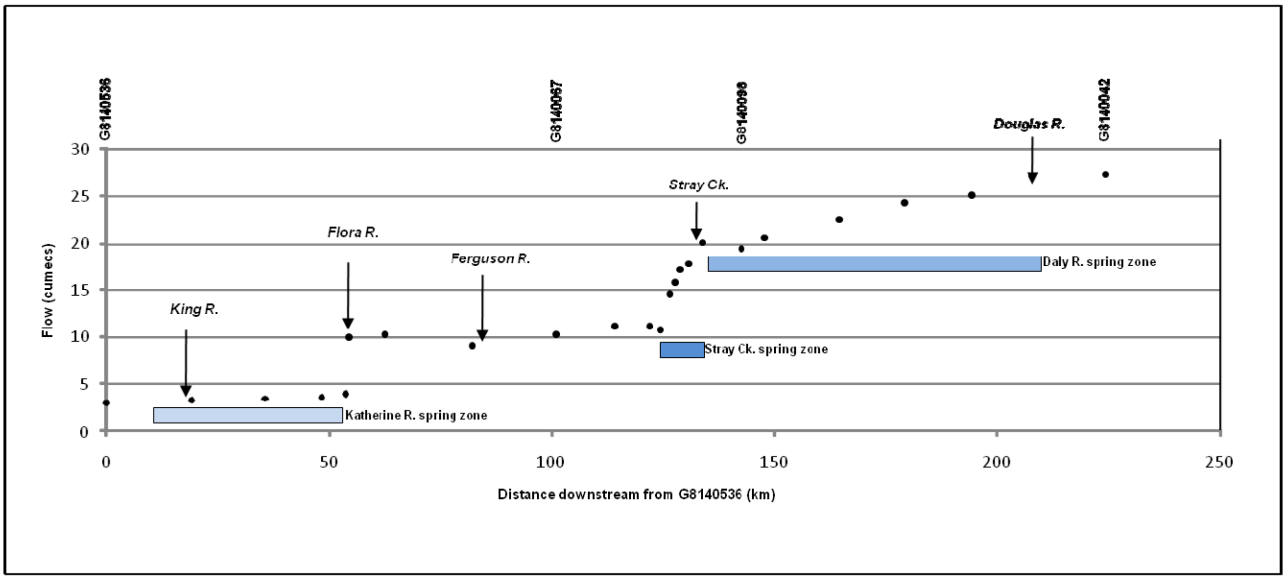


Figure 2-8 Stream flows, October 2009, section along the Katherine/Daly Rivers from G8140536 to G8140042, note that the Flora River contributed 4.3 m^3/s , sourced mainly from the Tindall aquifer.

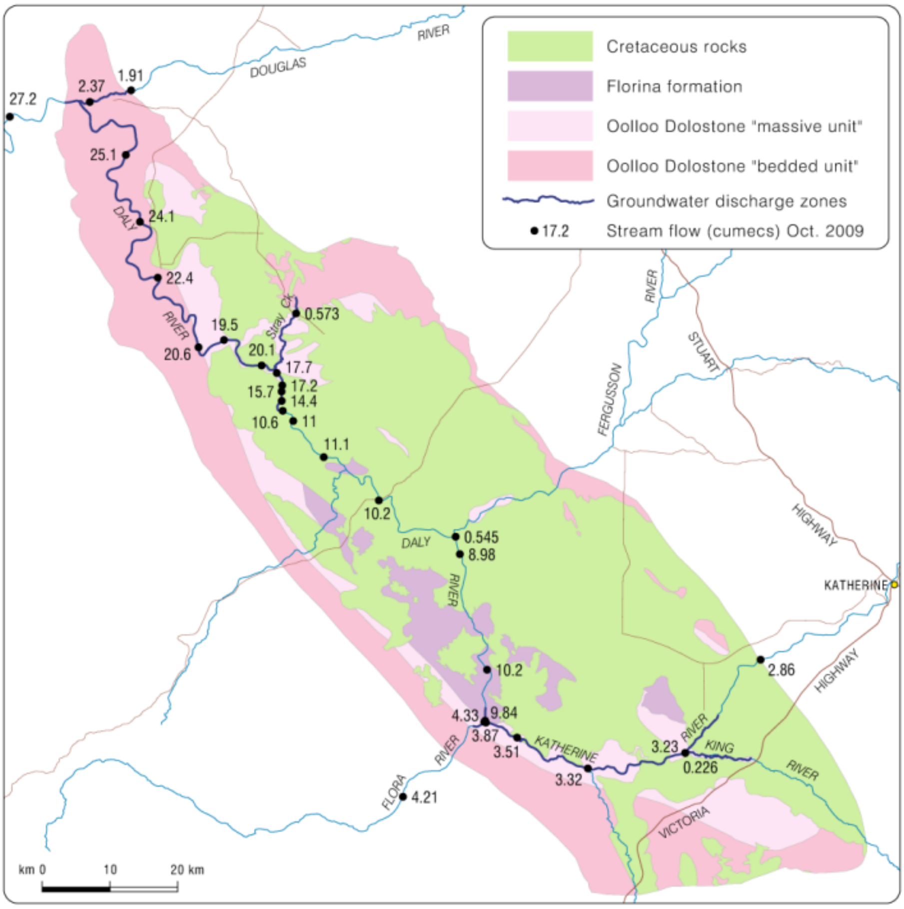


Figure 2-9 Stream flows, October 2009

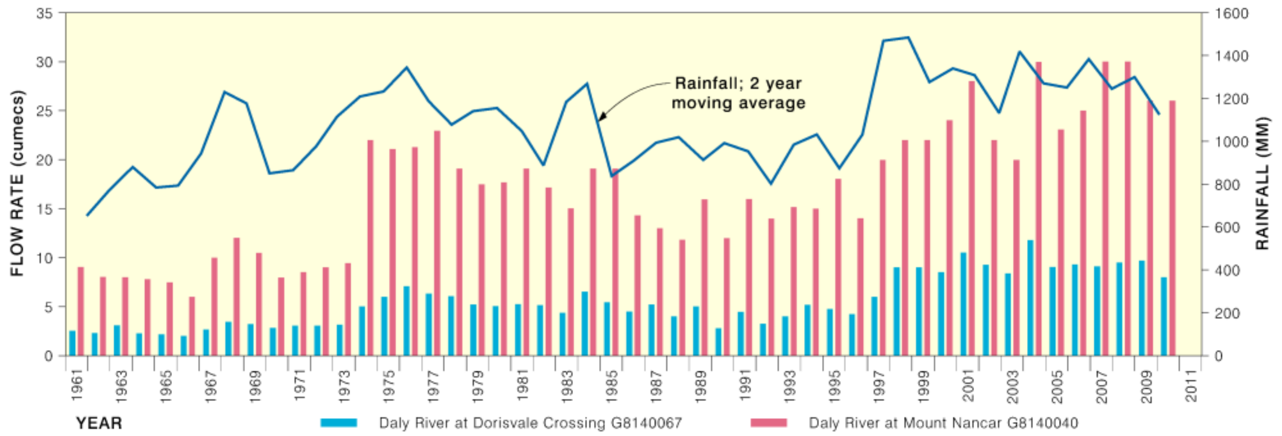


Figure 2-10 Annual minimum river flows and rainfall (Katherine).

An attempt was made to relate groundwater levels to spring discharge. Groundwater levels could act as an easily measured surrogate for spring discharge and could potentially be used to assess the impacts of local groundwater pumping on spring flows. To this end spring discharge, represented by the difference in Dry season flows between G8140098 and G8140067 were plotted against groundwater levels in the bore RN34367. The two gauging stations are situated downstream and upstream respectively of the section of the river with the largest groundwater inflow (Figure 2-7). The borehole is situated 13km downstream of G8140098. Records for only three Dry seasons are available because the downstream gauge was only installed in 2008. It is apparent that there is a different relationship between groundwater level and spring discharge for each of the Dry seasons plotted. At this stage the reason for this is unknown but possibilities may be that there is more than one source of water or that the relationship is affected by the hydraulic properties of the karstic "plumbing" of the aquifer.

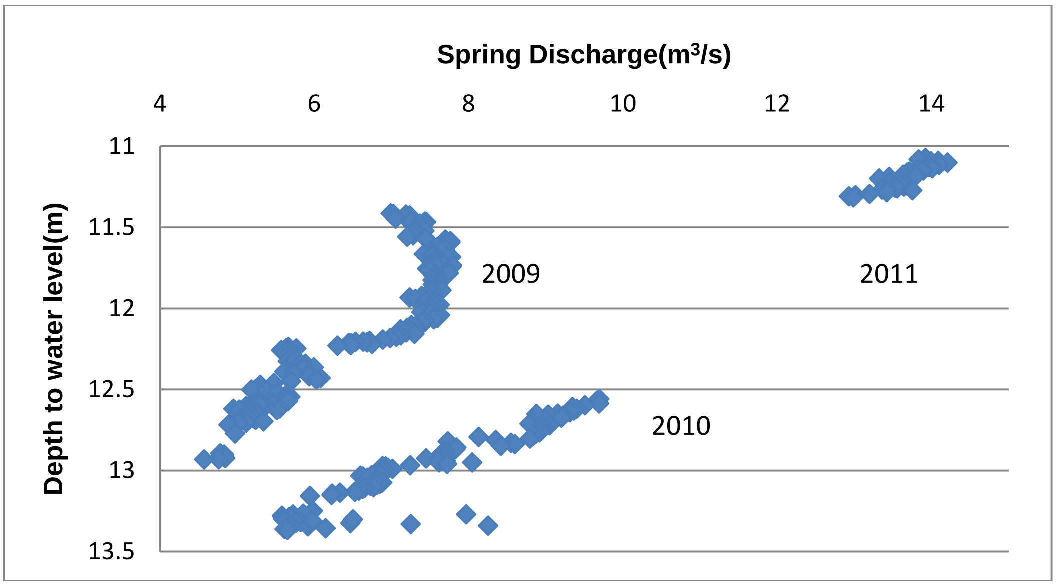


Figure 2-11 Spring discharge vs groundwater level(RN34364)

The Daly and Katherine Rivers support a range of flora and fauna that depend on the perennial or near perennial flows which in turn are controlled by the spring flows. Even though no species have yet been described that only live at spring outlets, much of the flora and fauna of the river could be described as "spring dependent". Maintaining the health of those ecosystems therefore requires that the spring flows be kept within specified limits. Studies conducted on fish, the pig nosed turtle, Vallisneria (a riverine plant), periphyton, phytoplankton and riparian trees have been utilised to determine the environmental water requirements of these elements (Erskine et al. (2003) and Erskine et al. (2004)). The guiding principles of Erskine (2003) Erskine et al. (2004) have been the basis for the deployment of the Oolloo WAP where minimum flows at Oolloo Crossing will trigger either reduction or cessation of major water extractions.

2.2.5 Monitoring network

Groundwater levels in the Oolloo aquifer are monitored by a network of 43 bores (Figure 2-7), 14 of which were drilled as part of the current project. There are eight gauging stations on the Daly River and some main tributaries that are either within the area of the Oolloo aquifer or immediately upstream or downstream of it. Several of these were only recently installed under The Australian Government's Watersmart Australia program, specifically to monitor baseflows originating from the Oolloo aquifer.

2.3 *Key Findings*

- The extent of the Oolloo aquifer has been considerably refined;
- A newly recognised geological unit, the Florina Formation has been confirmed as overlying the Oolloo aquifer and its extent has been mapped. It acts as a confining layer to the Oolloo aquifer;
- The aquifer was formed some 490 million years ago when the Oolloo Dolostone was exposed to the atmosphere and subjected to weathering. The sea returned and deposited the Florina Formation on top of the karstified Dolostone;
- Conceptual recharge zones have been mapped based on an updated knowledge of the geology;
- Groundwater discharges from the Oolloo aquifer via springs along the Daly and Katherine Rivers. The main springs have been mapped but the sum of their discharges is much less than total discharge as measured by stream gauging. Seepage from riverbeds accounts for the bulk of the inflow. Stream gauging surveys have identified where the spring/seepage zones are and the amounts that each discharge; and
- There is considerable natural variation in spring flows of the order of decades related to rainfall variations.

3 Hydrochemistry of the Oolloo aquifer

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The Oolloo aquifer supports water consumptive industries including irrigated agriculture and horticulture, forestry and pastoral operations. Generally, groundwater from the Oolloo aquifer is of good quality, however there is a poor understanding of the hydrochemical conditions for aquifers in the Daly Basin. Dissolved constituents reflect both naturally occurring hydrochemical processes (e.g., ion evolution along a flow path) and alterations due to anthropogenic activity (e.g., different water-rock interaction in pumping zones, introduction of agricultural chemicals, changes in redox conditions). Adequately characterising hydrochemical conditions underpins further investigation of potential effects that might be imposed by water consumptive and other operations.

The Cambrian-Ordovician Daly Basin is comprised of four distinct layers, which from bottom to top are the Tindall Limestone aquifer, the Jinduckin Formation (siltstone and mudstone aquitard), the Oolloo Dolostone aquifer, and the Florina Formation. Overlying the Daly Basin are discontinuous Cretaceous sediments, which are predominantly clay and sand. Carbonate terrain such as these often have complex hydrochemical conditions. Infiltrating rainwater promotes dissolution of carbonate minerals, forming a karstic system that can have extremely variable flow pathways (i.e., combination of highly permeable conduits within a permeable rock matrix).

The aim of this chapter is to characterise the chemical and nutrient composition of groundwater in the Oolloo aquifer. Characterisation will aid understanding of groundwater interaction between major hydrostratigraphic units (e.g., formations over- and underlying the Oolloo) and will provide a background on the nature of nutrient mobility.

3.1 *Methods*

Hydrochemical characterisation followed a regional-approach, whereby the field investigation focussed on sampling groundwater from bores that spanned the extent of the Oolloo aquifer (n = 34;Figure 3-1). A few additional water samples were collected from the Daly River (n = 6), Cretaceous sand aquifer (n = 6), and the Jinduckin Formation (n = 4).

Water samples were collected in November 2009, June 2010, and August 2011. At each bore, dissolved oxygen, pH, Eh, EC and temperature were continuously monitored in a flow cell. Samples were collected once the bore had been purged and the aforementioned parameters had stabilised. Samples were field filtered and those collected for cation/metal analysis were field acidified using AR grade nitric acid (HNO_{3-}). Samples were refrigerated from time of collection until time of analysis. Nutrient and DOC analyses were performed at the Northern Territory Environmental Laboratories by standard colorimetric methods. Anion analyses were determined by ion chromatography (IC) and cation/metal analyses determined by inductively coupled plasma optical emission spectroscopy (ICP-OES) at the CSIRO Land and Water Analytical Laboratory (Waite Campus, Adelaide, Australia).

For samples collected in November 2009 and June 2010 additional field and laboratory analyses were conducted. Fe^{2+}, Mn^{2+} and HS^- concentrations were

determined in the field using a portable spectrophotometer (HACH). Alkalinity was determined in the field using a digital titrator (HACH). $\delta^{13}C$ of dissolved inorganic carbon (DIC) was determined by Isotope Ratio Mass Spectrometry on an aliquot of CO_2 at CSIRO Isotope Analysis Service (Waite Campus, Adelaide, Australia) and results are expressed as parts per thousand (‰) relative to the standard Pee Dee Belemnite (PDB) formation. Water samples were also collected for Sulphur isotope composition, but insufficient sulphur was present to perform the analysis.
In addition to the above hydrochemical analyses, groundwater samples were collected from bores in the Oolloo Crossing and Stray Creek areas in November 2009 for analysis of the strontium isotope ratio ($^{87}Sr/^{86}Sr$) of dissolved strontium. Strontium isotopes were trialled as a means of investigating whether there was evidence of inter-aquifer leakage between the Oolloo aquifer and the Cretaceous sediments or Jinduckin Formation, respectively. $^{87}Sr/^{86}Sr$ analysis was performed by University of Adelaide using Thermal Ionisation Mass Spectrometry after the dissolved Sr had been concentrated with ion-specific exchange resins.

3.2 *Results*

3.2.1 Hydrochemical Composition

The chemical composition of almost all Oolloo groundwater samples is Ca-Mg-HCO_3 dominated, consistent with the dolomite matrix of the aquifer (Figure 3-2). Two samples from the Oolloo (RN20614 and RN32751) reveal different compositions (Na-HCO_3 and Ca-Mg-SO_4) possibly reflecting inter-aquifer leakage from the overlying Cretaceous aquifer and underlying Jinduckin Formation, respectively. Groundwater samples from the Jinduckin Formation range from Ca-Mg-HCO_3 to Mg-Ca-HCO_3 dominated, most likely reflecting the mineralogy of the underlying and confined Tindall Limestone aquifer and, where downward hydraulic gradients exist, the overlying Oolloo aquifer. Importantly, groundwater samples from the Cretaceous sand aquifer are distinct in their chemical composition from those of the Oolloo and Jinduckin formations; although they do exhibit a range of compositions from Ca-Mg-Cl type to Na-HCO_3 type.

Plotting major ion concentrations relative to chloride concentration enables interpretation of hydrochemical trends after accounting for the effects of concentration by evapotranspiration. As should be expected in this carbonate-rich basin, the major ions that exhibit strongest trends in groundwater are calcium, magnesium and bicarbonate (Figure 3-3). These plots suggest that either one or a combination of the following two mechanisms is occurring: (i) progressive concentration of recharge water is resulting in removal of HCO_3 from solution by precipitation of dolomite, or (ii) the composition of all groundwaters (and springs, the river etc.) can be explained by a two component mixture of waters: one relatively “fresh” (i.e. low Cl) end-member with high HCO_3/Cl and the other slightly more “saline” (i.e. higher Cl) end-member with low HCO_3/Cl. Given the lack of clear linear mixing trends in the Piper diagram (Figure 3-2) we propose that the range of groundwater compositions observed in the Daly Basin are reflective of both water-rock interactions and mixing between distinct end members.

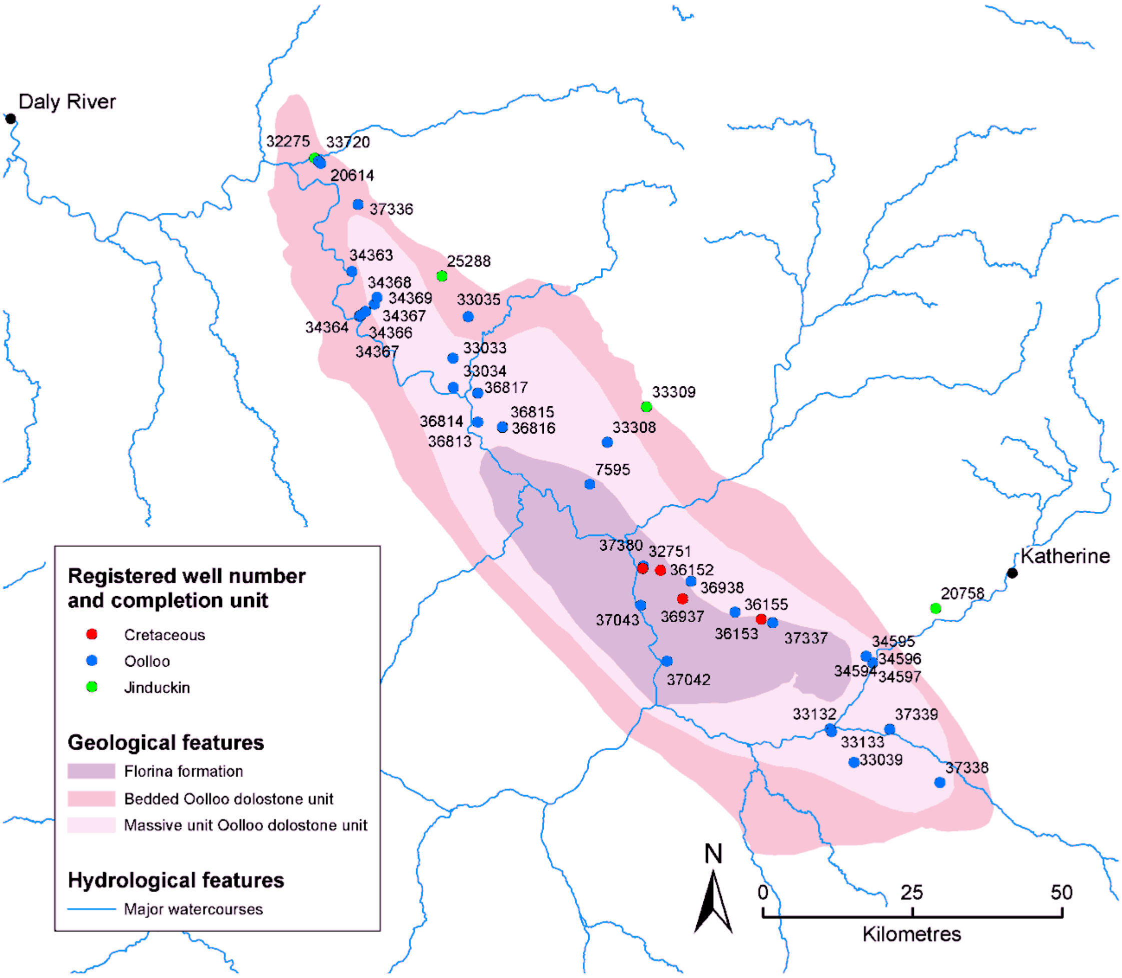

Figure 3-1 Geologic formations of the Daly Basin and location of groundwater bores sampled, differentiated by geologic unit.

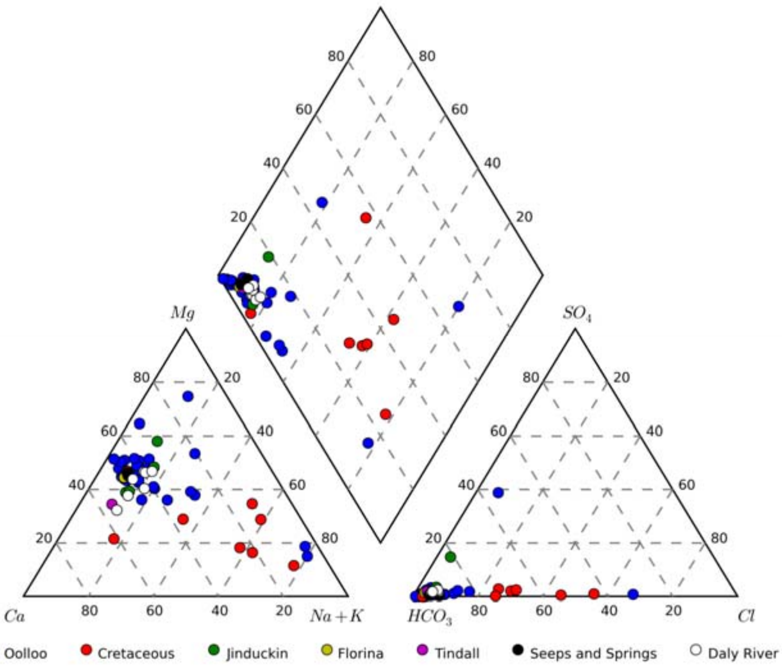

Figure 3-2 Piper diagram showing composition of water samples from each formation sampled, as well as river samples, seeps and springs.

Groundwater in the Cretaceous sand aquifer generally has low dissolved inorganic carbon, most of which is probably derived by equilibration of recharging water with soil CO_2 gas (Figure 3-4). In contrast, Oolloo and Jinduckin groundwater is relatively high in DIC, and the stable carbon isotope composition of this DIC is consistent with congruent dissolution of a marine carbonate matrix by dissolved soil CO_2 gas (Figure 3-4). Further support for this mechanism is provide by the saturation index of samples with respect to dolomite; all but one sample from these two formations is saturated with respect to dolomite (Figure 3-4b) and calcite (not shown).

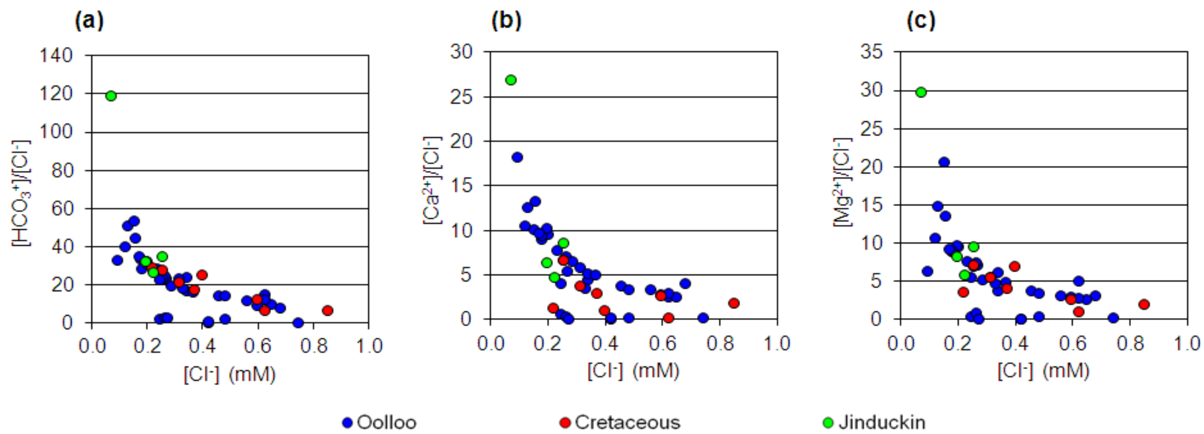

Figure 3-3 Major ion / chloride ratios versus chloride concentration for (a) bicarbonate, (b) calcium and (c) magnesium in water samples from each formation sampled, as well as river samples, seeps and springs.

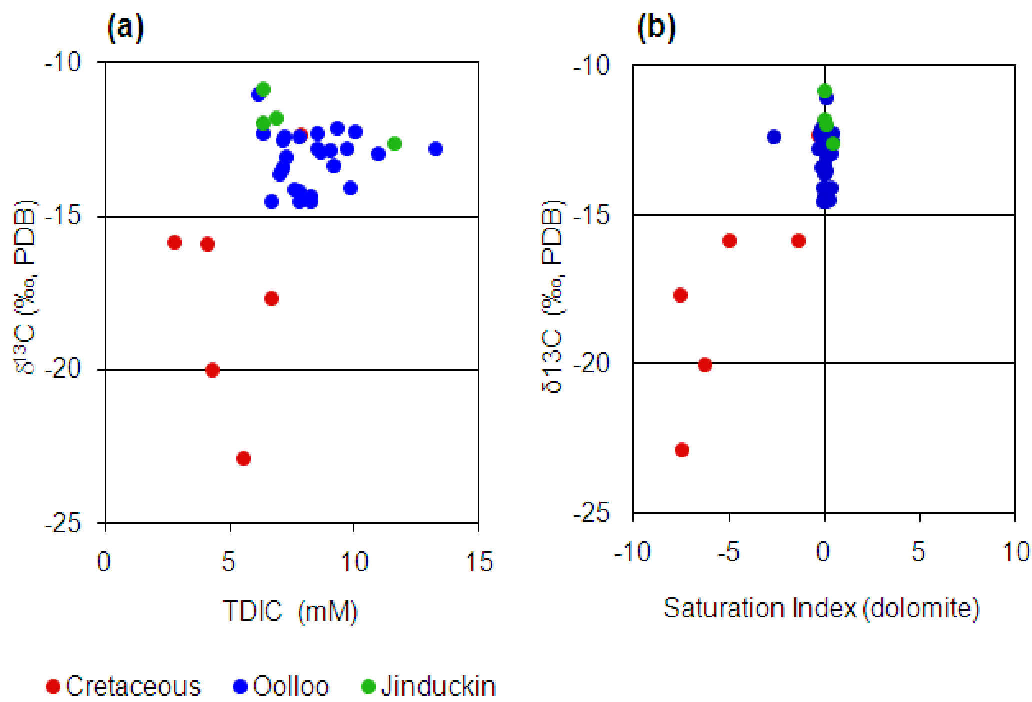

Figure 3-4 Stable carbon isotope composition of Total Dissolved Inorganic Carbon (TDIC) in groundwater samples versus (a) TDIC concentration, and (b) saturation index with respect to dolomite.

3.2.2 Nitrate in groundwater

Concentrations of nitrate in groundwater in this system are very low, with all samples returning less than 2 mg/L as N, and more than three quarters of samples having less than 0.5 mg/L as N (Figure 3-5). This finding is consistent with observations of very low soil N throughout the Daly Basin (pers. comm., Lindsay Hutley, 2011). Higher concentrations are generally found where dissolved oxygen is present and the concentrations of iron (II) are low – that is, conditions unfavourable for nitrate reduction. Conversely, low nitrate concentrations are often found where DO is low and iron (II) concentrations relatively high. This observation suggests the aquifers may have some capacity (or at least characteristics) for attenuating nitrate should surface loadings of nitrogen increase in future.

Further evidence of denitrification is seen in the profiles of nitrate concentration versus depth to water table and depth of sample below water table (Figure 3-6) in both cases deeper groundwater generally has lower nitrate concentration. Unfortunately, no further correlations have been observed, for example with potential electron donors such as DOC or Mn^{2+}.

3.2.3 Strontium Isotopes

The results of analysing seven groundwater samples – five from the Oolloo aquifer and two from the Cretaceous aquifer – for $^{87}Sr/^{86}Sr$ composition provide insight to processes of inter-aquifer leakage, supported by Cl^- concentration and/or Ca^{2+}/SO_4^{2-} ratios for the same samples (Figure 3-7). Oolloo aquifer samples can be broadly categorised into three different groups, the first (RN36817) is for groundwater at Stray Creek close to the Daly River, which exhibits a value ~0.706 consistent with marine carbonate deposited in the Cambrian-Ordovician (Burke et al., 1982). In this area there is an upward hydraulic gradient towards the overlying Cretaceous aquifer, and the measured $^{87}Sr/^{86}Sr$ composition of groundwater from this aquifer (one sample) suggests vertical leakage from the Oolloo aquifer is occurring in this area.

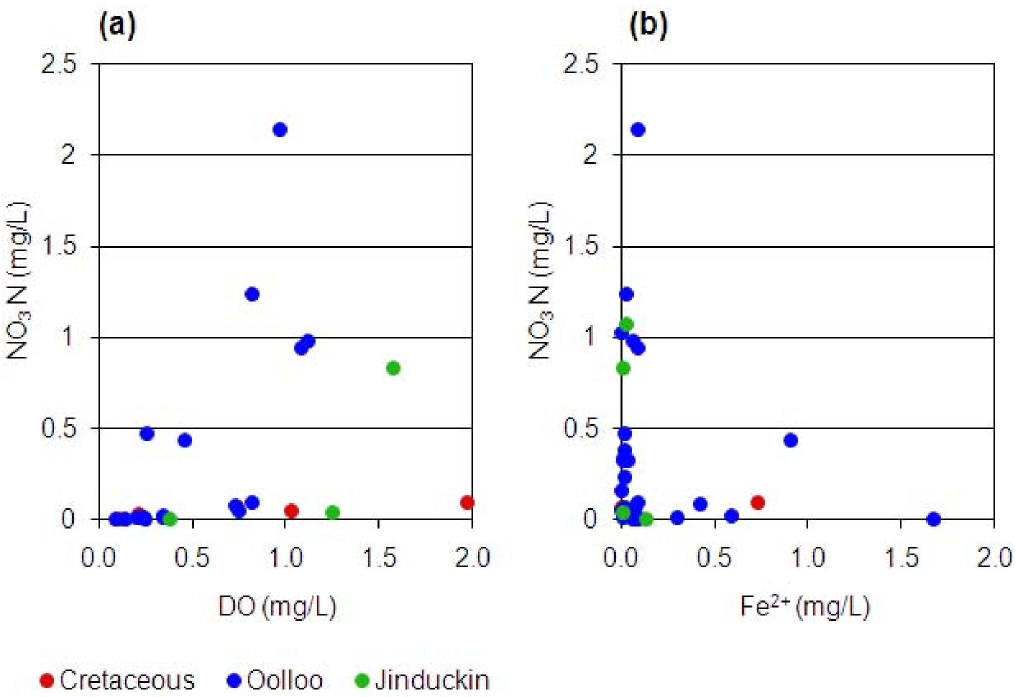

Figure 3-5 Nitrate concentration (expressed as mg/L N) in groundwater samples versus (a) dissolved oxygen concentration, and (b) iron (II) concentration.

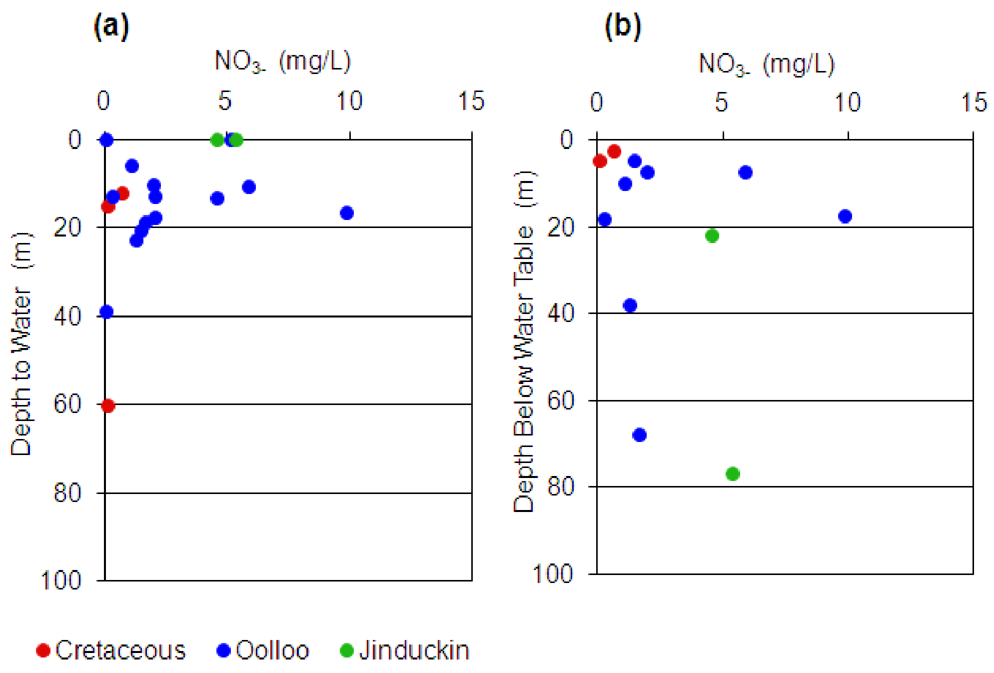

Figure 3-6 Nitrate concentration as a function of (a) depth to water table at sampling point, and (b) depth of sample below water table.

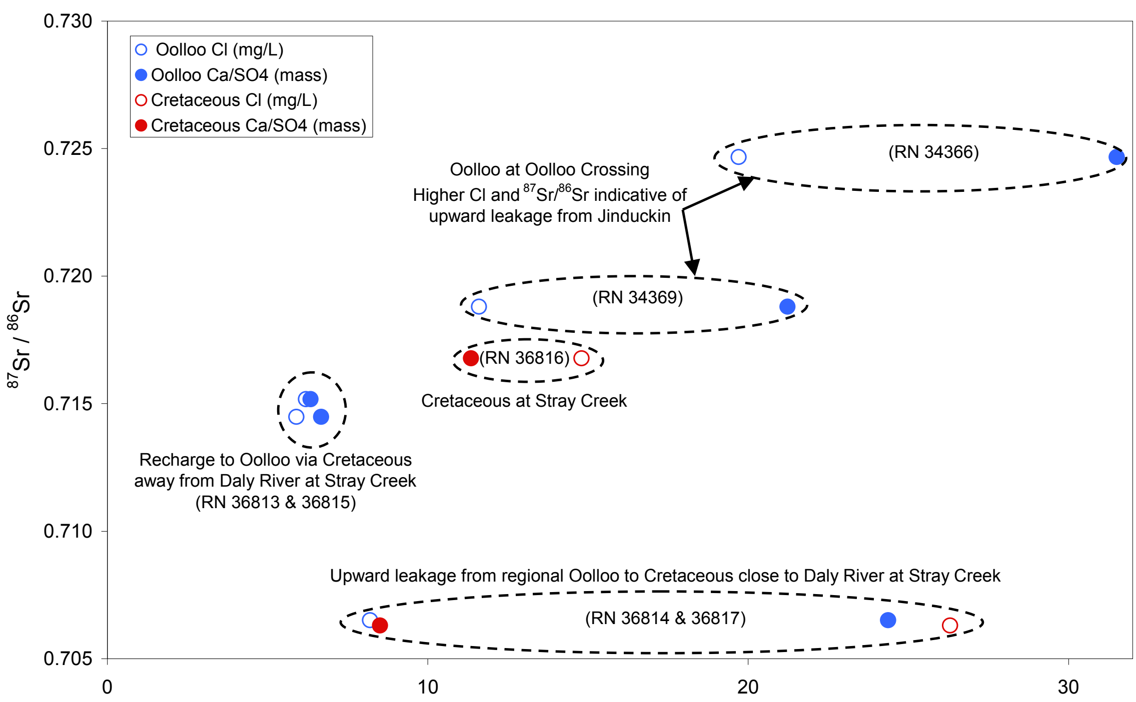

Figure 3-7 Strontium isotopic ratio versus chloride concentration and Ca/SO4 mass ratio (both plotted on the horizontal axis) for selected Oolloo and Cretaceous aquifer samples.

The second group (RN36813, RN36815) is for groundwater on the Stray Creek transect further from the Daly River, where there is downward hydraulic gradient from the overlying Cretaceous aquifer. The $^{87}Sr/^{86}Sr$ composition of groundwater from the Oolloo aquifer at these sites is more radiogenic than the first group (i.e. higher ratio), indicative of water-rock interactions with more siliceous sediments, such as the overlying Cretaceous aquifer. Thus there is evidence of downward leakage from the latter into the Oolloo aquifer at distance from the Daly River.

The third group of (RN34366, RN34369) groundwater samples from the Oolloo aquifer are from the Oolloo Crossing transect and exhibit much more radiogenic $^{87}Sr/^{86}Sr$ compositions than the first two groups and both samples from the Cretaceous aquifer (Figure 3-7). When combined with knowledge that the same groundwater samples have a component of very old groundwater (Chapter 4), this data suggests the Oolloo aquifer may be receiving upward leakage from the Jinduckin Formation in this area.

3.3 *Key Findings*

Preliminary hydrochemical and strontium isotope analysis of groundwater samples from the Daly Basin has revealed most groundwater in the Oolloo aquifer has a Ca-Mg-HCO_3 dominated composition, consistent with weathering of its dolomitic matrix. Groundwater sampled from the Jinduckin Formation exhibits similar compositions, while groundwater in the Cretaceous sediments has a range of compositions from Ca-Mg-Cl to Na-HCO_3 type.

Some groundwater sampled from the Oolloo aquifer has hydrochemical compositions that suggest mixing with water from either the overlying Cretaceous sediments (where existent) or underlying Jinduckin Formation. Limited $^{87}Sr/^{86}Sr$ analyses provide further support for inter-aquifer leakage; depending on local hydraulic gradients there evidence of both upward leakage from the Oolloo aquifer into the Cretaceous sediments (close to the Daly River) and vice-versa (farther from the Daly River). Radiogenic groundwater $^{87}Sr/^{86}Sr$ compositions in the Oolloo aquifer around Oolloo Crossing may be indicative of upward leakage into this aquifer from the underlying Jinduckin Formation.

Nitrate concentrations in groundwater are very low – less than 2 mg/L as N – in the area studied. There are no clear relationships between nitrate concentration and either other dissolved chemical properties or the physical setting. Groundwater sampling followed a regional approach utilising existing bores that were completed to various depths. Future investigation of nitrogen mobility would benefit from discrete sampling from bores completed close to the water table in order to better represent local recharge conditions. However, the broad trends in dissolved oxygen and iron(II) concentration, coupled with the fact that measured concentrations are so low, suggests there may be some capacity for denitrification to mitigate potential future nitrogen contamination of the groundwater.

4 Surface Water – Groundwater Interaction

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Groundwater maintains Dry season flow in the Daly River, which supports a diverse aquatic ecosystem. The Dry season flows are thought to be maintained by a combination of springs and discrete seepage from the river bank, since the Daly River flows occur regardless of the previous season's river flow or rainfall. The source of baseflow is an important, yet understudied component of the groundwater cycle, which is critical for environmental conditions that sustain in-stream aquatic habitat and the near-stream ecologic state (Hayashi and Rosenberry, 2002). In the vicinity of the study area, the Oolloo aquifer contributes approximately 5 GL/year of water for irrigated horticulture, and there is increasing pressure to further develop this resource, which is licensed for 25 GL/year. Balancing the apparent competition between the environment and agriculture for groundwater resources will rely on characterising groundwater interaction between the Daly River and Oolloo aquifer.

Several techniques exist for identifying the location and rate of groundwater interaction with rivers. Flow gauging indicates that annual river flows are dominated by Wet season events and Dry season flows represent only a small fraction of total annual flow. However, in the vicinity of major springs, the Daly River flow increases by approximately 2.5 times at the end of the Dry season. Thus, flow gauging readily identifies segments of the river that receive additional baseflow. Environmental tracers have also proven to be very useful in characterising groundwater interaction. Cook et al. (2003) developed a method for estimating groundwater influx to surface water by sampling of ^{222}Rn and CFCs along the Daly River in 2000 and 2001.

The aim of this chapter was to investigate groundwater interaction with the Daly River, identify the source of baseflow, and develop a conceptualisation of the groundwater age distribution in the Oolloo aquifer. A suite of environmental tracers was used (^{222}Rn, CFCs, SF_6, ^{14}C, and ^{4}He), that spans multiple time scales, collected from the river, springs, and groundwater from observation bores that were installed in 2004, unavailable at the time of the study by Cook et al. (2003). Interpretation of the tracer concentrations combined with a one-dimensional model to simulate tracer concentrations in the river identified the proportion of older groundwater from regional sources, compared to modern groundwater recharged seasonally on the floodplain.

4.1 *Methods*

Field investigation focused on locations where visible springs and seeps intersected the Daly River (Figure 4-1), and utilised a suite of environmental tracers that would identify the location and approximate rate of groundwater discharge (^{222}Rn) and the potential to differentiate modern versus old water (CFCs, SF_6, ^{14}C, ^{4}He). Atmospheric concentrations of chlorofluorocarbons (CFCs) and sulphur hexafluoride (SF_6) have increased steadily since the 1950s and have become ideal age tracers of modern water (Figure 4-2). Recharging groundwater also contains radionuclides from the atmosphere that decay asymptotically. In groundwater studies, radiocarbon (carbon-14) can be used to identify waters less than 50,000 years old. Within groundwater flow systems, the concentration of helium-4 accumulates due to alpha decay of aquifer solids and has become an ideal tracer of old water.

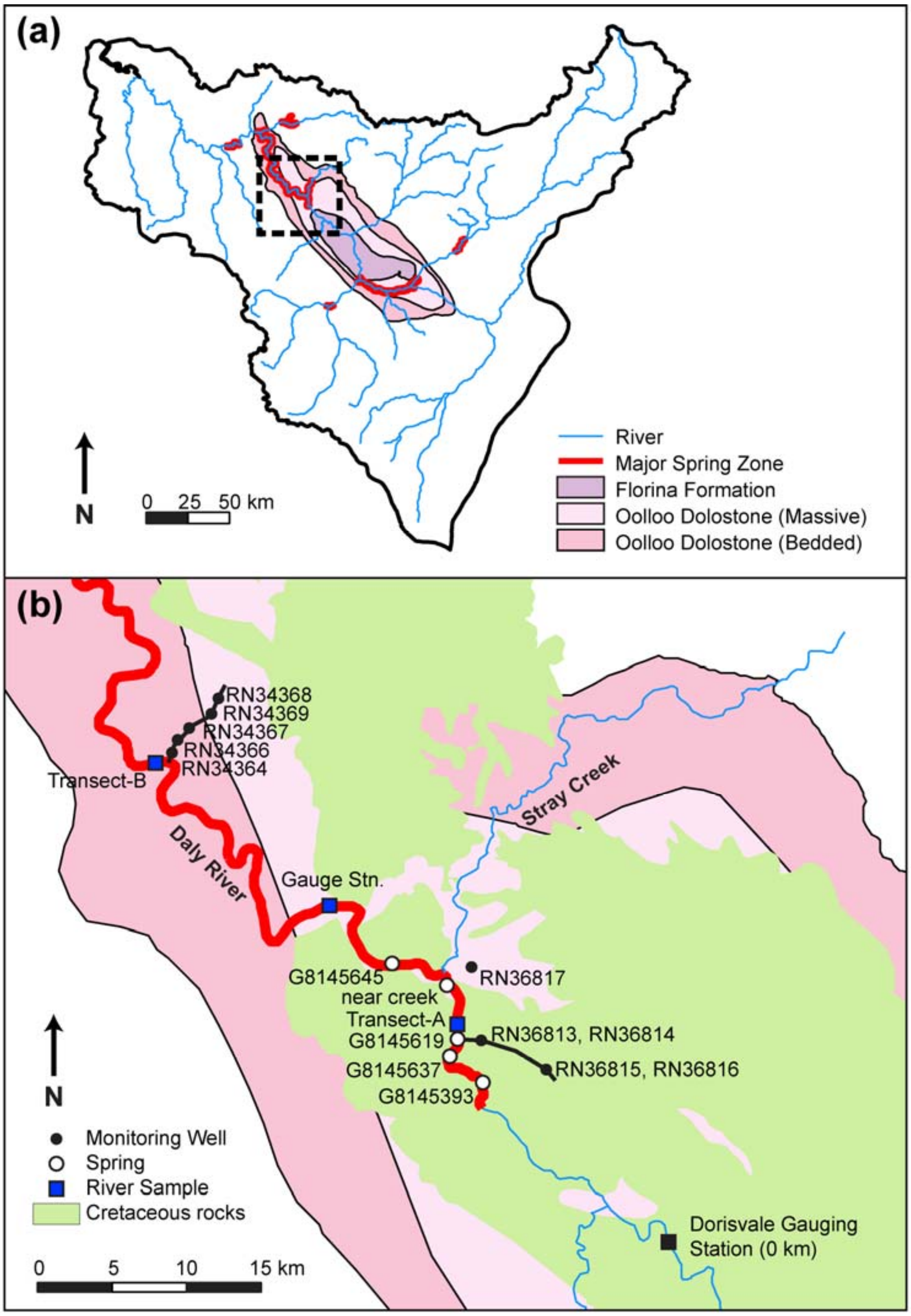

Figure 4-1 a The Daly River catchment and geologic formations of the Daly Basin. (b) Location of groundwater, spring, and river sampling sites for region outlined in (a).

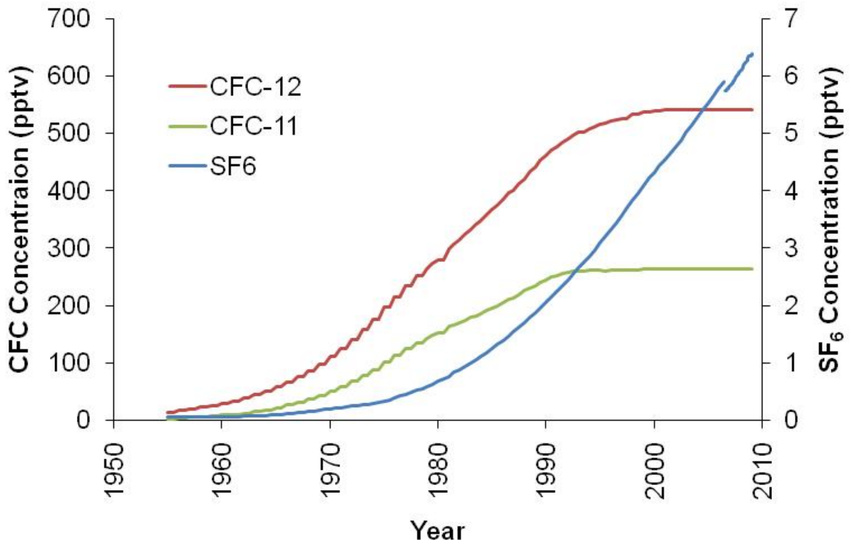

Figure 4-2 Atmospheric concentrations of CFCs and SF_6.

The combination of these environmental tracers would identify young water cycling through the shallow aquifer system and much older water contributing to the Daly River from a regional-scale groundwater flow system. Along the river in the study area, two transects of observations bores were identified to study interaction with the Oolloo aquifer (Figure 4-1). Each transect extends 8 km from the river and has bores completed in the Oolloo aquifer (Figure 4-3). Cretaceous sediments (overlying the dolostone) are present on Transect-A and additional observations bores had been installed to monitor groundwater conditions above the Oolloo aquifer.

Water samples were collected from the observations bores and at three locations in the Daly River in November 2009 and analysed for ^{222}Rn, CFC-11, and CFC-12. November is the end of the Dry season, and annual low flow gauging on the Daly River was completed by the Northern Territory Government in October 2009 (10.2 m^3/s at the gauging locations upstream of the study area). Sampling during low flow conditions was completed to compare with the results of sampling by Cook et al. (2003), during similar low flow conditions (10.3 m^3/s) nearly a decade previously. Water samples were then collected from the observations bores, the same three locations in the Daly River and at five springs in May 2010 and analysed for ^{222}Rn, CFC-11, CFC-12, SF_6, and ^4He. May was the earliest time that is logistically possible to access observations bores and springs on the Daly River, which was flowing at 28.5 m^3/s during sampling. For radiocarbon dating, only a subset of water samples were analysed, including 7 from the observation bores (collected in November 2009) and two from springs (collected in May 2010).

Groundwater from the observations bores was sampled after being purged and after temperature, electrical conductivity (EC), pH, and dissolved oxygen (DO) had stabilised in a continuously monitored flow cell. Water samples were collected from spring pools located at discharge orifices using a portable peristaltic pump and from the river either by sample bottle submersion near the river bank (November 2009) or by portable peristaltic pump from a small boat near the middle of the river (May 2010). Distances along the study segment of the Daly River are relative to the gauging station at Dorisvale (Figure 4-1) to remain consistent with distances reported by Cook et al. (2003).

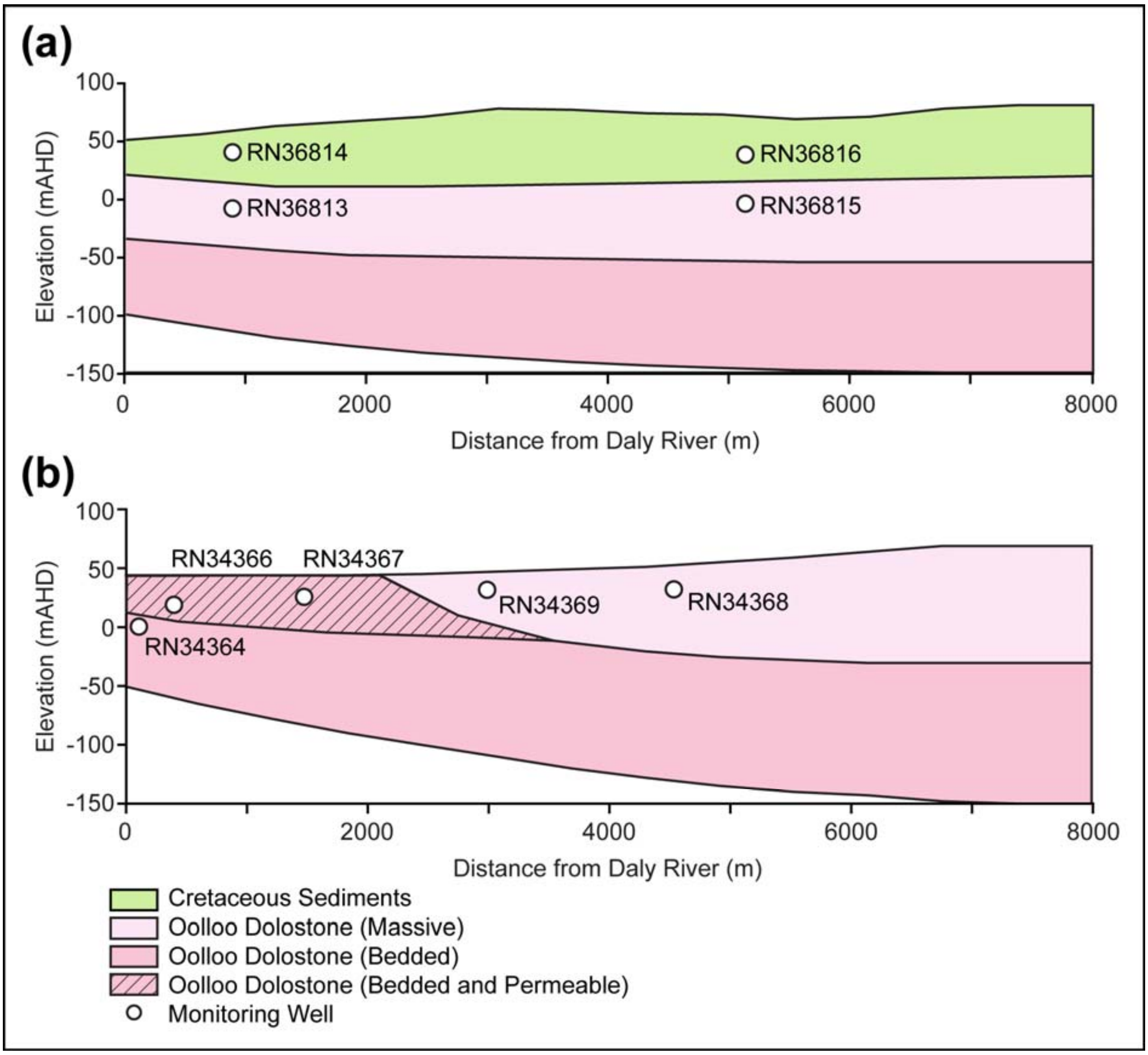

Figure 4-3 Geological cross-sections for (a) Transect-A near Stray Creek; and, (b) Transect-B near Oolloo Crossing.

Environmental tracers were analysed by CSIRO Environmental Isotope Laboratory (EIL; Waite Campus, Adelaide, Australia), with the exception of ^{14}C, which was analysed by the Australian National University (ANU; Canberra, Australia). Each environmental tracer required a specific container, sampling procedure, and analysis method, described briefly here. Samples for ^{222}Rn were collected in a 1.25 L PET bottle following the mineral oil extraction method of Leaney and Herczeg (2004), and radon activity was measured by liquid scintillation on a LKB Wallac Quantulus counter (Herczeg et al., 1994). Samples for CFC and SF_6 analyses were collected in glass bottles displaced in a larger container, with minimal exposure to the atmosphere, using a dedicated tracer sampling pump outfitted with nylon tubing. CFC-11, CFC-12, and SF_6 concentrations were measured by gas chromatography (with electron capture detector for SF_6 analysis) after stripping gas under a stream of ultra-high purity nitrogen gas following methods similar to Busenberg and Plummer (1992) and Busenberg and Plummer (2000). Samples for ^{14}C were collected in a 1.25 L PET bottle, and then precipitated at the EIL for subsequent radiocarbon analysis by Single Stage Accelerator Mass Spectrometer (SS-AMS) at ANU. Dissolved noble gases were collected using passive head space diffusion samplers (Gardner and Solomon, 2009) that were placed directly in well screened intervals of the observations bores or at the orifice of the springs. After a 24 hr period of equilibration, the diffusion samplers were retrieved and clamped vacuum tight. For the Daly River, copper tube aqueous-phase samples were collected by pumping through a 0.5 m length of 8 mm diameter tubing using a portable peristaltic pump and clamping the tube under pressure. Concentrations of ^{4}He, ^{20}Ne, ^{40}Ar, and N_2 were measured using isotope dilution with a Stanford Research Instruments RGA200 quadrupole mass spectrometer, either from gas collected in the diffusion samplers or gas stripped and collected under vacuum from the copper tubes.

4.2 *Results*

4.2.1 Field parameters

Field measured parameters, radon activities, and concentrations of CFCs and SF6 are shown on Table 4-1 and Table 4-2 for sampling in November 2009 and May 2010, respectively. Mean groundwater temperature was 32.9°C for November 2009 and 32.2°C for May 2010, varying from 30.4 to 36.4°C at different locations on the transects. Groundwater along Transect-A had temperature values that were average or higher, with a trend of higher temperature toward the river during both sampling events. Transect-B had groundwater temperatures that were average or lower, with a trend of higher temperature toward the river in November 2009 and lower temperature toward the river in May 2010. Groundwater springs (only sampled in May 2010) were 35.1 to 35.6°C, with the exception of a single spring on the west bank, which was 32.9°C. The Daly River had a mean temperature of 33.4°C and 29.1°C in November 2009 and May 2010, respectively. Mean groundwater EC in the Oolloo aquifer was 647 and 694 µS/cm in November 2009 and May 2010, and between 66 and 130 µS/cm in the overlying Cretaceous sediments on Transect-A (Figure 4-4a). In the Daly River, mean EC was 614 µS/cm in November 2009 and 474 µS/cm in May 2010.

4.2.2 ^{222}Rn

Radon activities in Oolloo aquifer varied from 0.7 to 18.0 Bq/L, with mean values of 9.1 and 7.4 Bq/L for November 2009 and May 2010. For groundwater in the Cretaceous sediments on Transect-A, radon activity was generally higher (13.3 to 27.5 Bq/L) than in the underlying Oolloo aquifer. On Transect-A, there was a general observation of increasing radon activity toward the Daly River. Radon activity in the spring discharge was found to span a narrower range than groundwater collected from the monitoring bores, varying from 7.9 to 17.3 Bq/L. In the Daly River, radon activities were found to increase in the downstream direction of the study area, with higher activities (1.2 to 3.3 Bq/L) in November 2009, compared with May 2010 (0.7 to 1.3 Bq/L). The observed trend and activities for November 2009 were approximately the same as those measured by Cook et al. (2003) for similar sampling locations in 2001.

4.2.3 CFCs

Results of analyses for CFCs are shown on Figure 4-5. CFC-11 and CFC-12 are plotted relative to atmospheric concentrations measured since the 1960s at the Cape Grim Station in Tasmania, Australia. CFC concentrations vary from below lab detection limits (25 and 20 pg/kg for CFC-11 and CFC-12, respectively) to 243 pg/kg for CFC-11 and 209 pg/kg for CFC-12. Results below lab detection have been included on Table 4-1and Table 4-2, and Figure 4-5 to correlate observed spatial trends with other environmental tracers, with the underlying objective of utilising tracer results to develop a conceptual model of groundwater interaction.

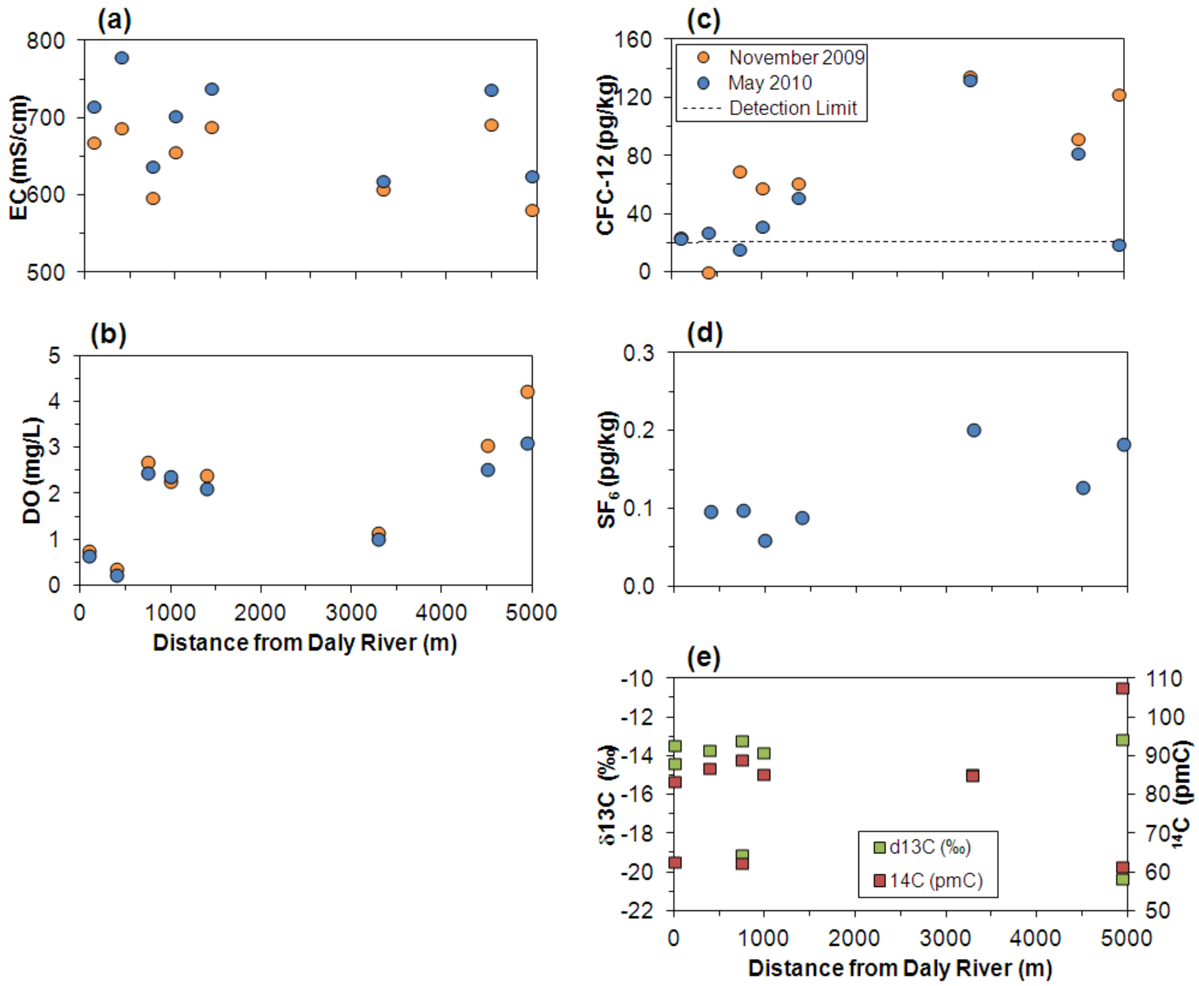

Figure 4-4 Measured values of selected field parameters (EC and DO), and age tracers (CFC-12, SF6, 14C) for groundwater observation bores completed in the Oolloo aquifer.

CFC-12 concentrations in groundwater are plotted against lateral distance from the Daly River (Figure 4-4c) and depth below groundwater level (Figure 4-6a). Up to 20 m below the groundwater level, there was a weak trend of decreasing CFC-12 with depth, with one exception of a monitoring bore completed in Cretaceous sediments (identified on Figure 4-6a). At the two locations where Cretaceous sediments overlie the Oolloo Dolostone (Transect-A), groundwater in the Oolloo aquifer was found to have widely varying CFC-12 between sampling in November 2009 and May 2010. Similarly, a weak trend of increasing CFC-12 with increased distance from the Daly River was found in the Oolloo aquifer groundwater samples (Figure 4-4c). Groundwater samples within 1 km of the Daly River had CFC-12 concentrations less than 30 pg/kg, and groundwater discharge from the springs was less than 50 pg/kg for CFC-11 and CFC-12. Samples collected from the Daly River were on the order of 190 and 120 pg/kg for CFC-11 and CFC-12 in November 2009, and 240 and 120 pg/kg for CFC-11 and CFC-12 in May 2010.

4.2.4 SF_6

To aid the interpretation of groundwater age, SF_6 results are plotted against CFC-12 (Figure 4-5b) and on the distance and depth profiles (Figure 4-4d and Figure 4-6b). For the groundwater samples, SF_6 age dates were corrected for excess air using measured N_2, Ar, and Ne concentrations and assuming unfractionated excess air addition. In groundwater samples, excess air varied from 0.2 to 5.5 g/L, and from 0.4 to 1.9 g/L in discharge from the springs. SF_6 concentrations in the Oolloo aquifer groundwater varied from 0.058 to 0.2 pg/kg. The only sample successfully analysed from the Cretaceous sediments contained 2.64 pg/kg. A trend with increasing depth below the water table was not as apparent as observed for CFC-12 (Figure 4-6b). However, SF_6 concentrations generally increased with increasing distance away from the Daly River (Figure 4-4d), where groundwater springs contained between 0.001 and 0.089 pg/kg. SF_6 concentrations in the Daly River were found to vary from 0.146 to 0.162 pg/kg.

4.2.5 ^{14}C

Results of carbon isotope analysis (δ13C and ^{14}C) are plotted on Figure 4-4e. A previous attempt to determine ^{14}C age of groundwater in the Oolloo aquifer found that common correction approaches (e.g., Fontes and Garnier, 1979; Pearson, 1992; Tamers, 1967) overestimated correction factors due to large uncertainty of CO_2 conditions at the time of recharge. Thus, in the present study, uncorrected ^{14}C values were used qualitatively to compare with results of CFCs, SF_6 and ^4He.

4.2.6 Noble gases

Dissolved noble gas and N_2 concentrations are shown on Table 4-3. In this study, ^4He has been used to investigate the role of old, regional-scale groundwater, which accumulates from alpha decay of uranium (U) and thorium (Th) present in aquifer solids. ^4He is a useful tracer for dating old groundwater and recent study has shown promise for detecting regional-groundwater in base flow for rivers (Gardner et al., 2011). Dissolved ^4He concentrations are plotted with CFC-12 (Figure 4-5c) and are within the range of 4.4e-8 and 1.0e-7 ccSTP/g for groundwater. Samples collected from the springs had higher ^4He concentrations, in the range of 7.5e-8 to 2.3e-7 ccSTP/g.

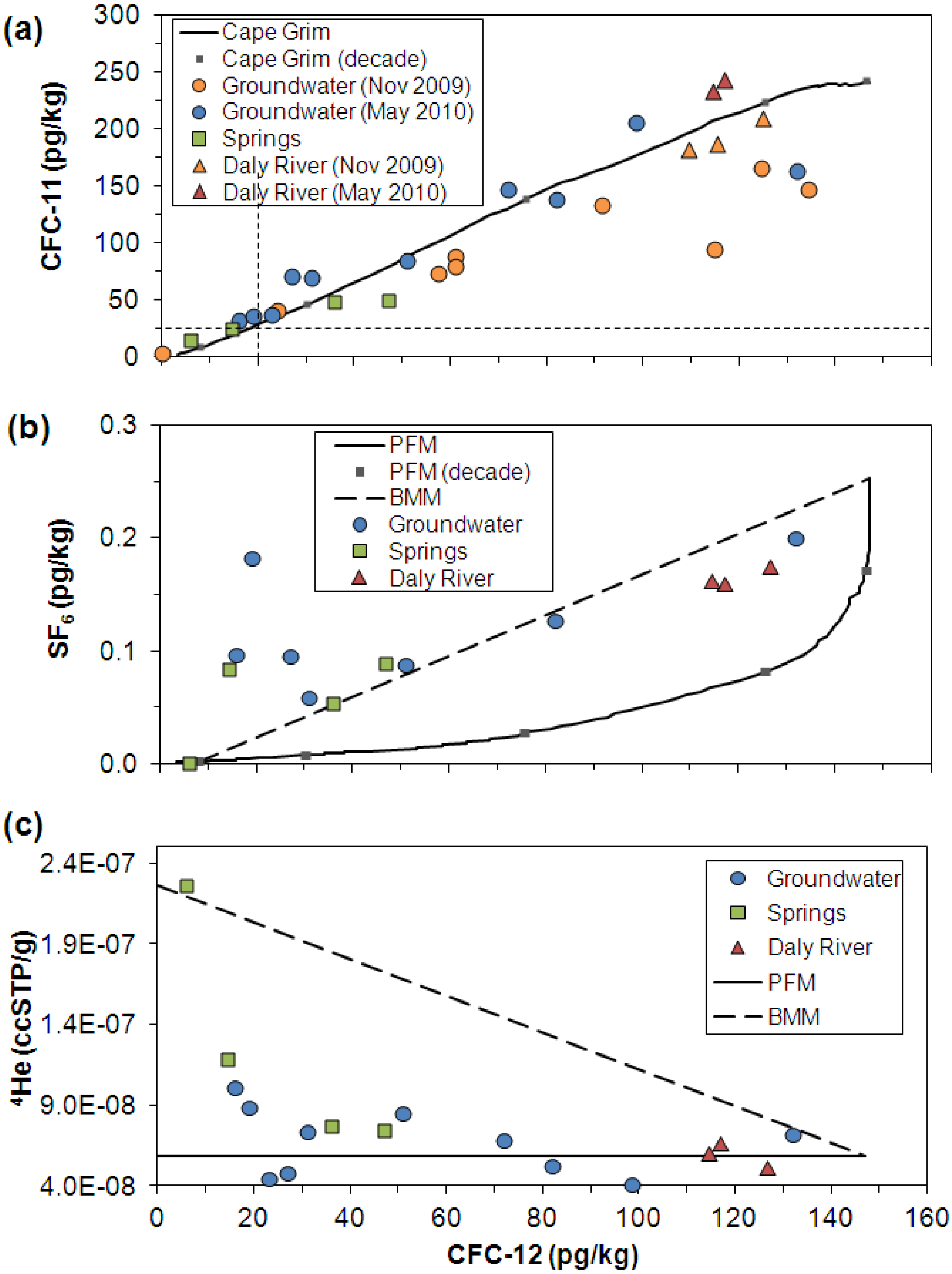

Figure 4-5 Bivariate tracer plots of (a) CFC-11 versus CFC-12, (b) SF6 versus CFC-12, and (c) 4He versus CFC-12. CFC data on (a) are plotted relative to atmospheric concentrations measured at Cape Grim, Tasmania, Australia. Data shown on (b) and (c) are plotted relative to piston flow model (PFM) that assumes transport without hydrodynamic dispersion, and a binary mixing model (BMM) that assumes a mixture of modern and very old (i.e. zero concentration) water

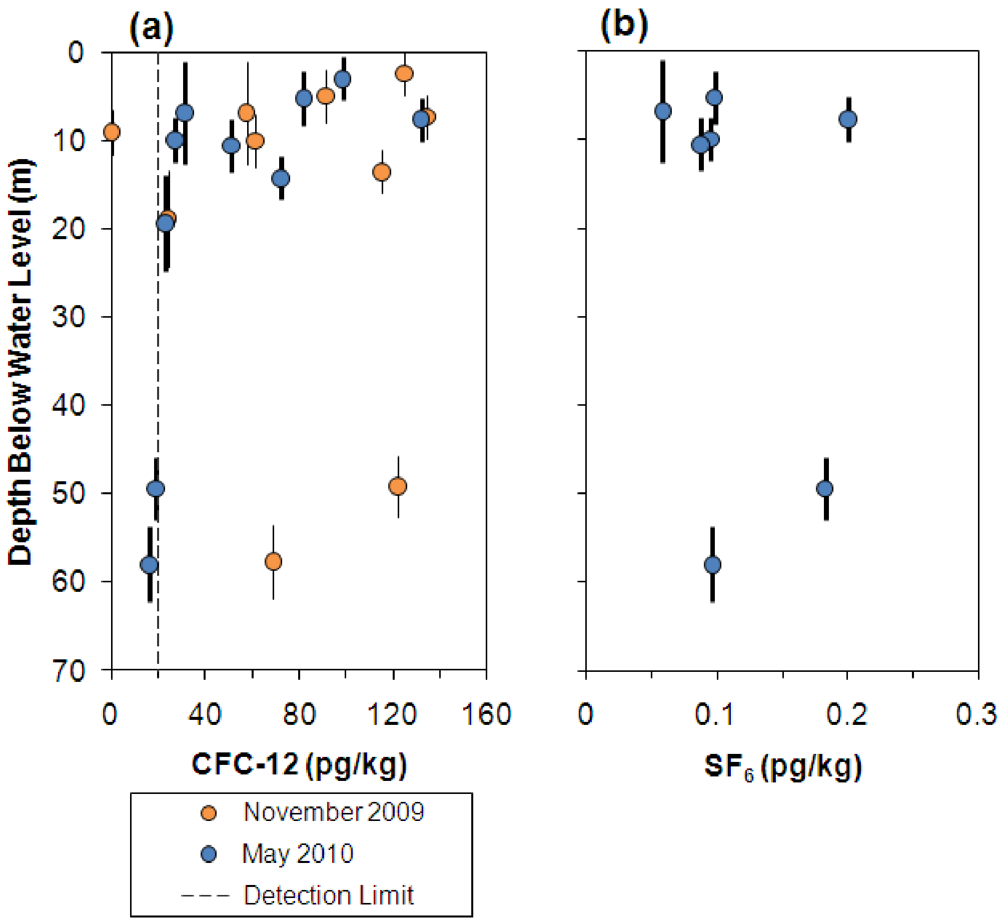

Figure 4-6 Concentration of (a) CFC-12 and (b) SF6 versus depth below measured groundwater level. Vertical bars represent the completion interval of monitoring bores.

4.3 *Interpretation*

4.3.1 Groundwater Flow Regime

Selected field parameters (EC and temperature) begin to illustrate the nature of connectivity between groundwater and the Daly River, and the influence of Cretaceous sediments overlying the Oolloo aquifer. Over the Wet season, EC values of groundwater in the dolostone increased almost uniformly by approximately 50 μS/cm for all bores sampled (Figure 4-4a). Where Cretaceous sediments were present over the dolostone, shallow groundwater EC was lower (less than 130 μS/cm;Table 4-2) and was found to decrease over this time, illustrating the addition of fresh recharge water during the Wet season. Results for CFC analyses also indicate an increased proportion of modern water during this time, which is not evident in the dolostone formation underlying Cretaceous sediments. Combined with low SF_6 concentrations for groundwater in the dolostone where Cretaceous sediments are present, these findings show that there is limited vertical interaction between the Cretaceous sediments and underlying dolostone.

Laterally, higher temperatures associated with the springs and groundwater close to the river indicates a potential for groundwater discharge to originate in part from regional-scale flow system originating beyond the aquifers underlying the floodplain and travelling deeper in the Daly Basin, rather than solely by localised flow from within the floodplain or in close proximity to the river. This interpretation is consistent with observed concentrations of CFCs and SF_6, which decrease toward the river (Figure 4-4c and Figure 4-4d). The bivariate plot of SF_6 and CFC-12 (Figure 4-5b) includes two hypothetical mixing models often used to explain observed variation in environmental tracers: piston flow (PFM), which represents sampled water that has not mixed by hydrodynamic dispersion during transport; and, binary mixing (BMM), which represents sampled water that is a mixture of two end members (i.e., modern and very old). While other hypothetical mixing models (e.g., exponential) would result in curves that plot between the PFM and BMM on Figure 4-5b, the PFM and BMM define a groundwater mixing envelope. This mixing envelope is defined as the region contained by PFM and BMM on Figure 4-5b, where tracer concentrations could be explained by any of the hypothetical mixing models. There are four samples that plot outside the groundwater mixing envelope, which correspond to a spring, two bores within one km of the river, and a bore underlying the Cretaceous sediments. These results could arise from either sample contamination for SF_6 or degradation of CFC-12. While SF_6 contamination remains a possibility, the observed trend of decreasing DO toward the river (Figure 4-4b) provides some evidence for the presence of anoxic conditions that may promote CFC degradation (Hinsby et al., 2007; Oster et al., 1996). Furthermore, elevated 4He concentrations were also found at these locations, indicating the addition of older water, assumed to originate from regional-scale groundwater and lower oxygen content, mixing with younger water and degrading CFCs.

4.3.2 Detection of Regional-scale Groundwater

^4He accumulates in groundwater due to the addition of radiogenic helium from alpha decay of crustal materials and fluxes of deep crustal and mantle derived helium, collectively called terrigenic ^4He. If the flux of ^4He from aquifer minerals into groundwater can be estimated, the terrigenic ^4He concentration in water samples can be used to calculate the groundwater residence time. Given average crustal U and Th composition, the steady state production rate of ^4He is approximately 1.7 µccSTP/m^{3}aquifersolid/yr (Solomon, 2000). Assuming a porosity of 0.3 and complete transfer from the rock to the aqueous phase the production rate in groundwater is approximately 4 µccSTP/m^{3}water/yr, and the time needed for terrigenic ^4He concentrations to equal the atmospheric ^4He concentration is 10,000 years. Variability in production rate is the principal difficulty in applying ^4He as a quantitative age tracer; however, given the low production rate, detection of elevated ^4He is indicative of groundwater residence times >1000 years and can thus be used as an identifier of regional groundwater.

In addition to ^4He concentration, noble gas fractionation factors were calculated to facilitate interpretation of groundwater exchange with the Daly River (Figure 4-7a). Fractionation factors for the ith gas were determined by:

$$F(i) = \frac{(i/^{40}Ar)_{samp}}{(i/^{40}Ar)_{atm}} \quad \text{[Eq. 4.1]}$$

where the mole fraction of He and Ne in the head space in equilibrium with the water are represented by *samp*, and *atm* indicates mole fractions in the atmosphere. For water in equilibrium with the atmosphere, the fractionation factor would be 1. As shown on Figure 4-7a, F(^{20}Ne) remain relatively close to 1, F(^4He) for groundwater samples varied from 1 to 2, and F(^4He) for the springs varied from 1.5 to 4.7. Given average crustal production values, the increase in F(^4He) as a function of groundwater residence time is shown in Figure 4-7b. Of the four samples that plot outside the groundwater mixing envelope on Figure 4-5b, three have F(^4He) values greater than 1.8, indicating a contribution of older water in the age mixture. A F(^4He) of 1.5 is indicative of groundwater residence times on the order of 4000 years. These three samples were also found to have the lowest ^{14}C values (61.3 to 62.5 pmC) suggesting an uncorrected age of approximately 4000 years, which also suggests the presence water older than expected for a modern ^{14}C groundwater source.

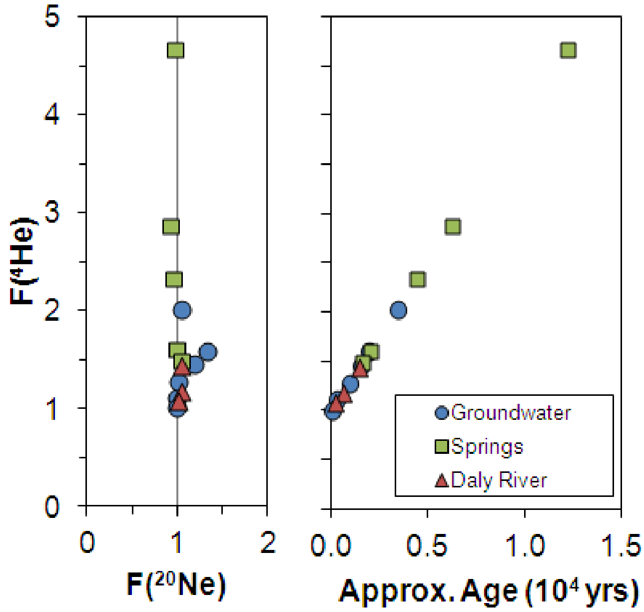

Figure 4-7 Fractionation factors for ^{4}He and ^{20}Ne relative to water in equilibrium with the atmosphere. F(^{4}He) greater than 1 (e.g., springs) indicate increased concentration with travel time, revealing a component of very old water. Fractionation factors for ^{4}He are plotted against the approximate groundwater age assuming average production of ^{4}He.

4.3.3 Groundwater Discharge Modelling

Cook et al. (2003) and Cook et al. (2006) describe an approach for quantifying groundwater discharge to rivers by using field measurements and a model that determines longitudinal concentrations of environmental tracer for a given length of river. The theory centres on calculating the change in river concentration for any environmental tracer, for a given river flow and dimensions, and specific tracer characteristics (e.g., radioactive decay, solubility, gas exchange with the atmosphere). For a given river width (w), change in river flow (Q) is expressed as:

$$\frac{\partial Q}{\partial x} = I - L - Ew$$

[Eq. 4.2]

where I, L, and E are rates of inflow, losses, and evaporation. Longitudinal river concentration (c) with distance (x) is expressed as:

$$Q\frac{\partial c}{\partial x} = I(c_i - c) + wEc - kwc - dw\lambda c + \frac{\gamma hw\vartheta}{1+\lambda t_h} - \frac{\lambda hw\vartheta}{1+\lambda t_h}c$$

[Eq. 4.3]

Development of the model and specific details of the parameters are documented in Cook et al. (2006) and the remaining parameters for Equation 4.3 are summarised in Table 4-4. Equations 4.2 and 4.3 were solved numerically by explicit finite difference in a spreadsheet for the river length (77 km) shown in Figure 4-1b. For specified river dimensions and flow, tracer characteristics, and measurements of tracer concentrations in groundwater, a longitudinal profile of groundwater was determined.

Groundwater discharge rates to the Daly River were estimated using the modelling approach described above, and parameters summarised in Table 4-4. Model parameters were based on values measured in the present study (e.g., river geometry, tracer concentration) and those reported by Cook et al. (2003) for previous study of the Daly River (e.g., gas transfer velocity). The present study incorporates measured groundwater data that was previously unknown, an additional timeframe with different river conditions, additional environmental tracers and inclusion of a hyporheic zone. The majority of model parameters remain consistent with Cook et al. (2003); however, revised longitudinal distribution and rates of groundwater discharge have been determined as a result of additional data. A hyporheic zone of constant thickness (1 m) was assumed to allow radon production from river sediments along the study area.

The groundwater discharge rates were estimated by achieving a best-fit between modelling and observed concentrations of environmental tracers given the assumption of in-river processes (i.e., flow, evaporation, gas exchange). The results of Cook et al. (2003) have been plotted for comparison and to help define the longitudinal profile of simulated river concentrations for ^{222}Rn and CFC-12. A visual best-fit was found by adjusting the rate of groundwater inflow and explicitly considering all environmental tracers and both timeframes simultaneously. The inflow concentrations are representative of measured concentrations in groundwater (Table 4-1). In the absence of groundwater measurements, previous modelling assumed that groundwater inflow had 5 Bq/L ^{222}Rn and zero CFCs. The present study found that ^{222}Rn was approximately two to three times greater than previously assumed and that while CFC-12 concentrations were low, they were at least 20 to 30 pg/kg for spring discharge and groundwater immediately adjacent to the river. The net result provided by these additional data was a refined longitudinal distribution of groundwater discharge compared to Cook et al. (2003). Modelled groundwater discharge, reported here as m^3 per day, per linear m (m^3/d/m), was found to peak at the onset of the discharge zone (180 m^3/d/m; Figure 4-8), and decrease in a downstream direction (to 10 m^3/d/m;Figure 4-8). A common distribution of groundwater discharge was found to fit both the November 2009 and May 2010 observation data, suggesting a relatively consistent baseflow source for the Daly River. Such consistency for different river flow conditions indicates that the source of the major springs is of regional-scale (i.e., well beyond the floodplain scale). Furthermore, the presence of elevated ^{4}He suggested that the source of groundwater discharge had a residence time of approximately 10,000 years. For the entire reach considered in this study (77 km), the regional-scale source discharging at the major springs represents approximately 35per cent of the baseflow to the Daly River.

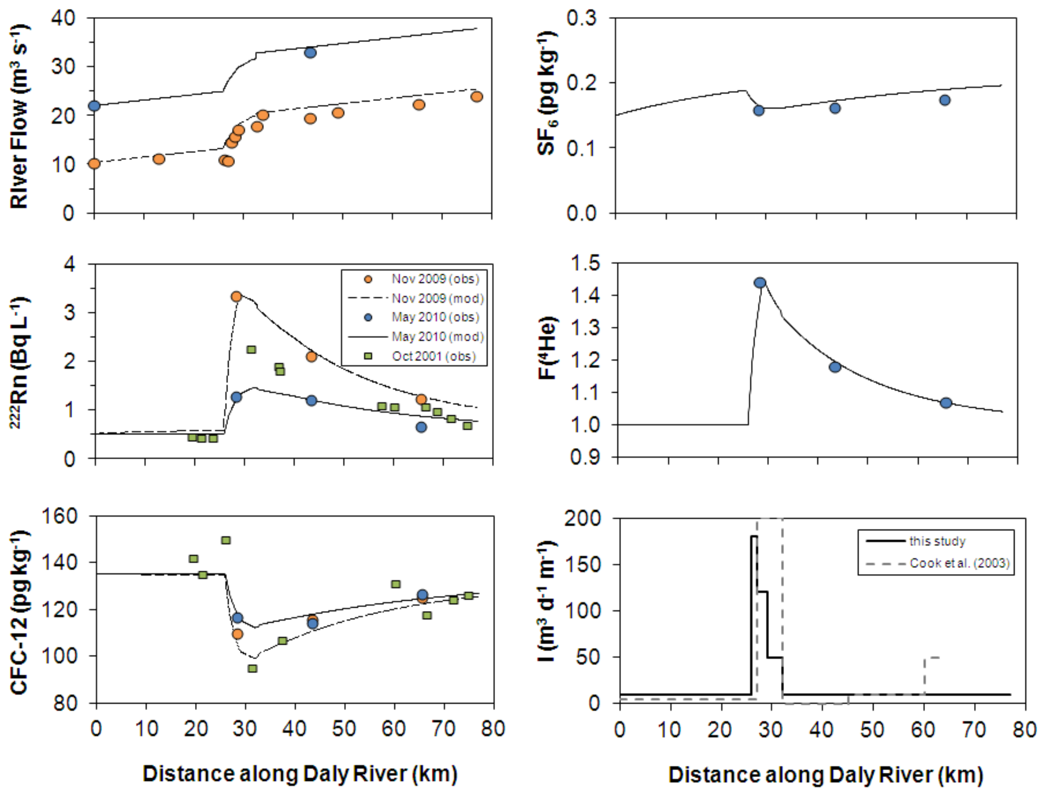

Figure 4-8 Observed and modelled concentrations of environmental tracers in the Daly River for November 2009 and May 2010. Data from October 2001 (Cook et al., 2003) is shown with November 2009 for comparison of low flow conditions. Modelled groundwater inflow (lower right box) illustrates a consistent groundwater discharge of 10 m^3/day per metre and the increased discharge across the major spring area, and is shown with the results of Cook et al. (2003) for comparison.

4.3.4 Groundwater Age Distribution

While specific ages have not been assigned to the results of the tracer analysis in this study, detection of tracers that reflect both modern and older, regional-scale groundwater at the springs and in monitoring bores reveals that a mixture of groundwater with a broad age distribution is converging toward the Daly River. A relatively large fraction of groundwater discharge (90 per cent across the spring zone; 35 per cent for the entire segment of river in the study area) originated from a regional-scale source. A schematic illustration of groundwater cycling and interaction with the Daly River is shown in Figure 4-9. The combination of regional-scale groundwater discharge, Wet season rainfall-driven recharge, and flood-driven bank recharge are expected to maintain shallow aquifer water levels and provide the basis for the observed distribution of environmental tracers. On Figure 4-9 the conceptual model is conveyed using the approximate distribution of F(^{4}He) contours and SF_6 derived ages for specific monitoring points.

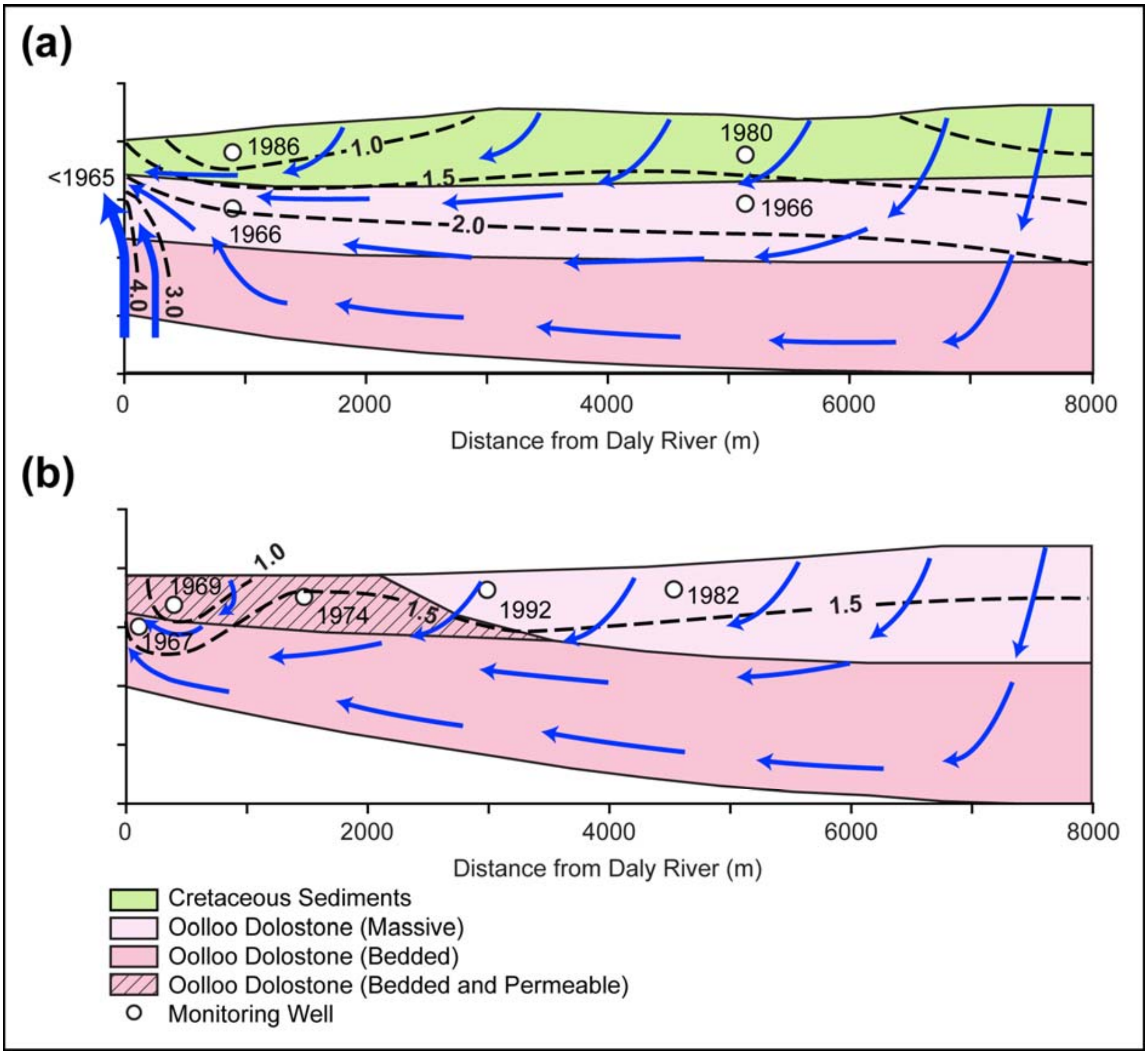

Figure 4-9 Conceptual models of groundwater flow for (a) Transect-A; and (b) Transect-B. Years refer to the apparent SF_6 age, and dashed lines represent idealised F(^{4}He) contours. The approximate depth of 1.5 F(^{4}He) represents the differentiation of shallow cycling of modern water and older water at depth. The lateral extent of flood-induced bank flow recharge is expected to be limited.

The conceptual model illustrated on Figure 4-9 has not been produced from statistically rigorous contouring of measured concentrations, but rather as a summary of findings. The summary illustrates that determining the depth of 1.5 to 1.75 F(^{4}He) provides a means to differentiate the influence of shallow cycling of modern water and upwelling of older groundwater. The conceptual model also illustrates that although annual flooding can increase river flow by approximately two orders of magnitude, the effects of bank-recharge may be countered by more dominant process of regional-scale groundwater flow toward the river. From this conceptualisation, the shallow aquifer appears to be sustained by vertical recharge, which is higher where Cretaceous sediments are absent, exposing the underlying dolostone aquifer. In-turn, recharge to the shallow dolostone aquifer supplies groundwater discharge in the form of evapotranspiration for vegetation near the river. Shallow, vertically recharged, relatively young groundwater mixes with older, regional groundwater to supply groundwater springs and base flow to the Daly River.

4.4 *Key Findings*

A suite of environmental tracers (^{222}Rn, CFCs, SF_6, ^{14}C, and ^{4}He) was used to characterise groundwater interaction between the Oolloo aquifer and Daly River. Interpretation of results by modelling groundwater inflow and through development of a conceptual model of surface water – groundwater interaction reveals the following key findings:

- Relatively high concentrations of SF_6 and CFC-12 in shallow groundwater indicate that vertical recharge is the dominant source of water. Groundwater recharge may be restricted where the aquifer is overlain by Cretaceous sediments;
- At the end of the Dry season, the average diffuse groundwater discharge to the Daly River is 10 m^3/d/m. Focussed groundwater discharge in the major spring area is 180 m^3/d/m;
- Major springs and groundwater close to the river have low CFC-12 and elevated ^{4}He, indicating that older regional-scale groundwater is the source of water during Dry season flow; and
- Along the entire segment of the Daly River that was studied, older regional-scale groundwater represents approximately 35 per cent of baseflow. In the vicinity of major springs, older regional-scale groundwater represents approximately 90 per cent of baseflow.

Table 4-1 Field parameters and environmental tracer results for November 2009

Sample Location		Distance Downstream (km)	Temp (°C)	EC (µS/cm)	pH	DO (mg/L)	^{222}Rn (Bq/L)	CFC-11 (pg/kg)	CFC-12 (pg/kg)
Transect-A	RN36813	28.3	36.4	597	6.89	2.68	1.0		69
	RN36814		34.6	130	5.49	1.97	27.0	165	125
	RN36815		34.0	581	6.91	4.20	0.7	176	122
	RN36816		32.0	95	5.31	1.03	16.8	94	115
	RN36817		32.3	656	6.84	2.25	9.6	73	58
Transect-B	RN34364	65.5	32.5	668	6.82	0.73	16.2	41	24
	RN34366		31.0	687	6.93	0.34	18.0	3	0
	RN34367		31.4	689	6.84	2.37		79	61
	RN34369		31.2	608	7.12	1.12		147	135
	RN34368		34.0	691	6.89	3.03		133	92
Daly River	Transect-A	28.3	32.8	598	7.60	6.67	3.3	181	110
	Gauge Stn.	43.5	33.5	613	7.67	7.11	2.1	186	116
	Transect-B	65.5	34.0	633	8.05	8.48	1.2	209	125

Table 4-2 Field parameters and environmental tracer results for May 2010

Sample Location		Distance Downstream (km)	Temp (°C)	EC (µS/cm)	pH	DO (mg/L)	^{222}Rn (Bq/L)	CFC-11 (pg/kg)	CFC-12 (pg/kg)	SF_6 (pg/kg)
Transect-A	RN36813	28.3	35.4	637	6.78	2.43	7.5	32	16	0.096
	RN36814		33.2	66	5.20	1.73	27.5	205	99	
	RN36815		33.4	625	6.85	3.10	5.1	36	19	0.183
	RN36816		31.8	75	4.84	0.54	13.3	147	72	2.644
	RN36817		32.0	702	6.82	3.35	10.9	70	31	0.058
Transect-B	RN34364	65.5	30.8	715	6.78	1.63	9.0	37	23	
	RN34366		30.4	779	6.86	0.21	10.6	70	27	0.095
	RN34367		31.4	738	6.77	2.10	8.6	84	51	0.088
	RN34369		31.4	618	7.09	1.00	2.4	163	132	0.200
	RN34368		32.1	737	6.79	2.52	5.1	138	82	0.098
Daly River	Transect-A	28.3	29.0	448	7.49	7.25	1.3	243	117	0.159
	Gauge Stn.	43.5	29.2	476	7.47	7.09	1.2	233	115	0.162
	Transect-B	65.5	29.2	499	7.84	7.44	0.7		127	0.146
Springs	G8145393	26.4	35.1	244	6.67	2.31	13.2	14	6	
	G8145637	27.6	35.6	679	6.69	1.90				0.001
	G8145619	28.3	35.1	648	6.74	2.97	7.9	25	15	
	near creek	32.4	32.9	692	6.72	1.65	17.3	48	36	0.085
	G8145645	36.5	35.5	698	6.67	1.97	15.9	50	47	0.054

Table 4-3 Dissolved noble gas and N_2 concentrations (ccSTP/g) for May 2010

Sample Location		Distance Downstream (km)	^{4}He	^{20}Ne	^{40}Ar	N_2
Transect-A	RN36813	28.3	1.0E-07	1.9E-07	2.8E-04	1.2E-02
	RN36814		4.1E-08	1.5E-07	2.6E-04	9.3E-03
	RN36815		8.9E-08	2.0E-07	2.8E-04	1.2E-02
	RN36816		6.9E-08	2.0E-07	3.3E-04	1.3E-02
	RN36817		7.4E-08	2.2E-07	3.0E-04	1.3E-02
Transect-B	RN34364	65.5	4.4E-08	1.5E-07	2.6E-04	7.8E-03
	RN34366		4.9E-08	1.7E-07	2.8E-04	1.1E-02
	RN34367		8.5E-08	2.5E-07	3.1E-04	1.2E-02
	RN34369		7.2E-08	2.2E-07	3.4E-04	1.5E-02
	RN34368		5.3E-08	1.6E-07	2.6E-04	7.1E-03
Daly River	Transect-A	28.3	6.6E-08	1.8E-07	2.9E-04	1.3E-02
	Gauge Stn.	43.5	6.1E-08	2.0E-07	3.1E-04	1.4E-02
	Transect-B	65.5	5.2E-08	1.8E-07	2.9E-04	1.4E-02
Springs	G8145393	26.4	2.3E-07	1.6E-07	2.6E-04	1.0E-02
	G8145637	27.6	1.4E-07	1.6E-07	2.6E-04	9.9E-03
	G8145619	28.3	1.2E-07	1.9E-07	2.9E-04	1.2E-02
	near creek	32.4	7.7E-08	1.7E-07	2.8E-04	1.1E-02
	G8145645	36.5	7.5E-08	1.8E-07	2.8E-04	1.1E-02

Table 4-4 Parameters for groundwater discharge model

Symbol	Description	November 2009	May 2010
Q_0	River flow (m^3/s)	10.2	22.0
E	Evaporation (mm/d)	7	5
w	River Width (m)	50	55
d	River depth (m)	1.5	2.0
h	Hyporheic zone depth (m)	1	1
θ	Hyporheic zone porosity	0.4	0.4
t_h	Hyporheic zone residence time (d)	0.25	0.25
γ	Hyporheic zone ^{222}Rn production (Bq/L/d)	0.2	0.2
$c_{0\text{-}RN}$	Initial ^{222}Rn activity	0.5	0.5
$c_{0\text{-}CFC}$	Initial CFC-12 concentration (pg/kg)	135	135
$c_{0\text{-}SF6}$	Initial SF_6 concentration (pg/kg)		0.15
$c_{0\text{-}HE}$	Initial $F_w(^4He)$		1
k_{RN}	^{222}Rn gas transfer velocity (m/d)	1	1
k_{CFC}	CFC-12 gas transfer velocity (m/d)	1	1
K_{SF6}	SF_6 gas transfer velocity (m/d)		0.9
k_{HE}	$F_w(^4He)$ gas transfer velocity (m/d)		2.5
λ	^{222}Rn decay (/d)	0.181	0.181
Q_1	Tributary inflow at 32.8 km (Stray Creek; m^3/s)	0.6	1.2
$c_{1\text{-}RN}$	Tributary ^{222}Rn activity (Bq/L)	1	1
$c_{1\text{-}CFC}$	Tributary CFC-12 (pg/kg)	135	135
$c_{1\text{-}SF6}$	Tributary SF_6(pg/kg)		0.15
$c_{1\text{-}HE}$	Tributary $F(^4He)$		1

5 Groundwater Recharge

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Groundwater recharge is one of the most important components in characterisation and assessment of groundwater resources. The rate and timing of recharge is needed for an accurate water budget, however the recharge process is generally difficult to measure directly. In the Daly Basin, groundwater is a dynamic resource, with strongly seasonal input from rains (vertical recharge) and interaction with surface water (flood recharge). These inputs are thought to replenish shallow, productive aquifers annually in the Wet season, which become significant water sources for rivers and through extraction from production bores in the Dry season.

Jolly et al. (2000) estimated recharge in the Katherine area, and generally found that for annual rainfall of 1000 mm, potential recharge could be 100 to 150 mm. Below 1000 mm annual rainfall, potential recharge diminished to less than 100 mm, and for annual rainfall greater than 1000 mm (up to 1600 mm), potential recharge increased to approximately 200 mm/year. As part of the Northern Australia Sustainable Yields (NASY) Project, diffuse recharge was estimated at 100 to 150 mm/year across much of the Daly River catchment, increasing to 300 mm/year at the northern most extent (CSIRO, 2009). These estimates were based on vertical flux modelling using historical climate data and idealised soil properties.

The aim of this chapter was to quantify groundwater recharge rates for the Oolloo aquifer, utilising data acquired during field work completed for Chapter 4 (surface water – groundwater interaction) in an effort to ground-truth previous estimations. Recharge was estimated from three approaches: (i) interpretation of selected environmental tracers described previously in Chapter 4; (ii) an analysis of time-series hydraulic head data; and, (iii) through development of a cross sectional numerical model to evaluate whether recharge rates would balance with groundwater discharge rates determined in Chapter 4. Thus, groundwater recharge was estimated utilising a variety of techniques in combination.

5.1 *Field-based Approaches*

5.1.1 Environmental Tracers

At the time of groundwater recharge, the concentrations of chlorofluorocarbons (CFCs) and sulphur hexafluoride (SF_6) are approximately equal to the atmospheric concentration (Figure 5-1) and remain fixed at this concentration while travelling through the groundwater regime. Subsequent sampling of groundwater determines the CFC and SF_6 concentrations, which can be used to interpret the apparent age.

Within a given aquifer, vertical profiles of the apparent groundwater age can be used to estimate vertical (downward) groundwater flow, and subsequently the approximate rate of groundwater recharge (Cook and Bohlke, 2000). Assuming that groundwater is sampled in close proximity to the water table, the recharge rate (R) can be approximated by:

[Eq. 5.1] $$R = \frac{z\phi}{t}$$

where z is the depth below the water table, φ is the porosity, and t is the apparent groundwater age.

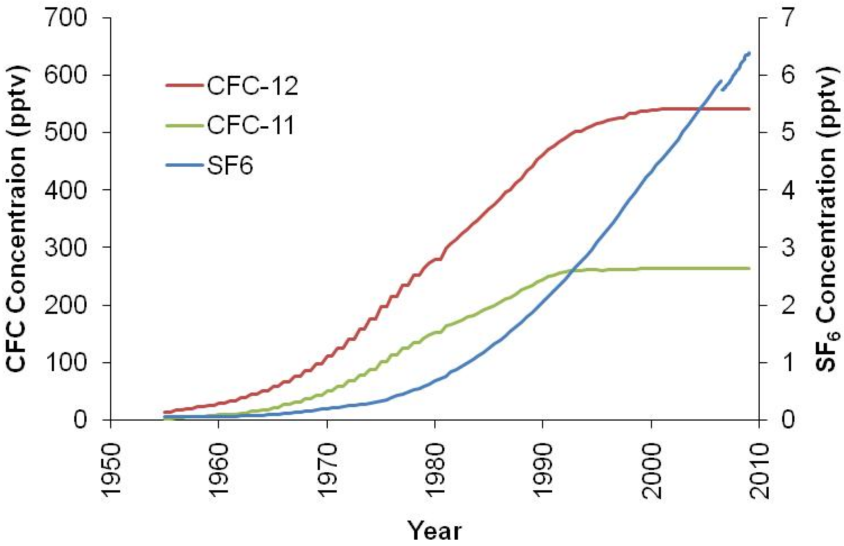


Figure 5-1 Atmospheric concentrations of CFCs and SF_6.

A sub-set of environmental tracer concentrations from chapter 4 was used to estimate groundwater recharge. The sub-set was chosen from four bores along the Oolloo Crossing transect (Figure 6-1a), where the top surface of the Oolloo aquifer was relatively close to the ground surface, and not overlain by thick Cretaceous sediments (Figure 5-2b). This criterion would allow interpretation of groundwater recharge by Equation 5.1.

Measured concentrations of CFC-12 and SF_6 in groundwater were converted to an apparent age based on known solubility relationships, assumed recharge temperature (equal to mean annual temperature in the region) and equivalent atmospheric concentrations (Figure 5-1). The apparent age is plotted with depth on Figure 5-3, with two profiles of calculated groundwater age using Equation 5.1. The calculated profiles assume a porosity of 0.3 and fit the data assuming annual recharge rates of 70 and 170 mm (7 and 17 per cent of annual precipitation, respectively). Annual recharge rates were fit by trial-and-error to provide approximate upper and lower bounds to the observed data. Following the same process to determine reasonable bounds for recharge rates, lower values of porosity would result in lower recharge rates and higher values of porosity would result in higher recharge rates. Thus, although this approach to estimating recharge requires assumptions of porosity and recharge temperature, a first-order approximation can be determined.

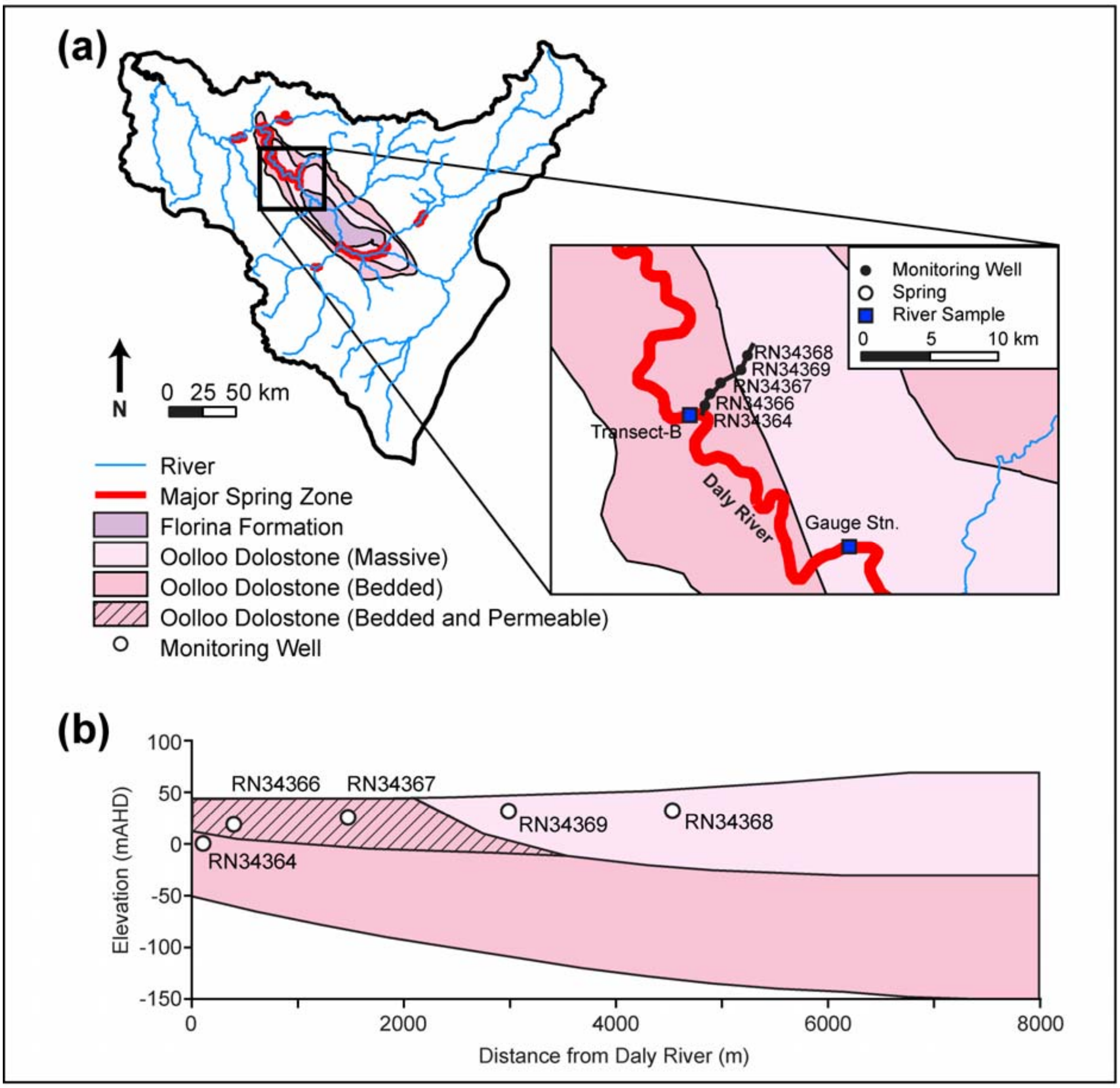


Figure 5-2 . (a) The Daly River catchment and geologic formations of the Daly Basin. Inset identifies monitoring bores that were sampled for modern age tracers (see Chapter 4 for sampling details). (b) Geological cross-sections for Oolloo Crossing area. Cross section extent and geometry were used in numerical modelling.

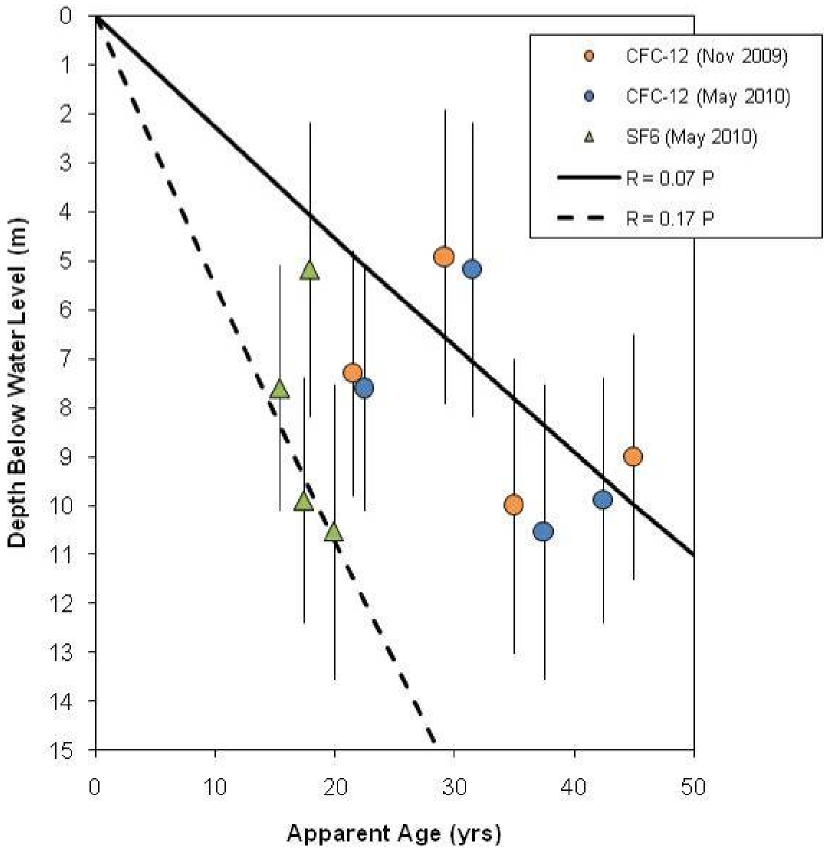


Figure 5-3 Estimate of annual recharge rate determined from sub-set of environmental tracers described in Chapter 4 and assumption of vertical downward flow. Vertical bars represent the extent of monitoring bores.

5.1.2 Hydraulic Head Data

As part of on-going groundwater research in the Daly Basin, hydraulic head is recorded at hourly intervals for selected monitoring bores using pressure transducers and dataloggers. Three bores on the Oolloo Crossing transect were instrumented in 2005 and two additional bores instrumented in 2008. The resultant groundwater hydrographs (Figure 5-4) provide a clear illustration of groundwater response to significant annual hydrologic events.

In each year from 2005 to 2009, annual flooding of the Daly River begins in November and ends in March or April, with a maximum increase in river stage of at least 15 m at Oolloo Crossing. Hydraulic heads respond from the combined effect of river stage increase and groundwater recharge during the same timeframe. Hydraulic heads increase by 5 to 10 m depending on distance from the river. Following annual flooding, the Daly River stage returns to within 2 m of baseflow level by May, with hydrograph recession occurring from May to November. However, over this same timeframe, corresponding hydraulic heads follow a nearly linear recession from peak conditions. In other words, the groundwater hydrographs exhibit long tails, with the exception of the bore closest to the Daly River (RN034364 on Figure 5-4). The shape of these groundwater hydrographs is indicative of the karstic nature of the Oolloo aquifer, whereby annual input from flooding and recharge causes rapid response through karst conduits and slower response through the rock matrix (e.g. Powers and Shevenell, 2000). Rapid response is observed for three bores on the Oolloo Crossing transect (RN034364 to RN034366), which are within a few kilometres of the Daly River, and a more subdued response is observed for two bores (RN034368 and RN034369) at greater distance from the river. The combination of rapid response, long recession period and muted response with increased distance from the river provides a unique hydraulic head signature that illustrates the hydraulics of the Oolloo aquifer. This unique response will be explored further by numerical flow modelling in Section 5.2.

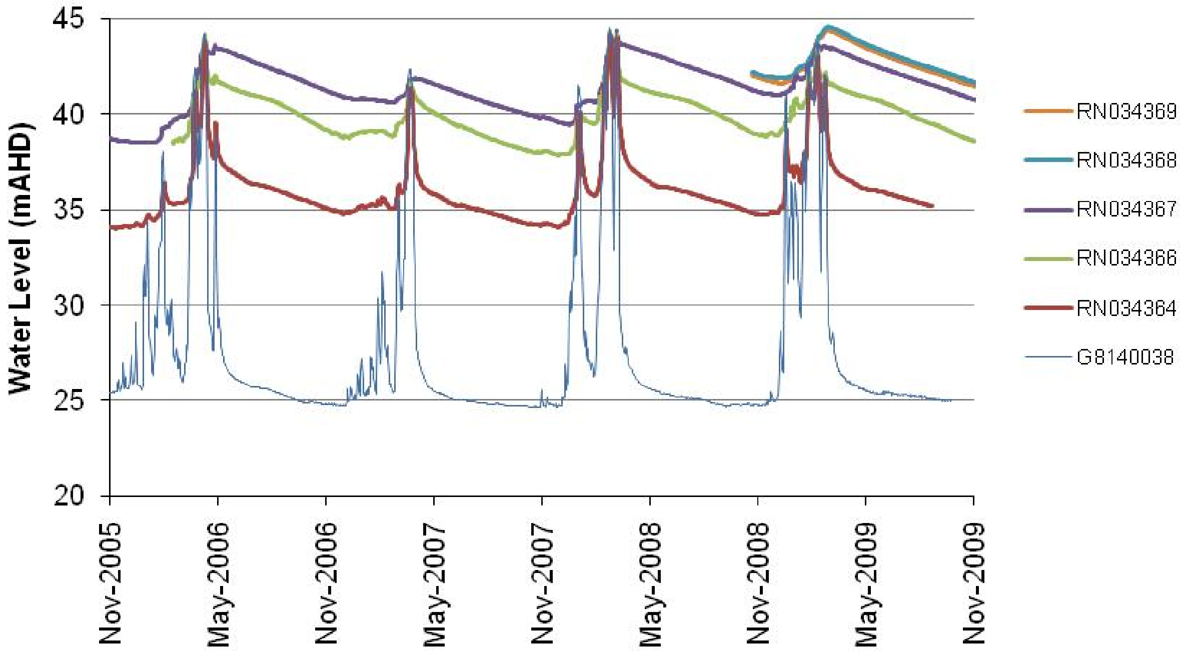


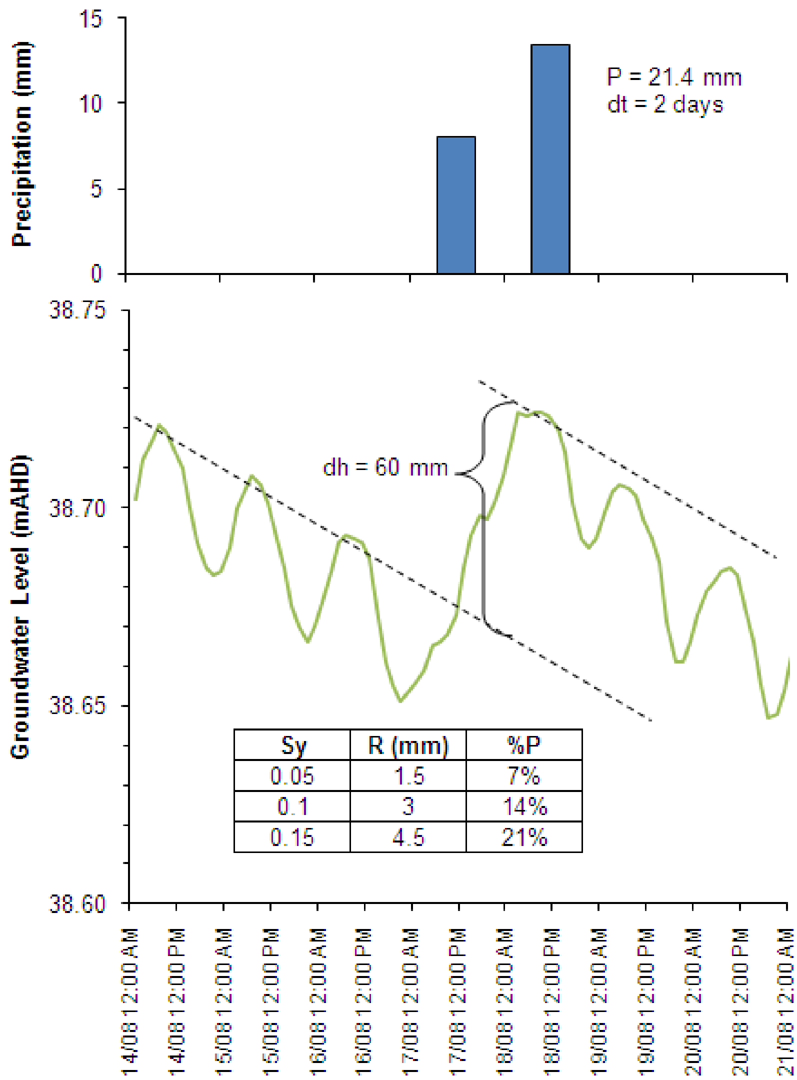
Figure 5-4 Hydrographs for the Daly River and monitoring bores on the Oolloo Crossing transect.

Closer inspection of the groundwater hydrographs (Figure 5-4) also reveals a relatively steep hydraulic gradient with the Daly River. Hydraulic heads at RN034364, located approximately 100 m from the Daly River, are maintained nearly 20 m higher than the river stage during the recession period. At the annual river flood peak, hydraulic heads are similar to the river stage. However, at distances greater than 100 m from the Daly River, the horizontal hydraulic gradient increases linearly at approximately 0.002. The abrupt change in hydraulic head conditions at close proximity to the river indicates hydraulic damming is occurring (i.e., a back-up of hydraulic heads adjacent to a natural groundwater outlet). Hydraulic damming is hypothesised to occur by two phenomena: (i) presence of low permeability sediments along the river valley sides; and, (ii) clogging of karst conduits or change in geology. Either of these phenomena could cause restriction of groundwater flow to the river and hydraulic damming. The steep hydraulic gradient also appears to be a unique condition for the Oolloo aquifer, and will also be explored further in Section 5.2.

One of the most widely used methods to estimate groundwater recharge directly from hydrograph data is the water table fluctuation (WTF) method (Healy, 2010). The premise of this method is that a rise in groundwater level in an unconfined aquifer originates from recharge event. The recharge rate (R) can be calculated by:

[Eq. 5.2] $$R = Sy\frac{dh}{dt}$$

where Sy is the specific yield, h is the water table height, and t is time. The assumption when using Equation 5.2 is that recharge water immediately goes into storage at the water table, and that all other sources and sinks for groundwater (e.g. evapotranspiration, pumping) are negligible at the timescale of interest. Equation 5.2 requires an estimate of Sy and is most applicable when sufficient time-series groundwater level data is available. The majority of hydraulic head response observed on Figure 5-4 can be attributed to very dynamic hydrologic events (i.e. flooding), which violates the second assumption of having negligible sources and sinks for groundwater. Analysis of the hydrograph data (Figure 5-4) found only one instance during the recession periods between 2005 and 2009 where an isolated rainfall event resulted in a distinct groundwater level rise. On 17 August 2008, 21.4 mm of rainfall occurred within a two day period, and the hydraulic head in RN034366 increased by 60 mm (Figure 5-5). Applying Equation 5.2 and assuming a range of Sy values (0.05 to 0.15) found that 1.5 to 4.5 mm or recharge might have occurred from this event, which equates to approximately 7 to 21 per cent of the rainfall event. Although this simplistic method requires assumption of an Sy value, which is highly uncertain, and only represents a single rainfall event at one location, the method provides a gross estimate that is similar to estimates from the tracer-based approach (7 to 17 per cent of rainfall).



Sy	R (mm)	%P
0.05	1.5	7%
0.1	3	14%
0.15	4.5	21%

Figure 5-5 Estimate of recharge rate by WTF method for an isolated rainfall event in August 2008 using water level data from RN034366. The assumed range for Sy would include effect of bypass (i.e. conduit) flow if present.

5.2 *Modelling Approach*

The field-based approaches described above utilise observations of naturally occurring tracers (CFCs and SF_6) and direct physical response (WTF method) to estimate groundwater recharge. Another approach to estimate groundwater recharge is through numerical modelling. For recharge studies, this is often achieved through used of a 1D model to represent the transfer of energy and moisture at the land surface (e.g. Chapter 6); and relate climate, vegetation, and soil characteristics, to the water table depth (e.g, Crosbie et al., 2010). Results from 1D modelling represent diffuse groundwater recharge and often neglect any bypass flow that could occur where karstic conduits and/or marcopores exist. Furthermore, 1D modelling also often neglects other transient processes that lead to dynamic water table responses (e.g. annual flooding). In order to account for these complexities, a 2D numerical model has been developed to further evaluate groundwater recharge.

Transient groundwater flow and hydraulic head response was simulated to investigate whether groundwater recharge estimates (Section 5.1) would balance with groundwater discharge estimates (Chapter 4) for the period of time when sufficient hydraulic head data were available for comparison. Considering the large degree of uncertainty associated with hydraulic properties of a karstic aquifer (e.g. permeability and storage), the apparent groundwater age distribution was also simulated by advective-dispersive transport and compared qualitatively with the conceptual model developed in Chapter 4. Such comparison does not provide a rigorous analysis of environmental tracer movement in the subsurface, but rather is used to provide additional constraint on future numerical modelling.

5.2.1 Cross Sectional Numerical Model

The groundwater flow model was developed for a 2D cross section extending from the Daly River along the Oolloo Crossing transect (Figure 5-2b). The model represented an 8 km slice across the Daly Basin, extending from -150 mAHD to ground surface, including both the lower bedded Oolloo aquifer and the upper massive Oolloo aquifer. The wedge-shape cross section was estimated from approximate locations of outcrop and hydrogeologic mapping by Tickell (2011a). The modelled 2D cross section was approximately oriented parallel to the observed groundwater flow pattern in the Oolloo aquifer however; an underlying assumption for any 2D modelling approach is that flow is aligned with the section. Numerical modelling was completed using the HydroGeoSphere code (Therrien et al., 2010), which solves groundwater flow and solute transport by finite element method.

The 2D cross section was conceptualised as a three layer system overlying the Jinduckin Formation. From bottom to top the hydrostratigraphic units represented were: (i) the lower bedded Oolloo aquifer (crystalline dolomitic silt and sandstone); (ii) an intermediate unit described by Tickell (2002) as a crystalline dolostone, assumed to be 10 m thick; and, (iii) the upper massive Oolloo aquifer (dolostone with abundant solution cavities). The 2D finite element mesh had a horizontal resolution of 10 m and variable resolution vertically. The lower bedded Oolloo aquifer was divided into five sub layers, the intermediate member was divided into five sub layers, and the upper massive Oolloo aquifer was divided into ten sub layers.

Hydraulic properties for the Oolloo aquifer members are poorly known and expected to be highly variable. Generally, the lower and upper members of the Oolloo aquifer have reported bore yields of 5 L/s and 100 L/s, respectively (Tickell, 2011a). Thus, in the 2D cross sectional model, the upper massive member was assumed to have a higher hydraulic conductivity than the lower “bedded” unit. It should be noted that where the lower bedded Oolloo aquifer is close to the ground surface, the permeability has been enhanced by weathering. In the modelling this has been represented by assigning equivalent hydraulic properties of the upper massive unit to this segment of "bedded and permeable" Oolloo aquifer.

Two different techniques were used to parameterise the hydraulic properties. First, the hydrogeologic units were represented as traditional porous media, each having a single hydraulic conductivity (K) and specific storage (Ss) value. Second, the upper massive Oolloo aquifer and the "bedded and permeable" segment of the bedded Oolloo aquifer was represented as a dual-continuum. In the dual-continuum approach each finite element in these layers is comprised of a matrix and conduit. The dual-continuum technique allows for conduits of high permeability to be coupled with a lower permeability matrix following the formulation of Gerke and Van Genuchten (1993). Conceptually the dual-continuum technique better represents the karstic nature of the upper massive Oolloo aquifer; however, each continuum (i.e. matrix and conduit) requires a K and Ss value. In this model the uppermost 10 sub layers were specified as dual-continua, with hydraulic parameters chosen for the given layer thickness (i.e., significantly thinner or thicker layers would require adjusting the matrix and conduit hydraulic properties to achieve the same outcome). Tabulated hydraulic properties are presented following description of the boundary and initial conditions and calibration procedure.

5.2.2 Boundary and Initial Conditions

The groundwater model only considered saturated flow conditions, with specified flux across the water table to represent recharge (i.e. drainage below the rooting zone). Annualised recharge rates determined from Section 5.1 provided a basis for defining time varying recharge rates to use during transient simulation. The higher recharge rate (17 per cent of rainfall) was specified from 0 to 3 km away from the Daly River where the lower bedded Oolloo aquifer outcrops. The lower recharge rate (7 per cent of rainfall) was specified for the remainder of the model region (3 to 8 km from the Daly River) where the upper massive Oolloo aquifer is present. To generate a time series of recharge rates, historical rainfall data were extracted from the SILO Data Drill of the Queensland Department of Natural Resources and Water (Jeffrey et al., 2001), which is interpolated from climate station data by the Australian Bureau of Meteorology. Monthly total rainfall was scaled (17 or 7 per cent) and applied as a flux to the water table.

Because the aim of the modelling was to evaluate whether recharge estimates balanced against discharge estimates (identified in Chapter 4), the 2D cross sectional model also included interaction with the Daly River. The Daly River was represented as a time varying specified hydraulic head on the left-hand-side of the model domain, for nodes above 10 mAHD. Because groundwater recharge occurs on a similar timeframe as annual flooding, the transient nature of the river boundary condition was explicitly considered (i.e., time varying). The remaining edges of the model domain (below 10 mAHD on left-hand-side, bottom, and right-hand-side) were assumed to coincide with no-flow boundaries. The right-hand-side of the cross section does not extend to a naturally defined groundwater divide, but was extended to a sufficiently great distance so as not to affect hydraulic head conditions where observations were known. The right-hand-side of the cross section represents an area of the Oolloo aquifer where groundwater flow would be divergent, with some flow directed northward.

Transient simulations were run for the period between July 2005 and December 2009 at a monthly timestep. Initial conditions assumed a horizontal hydraulic gradient of 0.00125, with a hydraulic head of 35 mAHD at the Daly River. Compared to the baseflow stage of approximately 25 m (Figure 5-4), a 10 m vertical offset was required to mimic the conditions of hydraulic damming described in section 5.1.2. To allow transient flow to establish, the first cycle of annual flooding was not evaluated as part of the calibration process described below. Preliminary simulations revealed that by the second annual flood, hydraulic head conditions were similar to those observed in the field.

5.2.3 Recharge Evaluation

Considering that the hydraulic properties for each layer were uncertain, the time varying recharge rates remained fixed and a manual calibration process was completed by adjusting K and Ss to best match the observed hydraulic head response. Although this procedure could hypothetically lead to a range of hydraulic properties, the shape of observed groundwater hydrographs (i.e. timing and magnitude of peaks) was considered unique, indicating that the combination of hydraulic properties to replicate 2D flow may also be unique. The transient groundwater flow resulted in time series of hydraulic heads and groundwater interaction with the Daly River for comparison with field observations and groundwater discharge estimation reported in Chapter 4. This procedure was completed for the traditional porous media and dual-continua simulation techniques.

Once the transient flow model appeared to be calibrated to hydraulic head response and groundwater discharge, a subsequent simulation of the apparent groundwater age was completed and visually compared with the conceptual model described in Chapter 4. Apparent groundwater age was simulated by advective-dispersive transport following the method of Goode (1996), which provides a more realistic age distribution than first-order approximations described by most simple mixing models (Sanford, 2011). Simulation of apparent age is similar to simulating concentrations of solutes in a groundwater system. Groundwater recharge is assigned a zero-age and each parcel of water within the model is assigned an accumulating age of unity for each time step. As the simulation progresses to steady-state, the resulting simulation traces advective movement and dispersion effects, yielding a distribution of apparent age across the groundwater regime.

5.2.4 Modelling Results

Simulated hydraulic heads for three locations corresponding to monitoring bores having a complete water level record are shown on Figure 5-6. The final hydraulic parameters determined from calibration are summarised in Table 5-1. The general trend of annual flood response can be replicated using either the traditional porous media or dual-continua approaches. However, given the combination of rapid response and long recession observed in the hydraulic heads, there appears to be a large storage effect, which is better replicated by the dual-continua approach. Manifestation of storage delay is more apparent with greater distance away from the river. As indicated earlier, other combinations of parameters may lead to very similar results, which could be explored further using parameter estimation software in subsequent work.

Simulated groundwater exchange with the Daly River is shown on Figure 5-7 with estimated groundwater discharge determined in Chapter 4. Generally, each simulation illustrates discharge of between 5 and 6 m/d per linear meter of river, which compares favourably with the tracer-based estimate of 5 m/d/m for November 2009 (end of the Dry season). Each simulation also illustrates a decrease in groundwater discharge during annual flooding. The timing of diminished groundwater discharge corresponds directly with the increase in river stage to an elevation greater than the hydraulic head recorded at RN034364. Once the river stage has exceeded the height of hydraulic damming, groundwater discharges temporarily ceases, until the river stage declines. The time series of simulated groundwater interaction with the Daly River begins to reveal a threshold for temporary flow reversal or at least seasonal cessation of groundwater discharge. However, immediately following the onset of river stage decline, groundwater discharge resumes. This cyclical pattern suggests that the bank storage process may be very short duration and possibly negligible where tropical rivers incise sedimentary rock aquifers. This finding is in contrast to the commonly assumed process of bank storage for alluvial sediments present on many rivers in Australia.

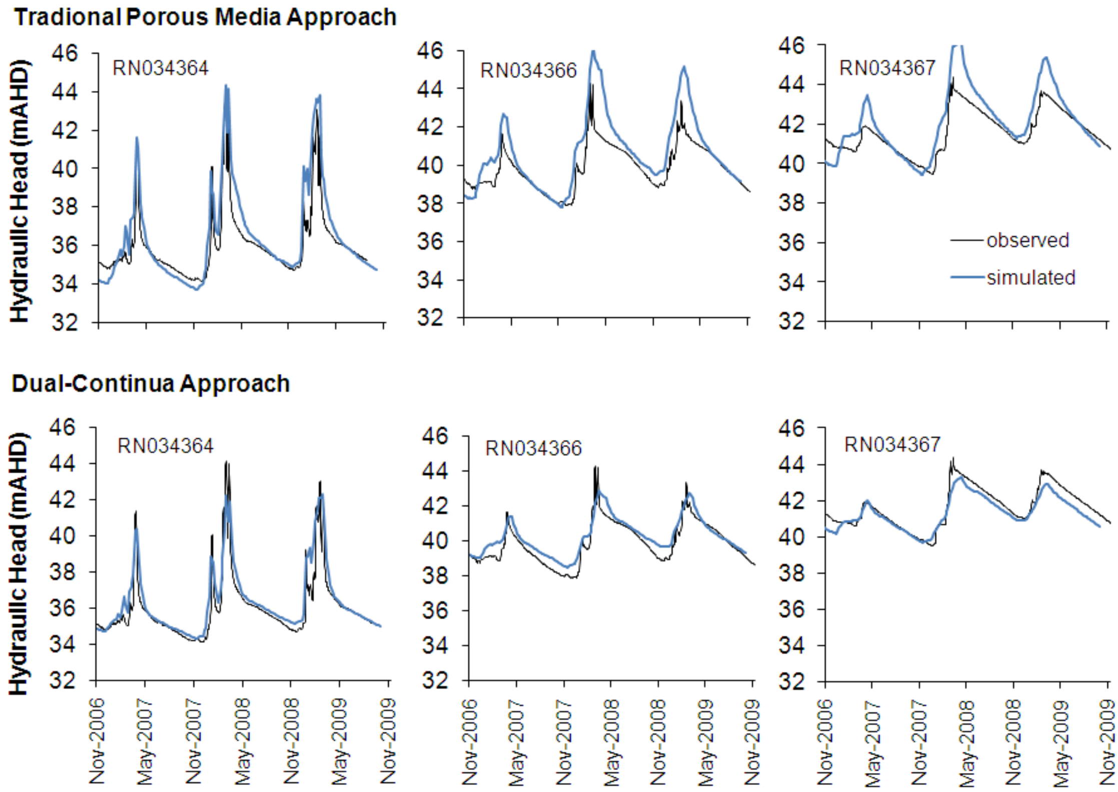


Figure 5-6 Comparison of observed and simulated hydraulic heads for 3 monitoring bores.

Table 5-1 Final calibrated Hydraulic Parameters

Parameter		Traditional Porous Media			Dual-Continua		
		Massive Dolostone	Inter-mediate Layer	Bedded Dolostone	Massive Dolostone	Inter-mediate Layer	Bedded Dolostone
Matrix	K (m/d)	60	0.01	2.5	0.15	0.75	2.5
	Ss (1/m)	5.E-04	5.E-04	5.E-06	1.E-03	5.E-04	1.E-05
	Porosity	0.3	0.3	0.3	0.3	0.3	0.3
	Volume Fraction	1	1	1	0.8	1	1
Conduit	K (m/d)	-	-	-	1000	-	-
	Ss (1/m)	-	-	-	1.E-06	-	-
	Porosity	-	-	-	1	-	-
	Volume Fraction	-	-	-	0.2	-	-
	Interface K (m/d)	-	-	-	0.01	-	-
	Fluid Exchange Coefficient	-	-	-	0.01	-	-

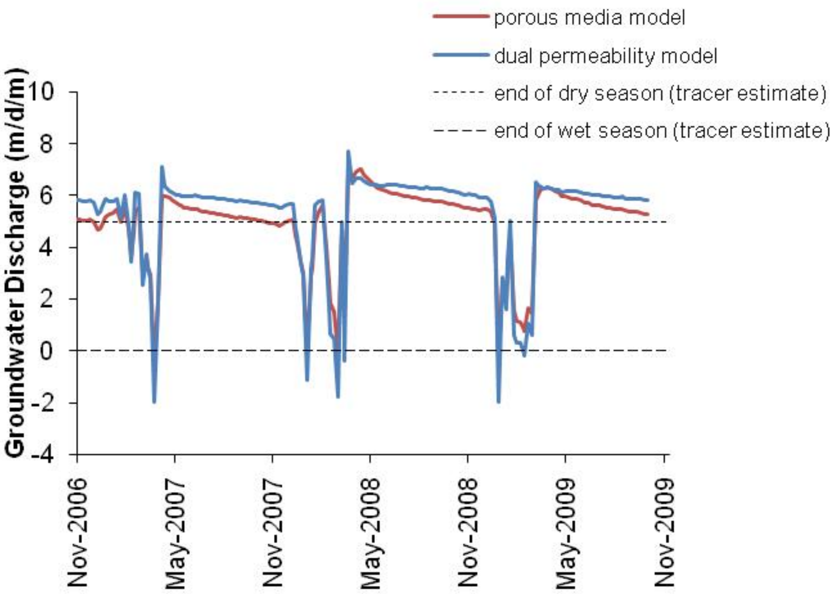


Figure 5-7 Time-series of simulated groundwater interaction with the Daly River compared with groundwater discharge estimates from Chapter 3.

Spatial distributions of simulated groundwater age provide a means of qualitatively comparing the numerical flow model with interpretations of groundwater age determined in Chapter 4. The traditional porous media approach resulted in groundwater with an apparent age of 500 years confined to the upper massive Oolloo aquifer and a vertical age gradient in the lower bedded Oolloo aquifer to a maximum age in the order of 10,000 years (Figure 5-8). Within 1 km of the Daly River, older regional-scale groundwater discharges to the river, as a result of the assumed boundary conditions in the flow model (i.e. the river is a regional sink). For the dual-continua approach, groundwater with an apparent age of 500 years is again observed in the upper massive Oolloo aquifer however stronger circulation with depth is present within 1 km of the Daly River. Furthermore, a large portion of the lower bedded Oolloo aquifer contains older regional-scale groundwater (Figure 5-8).

The difference between the two approaches is subtle, but illustrative of permeability control on mean transit time across the Oolloo aquifer layered sequence. The simulated distributions of groundwater age are the net result of minor variation in groundwater recharge rates across the cross section and three-layered hydrogeologic system. Thus, resultant isochones (lines of equal age) are not horizontal, but rather contain variability with depth and distance along the flow path.

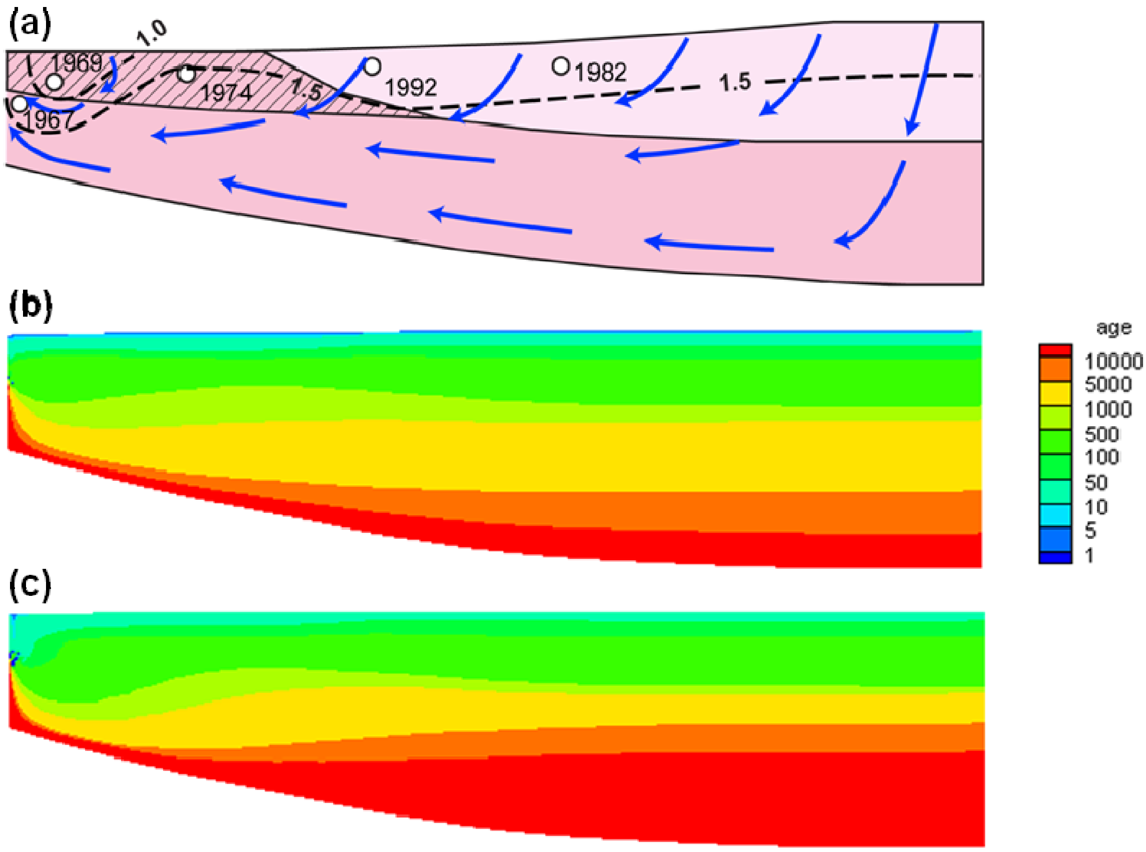


Figure 5-8 (a) Conceptual model of groundwater flow presented in Chapter 4. Years refer to the apparent SF_6 age, and dashed lines represent idealised $F(^4He)$ contours. The approximate depth of 1.5 $F(^4He)$ represents the differentiation of shallow cycling of modern water and older water at depth. (b) Simulated apparent groundwater age using traditional porous media model (age in years). (c) Simulated apparent groundwater age using dual-continua model (age in years).

5.3 *Key Findings*

Groundwater recharge was estimated for the Oolloo aquifer by three methods. Analysis of groundwater hydrograph data and subsequent numerical flow modelling build on the conceptual model of groundwater cycling proposed in Chapter 4. The following key findings add to a growing body of knowledge regarding the Oolloo aquifer:

- Vertical recharge was estimated to be 17 per cent of rainfall where the massive unit of the Oolloo aquifer (or more permeable sections of the bedded unit) is relatively close the the ground surface, and 7 per cent where overlain by sediments;

- For a simplified conceptual cross section, the modelled groundwater recharge rates appear to balance against estimated groundwater discharge (determined in Chapter 4). However, a high degree of uncertainty regarding the hydraulic parameters exists due to the karstic nature of the aquifer;

- When a dual-continua approach to modelling groundwater flow and apparent age is invoked, the unique transmission and storage properties (i.e. matrix and conduit flow) of the Oolloo aquifer could be replicated. Furthermore, qualitative comparison of apparent age appears to be useful for further constraining numerical models; and

- At Oolloo Crossing, groundwater levels exhibit a hydraulic damming effect that governs interaction between the Daly River and adjacent aquifer. This phenomenon suggests that bank-storage is minimal during the annual flooding, and that shallow groundwater adjacent to the river may be preferentially recharged vertically, rather than laterally.

6 Soil hydraulic properties of land units associated with the Oolloo Dolostone

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6.1 *Introduction*

Modelling surface water-groundwater interconnectivity requires data describing soil physical properties, vegetation water use, land use, topography and recharge processes. The relative contributions of surface runoff and drainage flux from the root zone to recharge needs to be quantified. One approach to archive this is to use biophysical models or SVAT models (soil-vegetation-atmosphere transfer). These models describe interactions between soil hydrological properties and depth, water table depth, vegetation characteristics and climate. A key component is the physical description of soil water holding capacity, the various forms of the soil moisture characteristic and unsaturated hydraulic conductivity. Most SVAT models use numerical solutions to solve the Richard's equation for unsaturated flow within the profile and can simulate redistribution and recharge below the root zone to aquifer. This enables water availability to vegetation to be calculated through a profile. Given water use, growth and root distribution of particular vegetation can be modelled as driven by climate, these models can be used to examine land use change scenarios and impacts on runoff and recharge processes.

Soil moisture dynamics are driven by soil water potential gradients developed by rainfall, surface evaporation, water uptake and drainage and SVAT models typically use soil hydraulic models such as those of Cambell and Shiozawa (1992) or van Genuchten *et al.* (1992) to describe both water holding properties plus saturated and unsaturated hydraulic conductivity as a function of water potential. There is a close coupling between soil available water and vegetation structure, particularly in savanna vegetation (Williams *et al.* 1996, Hutley *et al.* 2011), and modelling below-ground processes (root distribution, growth, canopy development and water use and soil moisture distribution) is critical for the accurate simulation of soil-vegetation-atmospheric transfer of water (evapotranspiration, ET). Robust simulation of soil water-vegetation dynamics results in accurate simulation of other components of the water balance such as runoff and drainage to aquifers.

This chapter aims to provide improved hydrological characterisation of land systems associated with the Oolloo region (the areal extent of the Oolloo Dolostone, Figure 1-1) that will enable more accurate modelling of surfacewater and groundwater connectivity via SVAT models (e.g. Chapter 7) for this groundwater system. While there has been extensive morphological descriptions and mapping of agriculturally important soil types across the Daly River catchment, there is little available data describing soil hydraulic functions and rainfall-runoff functions for all soil types. Data is available to describe rainfall-runoff relationships for agriculturally important red kandosol soils based on published functions of Dilshad *et al.* (1994, 1996b) but no data is available for land units with little agricultural potential that feature skeletal soils. These soils make up a significant fraction of the catchment and occur in upland, headwater areas and significant drainage and runoff is likely to arise from these land systems. If catchment scale modelling is to be precise enough to inform management decisions, hydraulic and runoff characteristics of these skeletal soils that occur in headwaters is required.

This chapter describes three aims to better describe surface hydraulics of land units associated with the Oolloo region, namely:

- measure of soil hydraulic properties with a focus on soils of the Oolloo region with little or no soil physical data;
- develop simple pedotransfer functions for the soil types sampled; and
- develop rainfall-runoff functions for land units featuring skeletal soils.

6.1.1 Methods

A range of observations were made characterising soils and vegetation types associated with the Oolloo region within the Daly River catchment, summarised in Table 6-1. These data will be combined with previous data collected and data from TRaCK Project 4.1 (Cresswell *et al.* 2011) to provide a comprehensive description of the hydraulic properties of major land unit types associated with the Oolloo region.

6.1.2 Site selection and sampling

Sites were systematically selected to ensure representative sampling of the dominate soil types associated with the Oolloo region. Soil types were selected on the basis of their extent, relative to the Daly catchment, their association with the Oolloo Dolostone and whether or not soil physical data were available. This was achieved using the Australian Soils Resource Information System (ASRIS) and in collaboration with NRETAS staff to design a field sampling protocol to capture the properties of dominant land units. Non-agricultural soil and vegetation units were targeted.

Sites representative of each of soil type were selected using criteria described above plus access to soil units of sufficient size to eliminated uncertainties related to edge effects. Replicated sampling of three soil types (Woggaman, Kimbyan, Beemla) at spatially independent sites was also undertaken across the Peanut Company of Australia's (PCA), Florina Road property, Katherine. These duplicated soil/sites were used to examine spatial heterogeneity within classified soil type. Sites were selected using a combination of the spatial ASRIS Level 4 soils product for the Daly catchment, NT roads and water course dataset. A site to be sampled had to be within a significant block of a particular soil unit to avoid boundaries, misclassification and influence associated with watercourses. Vehicle access was also a prerequisite although the record 2010/2011 Wet season with doubling of mean annual precipitation (MAP) restricted access to a number sites and significantly delayed sampling. Preselected sites were also assessed to ensure that were floristically representative of local vegetation type and prominent ecotones or variation in geomorphology was avoided. Sites also had to free from significant anthropogenic disturbance.

At each site representative of a soil type, three replicate locations were established within 100 m of each other and samples were collected at each location for analysis of texture, bulk density and for pressure plate analysis (tempe cells) for moisture release properties. Samples for all these analyses were taken from the surface 0-5 cm and at ~30cm depth. Infiltration and hydraulic conductivity measurements were also made at each of the three locations at a site.

Table 6-1 Land unit properties to be sampled across selected sites of the Oolloo region within the Daly catchment, with sampling conducted on land unit types with little or no previous hydraulic data.

	Variables	*Method*
Soils	Infiltration	Single ring infiltrometer
	Unsaturated and saturated hydraulic conductivity	Compact constant head permeameter and mini-disk tension infiltrometer
	Bulk density	Soil pits, ring sampling
	Particle size density	Soil pits, ring sampling and lab analysis
	Retention curves	Lab analysis, tempe cell 0-1 bar pressure range
Runoff	Rainfall-runoff function	Mini-flume installation, rainfall measurement
	Soil moisture dynamics	TDR sensor network, spatial surface sampling and profile / moisture redistribution analysis
Vegetation	Dominant species, basal area, mean height	NT Government vegetation unit classification, site observations

Additional sampling of soil physical properties was undertaken by TRaCK and NRETAS staff at three sites located in the Pine Creek area and on Theyona Station, Daly River, NT. The Pine Creek sites were located on skeletal soils of the Cully sub-group whereas the Theyona Station sites were deep Blain and Oolloo soils. These are included in these analyses and measurements are described by Kemei *et al.* (2012). At all six sites (Pine Creek, Theyona Station), a comprehensive sampling of soil physical properties was undertaken and included soil bulk density, infiltration, saturated and unsaturated hydraulic conductivity and water release characteristics.

Figure 6-1 provides a map of the Daly catchment and Oolloo boundaries, major roads and sampling sites plus the distribution of soils sampled. Table 6-2 provides the area of each of these soils as disturbed across the Daly catchment and the Oolloo region.

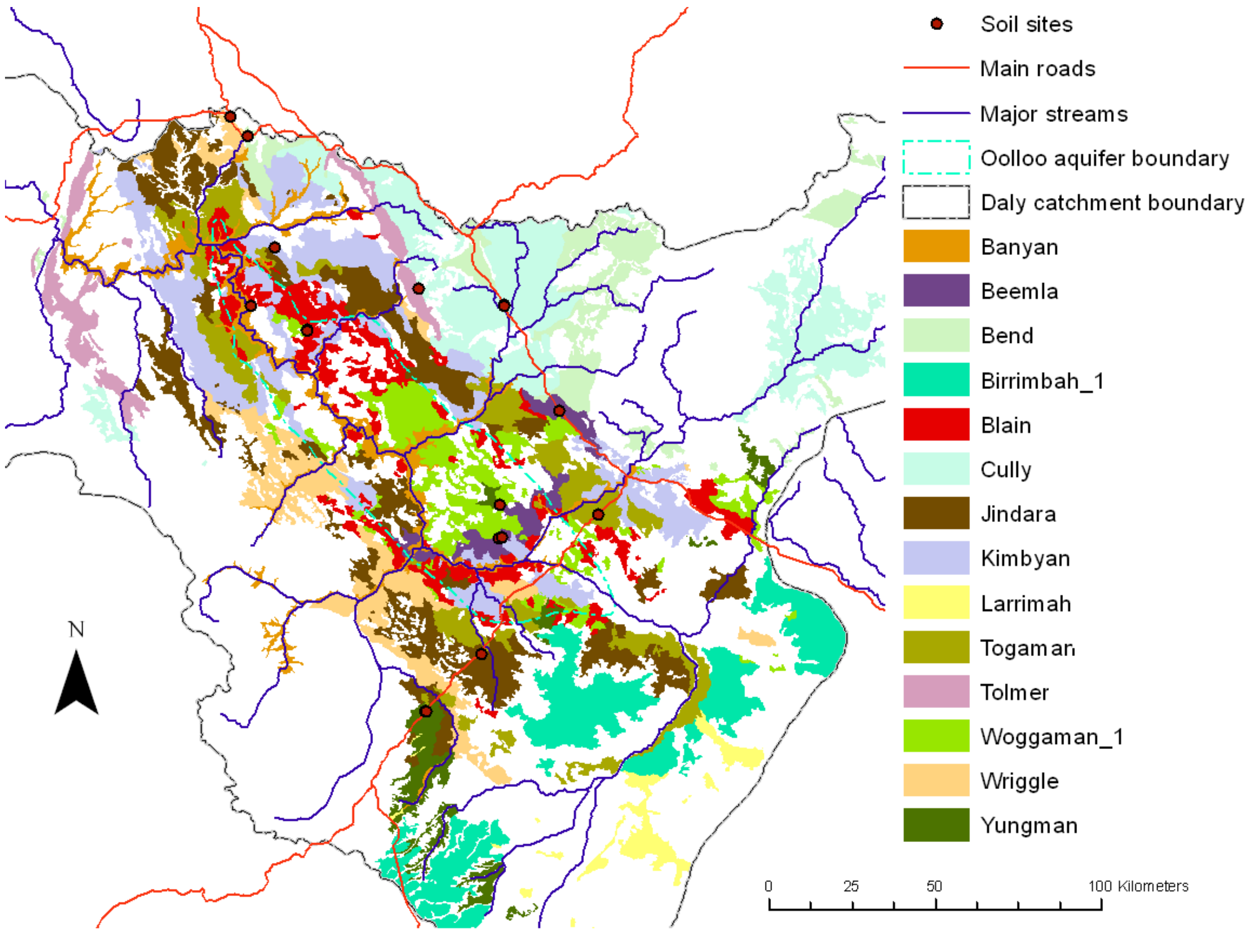


Figure 6-1 Sampling sites and the distribution of soil types associated with the Oolloo Dolostone within the Daly catchment.

Table 6-2 Relative extent of soil type within the Daly catchment and Oolloo region.

	Daly catchment		Oolloo region	
Soil type	Total area (ha)	% area	Total area (ha)	% area
Banyan	121611	2	57409	10
Beemla	38536	1	22279	4
Bend	130644	2	NA	
Blain	149640	3	106447	19
Cully	275928	5	NA	
Jindara	252200	5	23391	4
Kimbyan	236506	5	64578	12
Tagoman	162725	3	17623	3
Tolmer	64623	1	NA	
Woggaman	123653	2	91747	17
Wriggley	133263	3	13856	3
Yungman	60025	1	5773	1
Birrimbah	213262	4	NA	
Larrimah	43530	1	NA	
Total extent	2, 300,706	38	403,103	73
Catchment area	5, 232, 304		548,502	

6.1.3 Soil physical measurements

6.1.3.1 Bulk density

Bulk density (BD) was sampled in general accord with using stainless steel bulk density rings with an internal diameter of 73 mm x 50 mm height. The rings were bevelled on the outside face creating a cutting edge to ensure accurate sampling volume. A purpose built driving unit was used to forcibly insert the ring 25 mm below the surface to avoid organic matter or, in the case of the 30 cm sample, the disturbance associated with excavation of the pit. Once inserted, rings were carefully excavated, trimmed to length and bagged for laboratory processing. Samples were oven dried at 105^{o} C for 3-5 days, weighted and then passed through 2 mm sieved to remove of gravel. The separated gravel components where then shaken to remove any attached soil material before being re sieved. The clean gravel component was the weighted and its volume calculated by displacement in water.

Separation of gravel enabled both the total and fine earth fraction bulk density to be calculated:

Total (g cm^3) = dry soil weight / ring volume
Fine earth bulk density (g cm^3) = (dry soil weight – gravel weight) / (ring volume – gravel volume).

6.1.3.2 Textural analysis

Textural analysis of the soil types was used to quantify the relationship between texture and hydraulic properties (water characteristic curves, infiltration rate, hydraulic conductivity). Particle size distribution (per cent fine and coarse sand, silt, clay fractions) was determined using standard methods described by New South Wales Department of Sustainable Natural Resources (2001). Analyses were undertaken at The University of Melbourne's soils laboratory, Creswick, Victoria. The method employs sieving and sedimentation of a soil/water/dispersant suspension to separate particle of differing sizes. The sedimentation technique is based on an application of Stokes' law to a soil/water suspension and periodic measurement of the density of the suspension. For each soil type sampled, 50 g of air-dried soil was shaken for 16 h in a dispersion solution consisting of 200 mL of deionised water and 20 mL of 25 per cent sodium hexametaphosphate. The dispersed sediments are then stirred and suspended and subjected to hydrometer measurements over time after suspension (30, 93 and 420 minutes). Hydrometer measurements of a blank solution is also measured and temperature taken. Coarse sand fraction is extracted from the suspension following the hydrometer measurement using a 0.02 mm sieve with finer particles washed free. Particle size of each fraction is calculated as a function of hydrometer readings, sedimentation constants for particle densities and time (Laker and Duprez, 1982).

6.1.3.3 Soil moisture characteristic

Soil moisture characteristic curves were determined for the soils types sampled across the Oolloo region for the wet range of the curve, namely the 0.01 and 1.0 bar pressure (0.001 to 0.1 MPa). Hydraulic properties over this range determine both saturated and unsaturated flow through the soil profile and influence runoff characteristics. Parameters derived from water release functions are key components of soil moisture modelling in SVAT models. Curves were fitted to a range of common soil types. Data over the full range of matric pressures (0 to 15.3 bar) was determined using pressure chambers and will be presented for sites at Pine Creek with data from Theyona Station sites reported by Kemei *et al.* (2012). Release properties of soils over the wet range can be determined using a pressurised chamber or tempe cell into which an undisturbed soil core is inserted. A ceramic disc at the base of the cell acts as a semi-permeable barrier confining the soil material while allowing water within the sample to be expressed up to a known pressure, 1 bar (0.1 MPa) in this study. Expressed water from the cell exits through a port in the base of the chamber. The tempe cells (Plate 6-1) are pressurised with compressed air over a range of pressure increments up to 1 bar. Once the equilibrium soil mass and water content is reached for a given pressure, the cell is weighed and volumetric water content calculated. A curve of pressure versus volumetric water content is thus developed for each sample.

In this study, soil cores for the tempe cells were collected immediately adjacent to the bulk density ring sampling. Tempe cell samples were keep in the stainless steel ring used for bulk density and stored in plastic storage containers of similar dimensions and returned to the lab. This ensured soil structure was maintained for the determination of water characteristics. Support for both the top and bottom face of the sample is provided by the container ensuring that soil cannot become detached, altering sample structure.

Measurement started with a soil core being saturating in a water bath for 24 hrs prior to it being installed into a cell with saturated weight recorded. The core is then loaded into the cell within the stainless steel ring it was collected in with the bevelled edge first to ensure that the sample maintains the same orientation as it had in the soil profile and assists with inserting the ring into the tempe cell chamber. An o-ring seal was used with an air-tight cap to pressurise the tempe cell. The tempe cell apparatus constructed for this activity has the capacity to run up to nine cells simultaneously at two different pressures.

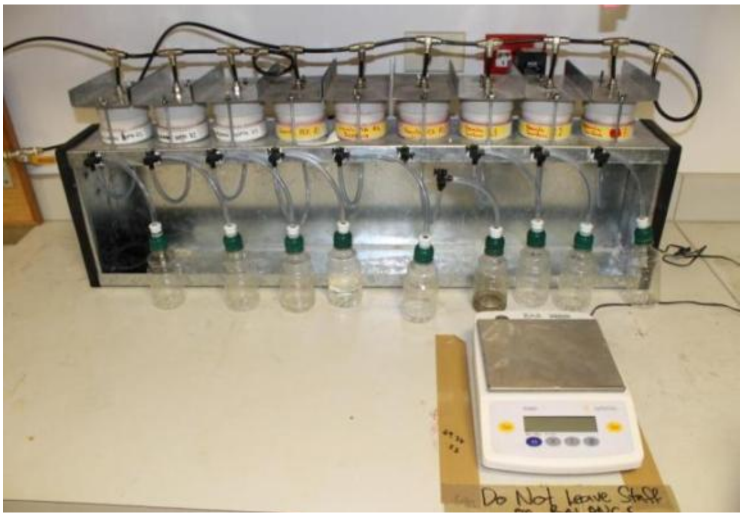


Plate 6-1 Tempe cells designed and constructed at CDU's ecophysiology laboratory to determine the soil moisture characteristics for each soil type over a 0.1 to 1 bar pressure range. Using this apparatus, nine samples can be tested simultaneously at two pressures.

Plate 6-2 Careful preparation of the soil horizon at 30 cm for mini-disc infiltrometer measurements

The pressurized cells are removed from the rig and weighted daily to determine the water loss. Equilibrium between water content and pressure was assumed to have occurred once no significant change in cell mass (due to water loss) was recorded. The time required for equilibrium to be achieved was highly variable between soil types and pressures. Once a group of cells reached equilibrium (no more water loss), the pressure was increased to the next increment. Pressures used were 0.01 (saturation), 0.1, 0.3, 0.5 and 1.0 bar. At the end of a run, soil within the tempe cell was removed, weighted and oven dried to determine volumetric water content.

6.1.3.4 Soil infiltration and conductivity

Hydraulic conductivity of soil at or near saturation is an important hydrological parameter and required for modelling of soil water redistribution and deep drainage. Three instruments were used to assess this important soil property, 1) a compact constant head permeameter (CCHP, Ksat Inc. Raleigh, North Carolina; Amoozegar 1989) to measure within profile, 2) a mini-disc tension infiltrometer (Decagon Devices, Pullman, WA, USA) and 3)(Plate 6-2) a single ring infiltrometer (Reynolds *et al.* 1990). The mini-disc infiltrometer was used across all sites and is able to impose a tension on the water column thus measuring unsaturated flow into the soil matric. Measurements were made at -2 cm tension for all observations at the soil surface and at 30 cm depth. Single ring infiltration was measurements were made at the three replicate locations, although not all sites were sampled for due to access issues.

6.1.4 Vegetation assessment

Vegetation floristic assemblage and structure was assessed via tree species identification and, basal area and tree height estimates at each site. At each site, mean canopy height was assessed from height measurements of a population of 15-20 trees randomly sampled across the three replicate locations used for soil sampling. Tree height was estimated using a using a clinometers with the observer at a known distance from each tree. Site basal area was assessed using a Bitterlich wedge prism. Sites were classified into floristic assemblages following Wilson et al. (1990) and the savannah vegetation classification of Fox et al. (2001).

6.1.5 Rainfall-runoff measurements

A small scale flume was constructed on a well defined ephemeral creek that captured runoff from a small headwater catchment (Plate 6-3 and Plate 6-4). The site was located on the Peanut Company of Australia (PCA) property, Florina Road, Florina (-14.606147°, 131.943513°). Soils at this site were classified as a red kandosol of the Woggaman group and were shallow (0.2-0.3 m soil depth), with a significant surface and sub-surface rock fraction. Slopes were up to 5 per cent with a catchment area of 2.75 ha. The flume consisted of a V-notch plate, a small stilling pond equipped with an Teledyne ISCO Bubble Flow Meter (Model 4230) to monitor water height above the V-notch base during periods of flow as well as rainfall events via a tipping bucket rain gauge. In addition, pressure sensors (Onset Hobo, U20 Water Level Data Logger) were installed at the V-notch base and within the power supply and data logger housing to monitor water and atmospheric pressure respectively. Logging of rainfall and runoff events was undertaken at high temporal resolution (two minute intervals). Three soil moisture monitoring stations were located across the catchment to monitor the spatial and soil moisture dynamics of moisture at the surface (5 cm) and the bottom (20-30 cm depths) of the soil profile. The ISCO flow meter was set to record water heights once rainfall occurred and sampling was undertaken at high temporal resolution (5 min measurements) given the likelihood of highly dynamic flow events given the small size of the catchment and shallow soils.

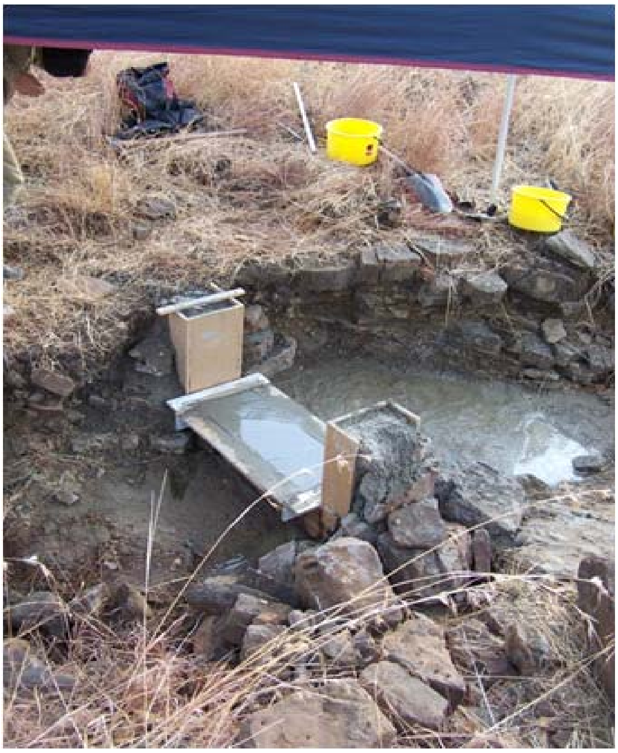


Plate 6-3 Mini-flume construction, November 2009 at the PCA site, Florina Rd, Florina, NT. The catchment was approximately 2.6 ha, consisting of undulating hills with shallow, rocky, skeletal soils. Photo, M. Northwood.

a b

Plate 6-4 Catchment conditions a) dry (August 2010) and b) during a Wet season flow event (March 2011). Photos, M. Northwood

6.2 *Results*

Below key data are presented for all available observations of soil physical and hydraulic properties and associated vegetation. Relationships between physical properties were examined and useful relationships are given. Standard water release functions are fitted and parameter estimates presented and also regressed against physical properties. The spatial distribution of infiltration and hydraulic conductivity is also presented by linking conductivity observations to existing soil maps for the Oolloo region. A rainfall-runoff function is developed for a small catchment characterised by shallow skeletal soil of the Woggaman type.

6.2.1 Soil and vegetation

Vegetation associated with each soil type sampled is given in Table 6-3. These soils occur across a wide range of land forms associated with the Oolloo region, from undulating plains or ridges with deep sandy loams to skeletal soils occurring in sandstone, granite or quartzite hills. The best developed stands in terms of productivity (height and stand basal area) occur on deep, well drained soils as opposed to skeletal, rocky soils.

6.2.2 Bulk density and texture analysis

Bulk density and particle size analysis (per cent clay, silt, fine and coarse sand fractions) for 18 soil types associated within the Oolloo region are given in Table 6-4. Bulk density was generally around 1.5 to 1.7 g cm^3, typical of earth soils with high siliceous content, which was ~ 80 per cent in the surface soils, with Blain soils 93 per cent sand in the surface horizons (Table 6-4). Clay content was variable and ranged from 5 to 35 per cent with Beemla, Bend, Cully and Wrigley soils types featuring rapid increases in clay at 30 cm. Gravel content was also variable, with Beemla, Birrimbah, Cully and Kimbyan having significant gravel by volume up to 35 per cent . Bulk density did not correlate with any of the texture classes.

6.2.3 Water release properties

Water release data is provided in Figure 6-2 and Figure 6-3. Figure 6-2 provides an examination of differences between soil types. Two groupings are evident, with the slope of volumetric water content (θ_v) vs H lower for soils (Blain, Oolloo, Mason, Cahill, Woggaman) with high sand (>85 per cent) and low silt (<8 per cent) fractions when compared to finer textured soils (Dashwood, Kimbyan, Cully, Wrigley, Beemla, Bend).

Water release data were fitted to standard functions given by van Genuchten et al. (1992) and a modified Campbell function (Paydar and Cresswell, 1996). Release curves were available over the full range of pressures (0.001 to 15.3 bar) and the wet end of the curve (0.01 to 1 bar). The Campbell B parameter is commonly used in soil hydraulic modelling and is predictable from sand and silt fraction for these soils. For all data sets, the Campbell model was used to fit parameters the air entry water potential (Ψ_a) and the B parameter. For sites with data over the full pressure range (Pine Creek and Theyona Station sites), both the Campbell and the van Genuchten models were fitted. Parameters derived from the van Genuchten equation include a, n, m and θ_r the residual water content. Parameters B and Ψ_a, the air entry water potential were derived from the Campbell model (Cambell and Shiozawa, 1992). Curve fits and parameter estimates were derived using Statistica Ver. 10 (StatSoft, Tulsa, USA) and were significant to P<0.01 (Table 6-5). The van Genuchten model reported correlation coefficients of 0.97 or higher with coefficients at 0.94 or higher for the Campbell model curve fits. The van Genuchten function produced the best fit to the data when compared to the simpler Campbell model (Figure 6-3).

Table 6-3 Vegetation and land forms typically associated with each soil type sampled. Descriptions taken from NVIS (http://www.environment.gov.au/erin/nvis/). At each site supporting woody vegetation, overstorey height and basal area was estimated. Shaded landform descriptions indicate soils that are typically skeletal and associated with rocky, upland land units, often headwaters of creeks and streams.

Soil type	*Floristic formation*	*Dominant species*	*Height (m)*	*Basal area (m^2 ha^{-1})*	*Land formation description*
Oolloo*	Eucalyptus woodland	*Eucalyptus tetrodonta, Eucalyptus miniata, Corymbia bleeseri*			Gently sloping or undulating lateritic plateaux. Soils, sandy or gravelly with some sandy loams and loams, extremely low fertility and moisture holding capacities
Banyan	Eucalyptus woodland		11.9	2.9	
Blain	Eucalyptus open forest	*E. miniata, E. tetrodonta, Erythrophleum chlorostachys*	16.4	8.3	Undulating low plateaux, rises and upper slopes of ridges. Soils vary from deep, well drained, yellow to red earthy sands, varying amounts of lateritic gravels, shallow, sandier soils are common
Beemla	Eucalyptus low woodland	*E. tintinnans, Corymbia dichromophloia, E. chlorostachys*	7.3	7.7	Sandstone, granite and quartzite hills and strike ridges, plains and valleys associated with rocky hills are also common. Shallow or skeletal gravelly sands between sandstone and granite rocks
Bend	Eucalyptus woodland	*E. tectifica, E. chlorostachys, Corymbia latifolia*	11.7	13.9	Undulating rises and plains, extending onto low hills. Soils, moderately drained loams and sandy loams. Some rock outcrops occur on hillier portions
Birrimbah_1	Corymbia woodland	*C. dichromophloia, E. tetrodonta, E. chlorostachys*	12.3	8.4	Flat to gently sloping plains, moderately deep and well drained red earth soils
Cahill	Eucalyptus low woodland	*E. tintinnans, C. dichromophloia, E. chlorostachys*			Sandstone, granite and quartzite hills and strike ridges, plains and valleys associated with rocky hills are also common. Shallow or skeletal gravelly sands between sandstone and granite rocks
Cully	Eucalyptus low woodland		8.9	8.1	
Dashwood	Eucalyptus low woodland				
Jindara	Eucalyptus woodland	*E. tectifica, E. chlorostachys, Corymbia latifolia*	7.6	5.0	Undulating rises and plains, extending onto low hills. Soils, moderately drained loams and sandy loams. Some rock outcrops occur on hillier portions.
Kimbyan	Eucalyptus woodland		10.1	12.5	
Larrimah	Melaleuca low woodland	*Melaleuca citrolens, Melaleuca minutifolia, E. pruinosa*			Low woodland/open woodland, plains/relict drainage fringe.

Table 6-3 continued

Table 6-3 continued

Soil type	*Floristic formation*	*Dominant species*	*Height (m)*	*Basal area (m^2 ha^{-1})*	*Land formation description*
Mason	Eucalyptus low woodland	*E. tintinnans, C.dichromophloia, E. chlorostachys*			Sandstone, granite and quartzite hills and strike ridges, plains and valleys associated with rocky hills are also common. Shallow or skeletal gravelly sands between sandstone and granite rocks.
Tolmer	Eucalyptus open forest	*E. miniata, E. tetrodonta, E. chlorostachys*	9.5	6.99	Undulating low plateaux and peneplains and rises and upper slopes of ridges. Soils vary from deep, well drained, yellow to red earthy sands, varying amounts of lateritic gravels, shallow, sandier soils are common.
Tagoman	Eucalyptus woodland	*E. tectifica, E. chlorostachys, Corymbia latifolia*	7.9	5.05	Undulating rises and plains, extending onto low hills. Soils, moderately drained loams and sandy loams. Some rock outcrops occur on hillier portions.
Wriggley	Eucalyptus low woodland	*E. tintinnans, C. dichromophloia, E. chlorostachys*	12.6	14.2	Sandstone, granite and quartzite hills and strike ridges, plains and valleys associated with rocky hills are also common. Shallow or skeletal gravelly sands between sandstone and granite rocks.
Woggaman	Eucalyptus woodland	*E. tetrodonta, E. miniata, C. bleeseri*	19.1	11.1	Gently sloping or undulating lateritic plateaux. Soils, sandy or gravelly with some sandy loams and loams, extremely low fertility and moisture holding capacities.
Yungman	Eucalyptus woodland	*E. tectifica, E. chlorostachys, Corymbia latifolia*	9.7	8.1	Undulating rises and plains, extending onto low hills. Soils, moderately drained loams and sandy loams. Some rock outcrops occur on hillier portions.

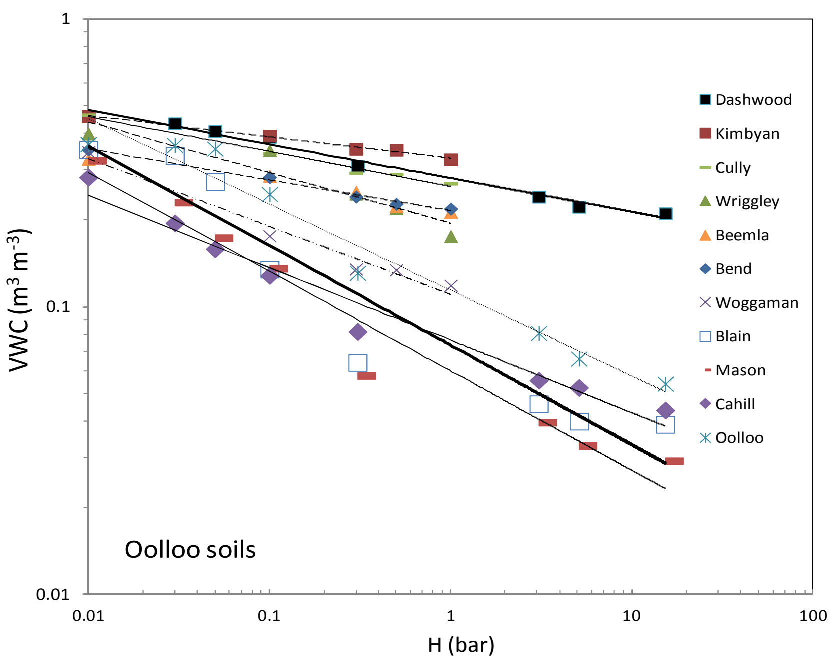


Figure 6-2 Log-log plot of volumetric water content (VWC) vs soil matric potential (H) derived from the tempe cell measurements for all soil types sampled. Data for the Blain and Oolloo soils taken from Kemei et al. (2012) and cover a 15 bar range of pressure.

Table 6-4 Mean soil bulk density and particle size analysis for soils across the Oolloo catchment. Samples were taken at the surface and 30 cm depth. SE is the standard error of the mean.

Soil unit	*Horizon*	*Bulk density (g cm^3)*	*SE*	*% Gravel*	*SE*	*% Clay*	*SE*	*% Silt*	*SE*	*% Sand*	*SE*
Blain	Surface	1.45		0		5.8		1.0		93.2	
	Depth	1.59		0		6.79		3.91		89.2	
Oolloo	Surface	1.64		0		10.7		1.9		87.4	
	Depth	1.44		0		9.87		3.0		87.2	
Banyan	Surface	1.36	0.06	0.17	0.13	8.31	0.60	9.18	0.76	82.51	1.36
	Depth	1.37	0.01	0	0	11.57	0.93	7.56	0.65	80.87	1.37
Beemla	Surface	1.79	0.07	21.12	7.46	9.20	1.73	13.95	3.05	76.85	4.76
	Depth	1.85	0.15	23.17	10.91	20.16	9.14	8.67	2.33	71.17	10.13
Beemla PCA	Surface	1.61	0.07	3.28	1.89	5.60	2.00	6.80	1.94	87.60	3.90
	Depth	1.71	0.04	4.63	1.64	14.56	4.05	8.53	0.47	76.91	3.64
Bend	Surface	1.6	0.03	1.48	0.92	9.05	1.14	12.85	0.25	78.10	1.17
	Depth	1.58	0	0.74	0.27	20.35	3.24	12.10	0.75	67.55	3.35
Birrimbah	Surface	1.72	0.11	13.54	12.4	11.54	5.80	6.04	3.05	82.42	8.63
	Depth	1.64	0.11	16.29	13.68	22.52	13.01	5.58	2.22	71.90	14.96
Cully	Surface	1.55	0.02	11.25	0.89	10.53	1.92	7.23	0.61	82.25	2.40
	Depth	1.72	0.11	15.67	4.23	30.31	12.78	8.83	2.86	76.44	2.39
Dashwood	Surface	1.42		6.5		24.1		45.3		30.6	
	Depth	1.51		12		50.3		25.6		24.1	
Jindara	Surface	1.51	0.04	4.08	3.17	12.37	0.53	21.71	1.39	65.93	1.31
	Depth	1.65	0.04	2.09	1.39	37.77	4.64	18.78	1.86	43.45	3.88
Kimbyan	Surface	1.76	0.03	27.82	4.66	8.38	0.85	12.54	1.12	79.09	0.51
	Depth	1.78	0.04	35.15	1.59	25.05	1.05	10.49	0.32	64.46	0.95
Kimbyan PCA	Surface	1.34	0.03	0.08	0.02	38.85	1.71	18.65	3.33	42.50	1.81
	Depth	1.35	0.04	0.04	0.02	43.85	3.25	18.82	2.01	37.34	1.30
Larrimah	Surface	1.56	0.05	4.33	2.38	40.70	3.18	12.49	2.43	46.81	5.54
	Depth	1.49	0.1	2.55	1.01	47.58	2.34	13.10	1.44	39.33	3.77
Masson	Surface	1.42				4.8		5.8		89.4	
	Depth	1.51				5.8		7.8		86.5	
Tagoman	Surface	1.63	0.03	1.85	1.54	13.31	3.22	12.15	2.23	74.54	5.44
	Depth	1.67	0.06	4.05	2.6	18.46	3.69	15.03	3.28	66.51	6.92
Tolmer	Surface					11.83		5.03		83.14	
	Depth					17.71		4.78		77.51	
Woggaman	Surface	1.61	0	7.25	3.04	8.58	4.46	4.64	1.31	86.78	5.09
	Depth	1.61	0.04	5.67	1.44	3.90	0.12	5.42	0.76	90.68	0.86
Woggaman PCA	Surface	1.61	0.03	0.83	0.47	7.35	0.36	12.34	1.25	80.31	0.98
	Depth	1.66	0.02	0.78	0.36	12.82	1.95	11.13	0.46	76.05	2.23
Wriggley	Surface	1.53	0.03	0.36	0.18	9.03	0.10	10.60	0.35	80.37	0.26
	Depth	1.61	0.04	0.18	0.02	23.55	2.58	12.14	0.84	64.31	2.79
Yungman	Surface	1.62	0.06	7.6	2.24	5.37	0.88	6.81	0.52	87.82	0.54
	Depth	1.76	0.11	27.8	7.49	10.72	4.63	6.36	0.74	82.92	4.88

Table 6-5 Fitted parameter values from surface soil water retention curves using Campbell and van Genuchten soil functions (van Genuchten and Nielsen, 1985). Release curves were available over the full range of pressures (0.001 to 15.3 bar) and the wet end of the curve (0.01 to 1 bar). Parameters derived from the van Genuchten equation include a, n, m and parameters B and Ψa, the air entry water potential, derived from the Campbell model (Cambell and Shiozawa, 1992). All parameter estimates were significant to P<0.01 using Statistica Ver. 10 (StatSoft, Tulsa, USA).

Soil type	θ_s ($m^3\ m^{-3}$)	θ_r ($m^3\ m^{-3}$)	a	n	m	B	Ψ_a (bar)	Water release ($m^3\ m^{-3}\ bar^{-1}$)
Oolloo*	0.373	0.054	0.175	5.220	0.176	4.13	0.019	0.286
Blain	0.330	0.030	0.230	3.576	0.258	2.76	0.015	0.283
Blain	0.354	0.039	0.207	3.931	0.414	2.89	0.011	0.307
Mason	0.350	0.022	0.584	2.066	0.318	2.89	0.008	0.277
Dashwood	0.469	0.186	0.171	1.206	0.365	10.41	0.015	0.192
Cahill	0.319	0.044	0.719	1.855	0.364	3.97	0.024	0.216
Bend	0.351					9.33	0.070	0.149
Kimbyan	0.459					13.46	0.087	0.136
Wriggley	0.399					4.32	0.037	0.263
Woggaman	0.345					4.25	0.008	0.264
Cully	0.464					8.26	0.009	0.202
Beemla	0.394					10.57	0.014	0.181

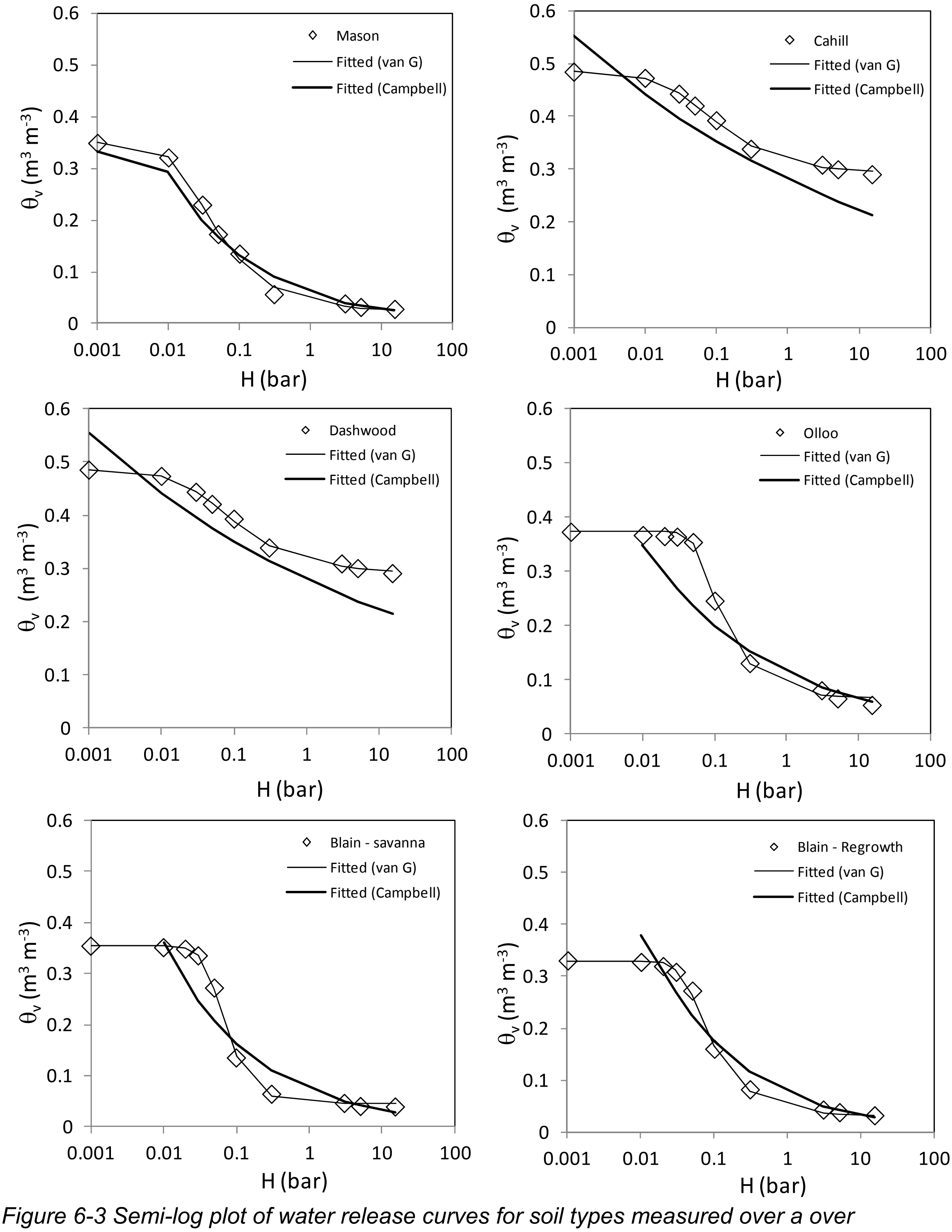


Figure 6-3 Semi-log plot of water release curves for soil types measured over a over a 0.01 to 15 bar range. Data from Kemei et al. (2012) for the Blain and Oolloo soil types. Blain samples taken from an intact savanna site and an eight year old regrowth site post-clearing with the Oolloo sampled from an improve pasture. Data were fitted using van Genuchten et al. 1992 and Cambell and Shiozawa, 1992) water release functions.

The slope of the lines in Figure 6-3 is the water released over 0.01 to 1 bar range (Table 6-5) and this was positively correlated with per cent sand and negativity correlated with per cent silt (Figure 6-4). No correlation was found with clay content (data not shown). Again, clay fraction was not correlated with this parameter, as was found with the relationship between the slope of the water release function (Figure 6-5). A similar measure of soil storage and release is the plant available water (θv at field capacity - witling point) and sandy, sandy loam soil types (Blains, Oolloo, Mason) ranged from 0.295 to 0.32 $m^3 m^{-3}$ compared with the heavier textured soils (e.g. Dashwood) with 0.18 $m^3 m^{-3}$ available.

6.2.4 Infiltration and hydraulic conductivity

Infiltration and hydraulic conductivity were sampled at the same locations as bulk density sampling, with data from the single ring infiltrometer (K_i), the mini-disc tension infiltrometer (K_{us}) and the constant head permeameter (K_{sat}) given in Table 6-6 . Single ring infiltrometer measurements followed an initial sorptivity phase followed by an increase in flow indicating a steady state, gravity dominate phase. The slope of this line is used to compute infiltration in units of m d^{-1}. Surface infiltration was variable, but relatively high, ranging from 0.15 to 37 m d^{-1}. Blain soil types had the highest rates and Jindara the lowest (Table 6-6). The most comprehensive assessment was made using the mini-disc infiltrometer and again rates were highly variable, with Blain, Woggaman and Jindara having rates ranging from 15, 5 and 0.75 m d^{-1} respectively (Table 6-6).

K_{us} was regressed against a range of physical properties including bulk density and texture classes with a strong relationship between per cent clay K_{us} at depth described by a power curve (Figure 6-6). The relationship with surface K_{us} was significant but with a higher degree of scatter and a regression coefficient of 0.55 (data not shown). To assess the spatial distribution of K_{us} across soil types of the Oolloo region, spatial maps of K_{us} based on ASRIS soil maps and observations of K_{us} were drawn for each soil type. Maps were prepared for both surface and 30 cm measurements (Figure 6-7). A spatial map for ring infiltration measurements, K_i was prepared similarly, although there are fewer data points available (Figure 6-8).

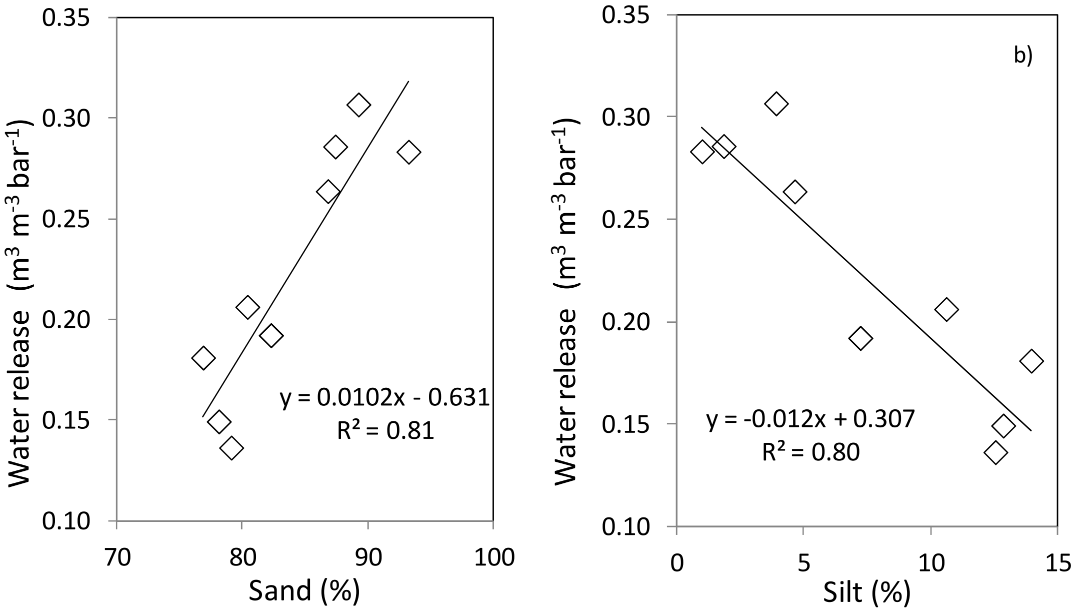


Figure 6-4 Water released per unit pressure plotted against a) per cent sand and b) per cent silt for all soils where both variables are available.

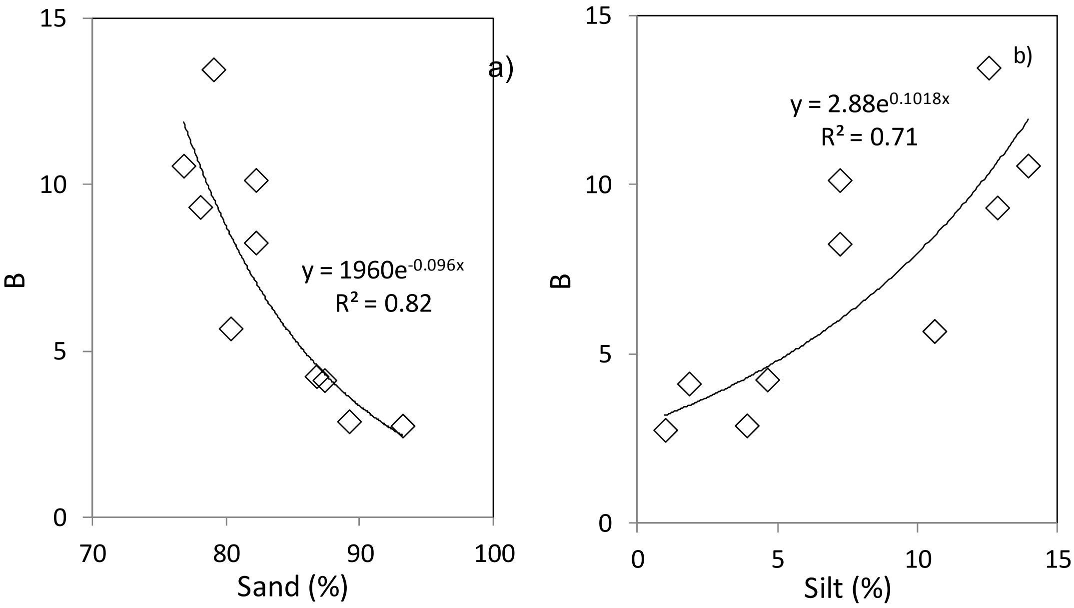


Figure 6-5 B parameter values from Campbell function plotted against a) per cent sand and b) per cent silt for surface soils where both variables were available.

Table 6-6 Infiltration rates measured using a single-ring infiltrometer (K_i) and a mini-disc tension infiltrometer measured at -2 cm tension for a range of soils (K_{us}). Observations were taken at the surface with litter removed and at 30 cm depth. Also given is saturated hydraulic conductivity (K_{sat}) measured using a constant head permeameter at 30, 60 cm and at 90 cm depth for the Yungman soil type.

Soil unit	Horizon	K_{us} ($m\ d^{-1}$)	SE	K_i ($m\ d^{-1}$)	SE	K_{sat} ($m\ d^{-1}$)	SE
Blain*	Surface	15.60	0.89	21.6	0.96		
	Depth	13.50	4.80	20.1	4.9		
Oolloo	Surface	2.43		2.32			
	Depth	2.15		2.37			
Banyan	Surface	3.39	0.28				
	Depth	5.73	1.94				
Beemla	Surface	0.60	0.12				
	Depth	0.62	0.14				
Bend	Surface	1.24	0.14				
	Depth	1.17	0.12				
Birrimbah	Surface	3.34	0.50				
	Depth	8.26	0.75				
Cully	Surface	0.50	0.09				
	Depth	0.53	0.20				
Jindara	Surface	0.75	0.07	2.74	0.30	0.19	0.03
	Depth	0.18	0.00			0.07	0.04
Kimbyan	Surface	2.66	0.06	7.42	0.76	1.02	0.17
	Depth	1.69	0.08			0.16	0.05
Tagoman	Surface	5.05	3.46				
	Depth	6.82	0.93				
Tolmer	Surface						
	Depth						
Woggaman	Surface	5.00	0.14	7.12	1.17	2.72	0.25
	Depth	14.00	0.20			0.88	0.24
Woggaman PCA	Surface	0.92	0.19				
	Depth	3.03	0.59				
Wriggley	Surface	1.64	0.22				
	Depth	0.61	0.05				
Yungman	Surface	3.96	0.17			0.77	0.10
	Depth	12.50	0.60			0.97	0.11
	Depth 2					1.23	0.26

*Rates for the Blain soils were derived from this study, Kemei et al. (2012) and Hignett (2011).

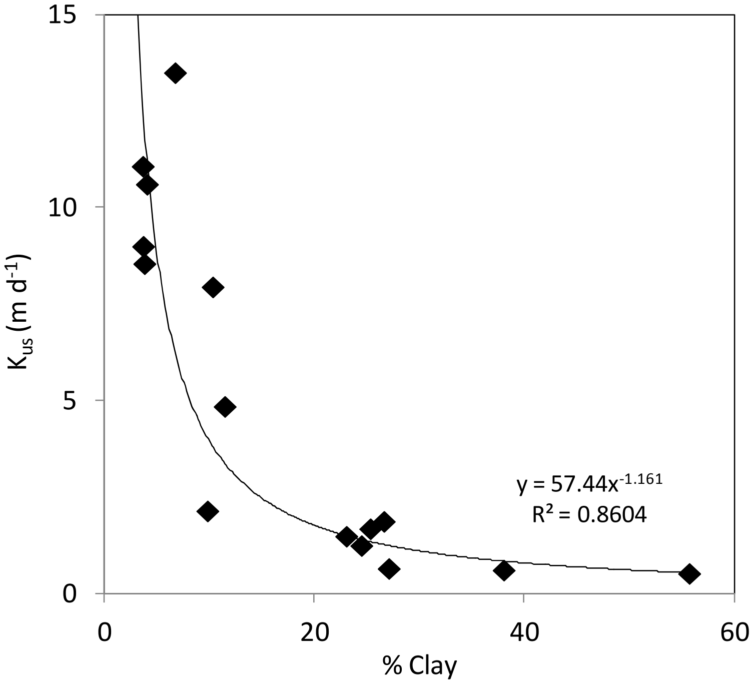
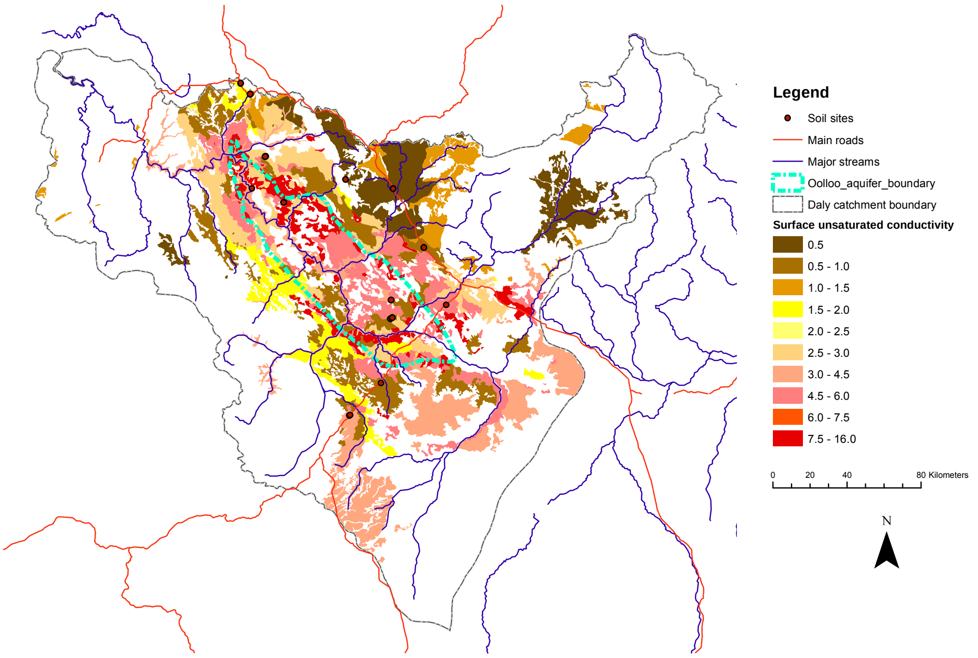


Figure 6-6 Plot of Kus at 30 cm depth vs per cent clay for observations at 30 cm depth.

a)



b)

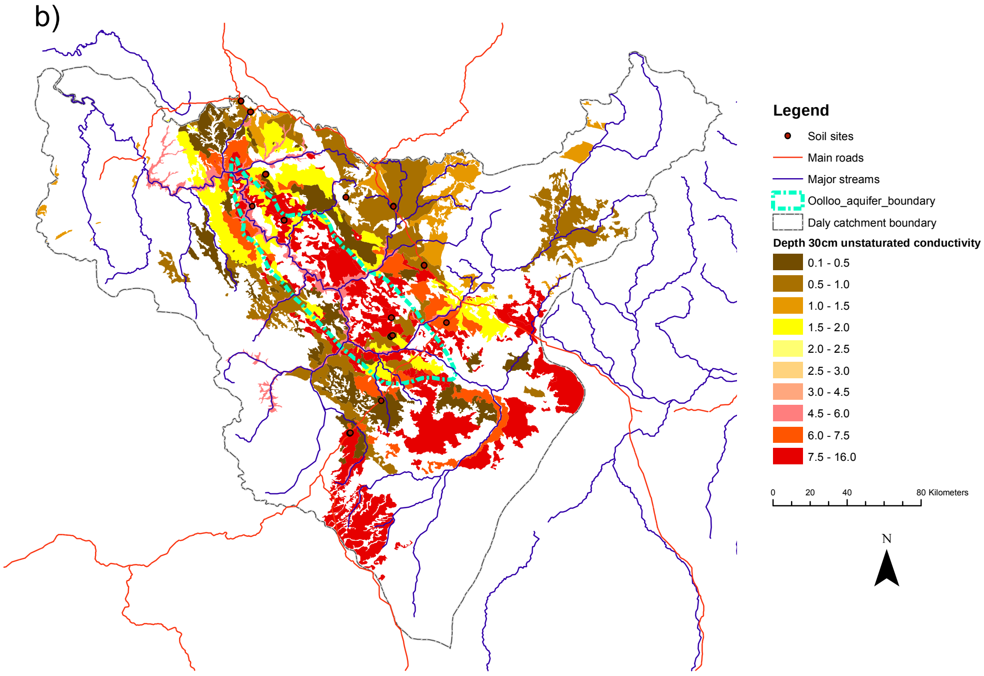


Figure 6-7 Spatial map of K_{us} for the Oolloo region derived from ASRIS soil mapping of Figure 6-1 but linked to estimates of K_{us} for measurements at a) surface and b) 30 cm depth. Coloured legend represents rates of K_{us} in m d^{-1}.

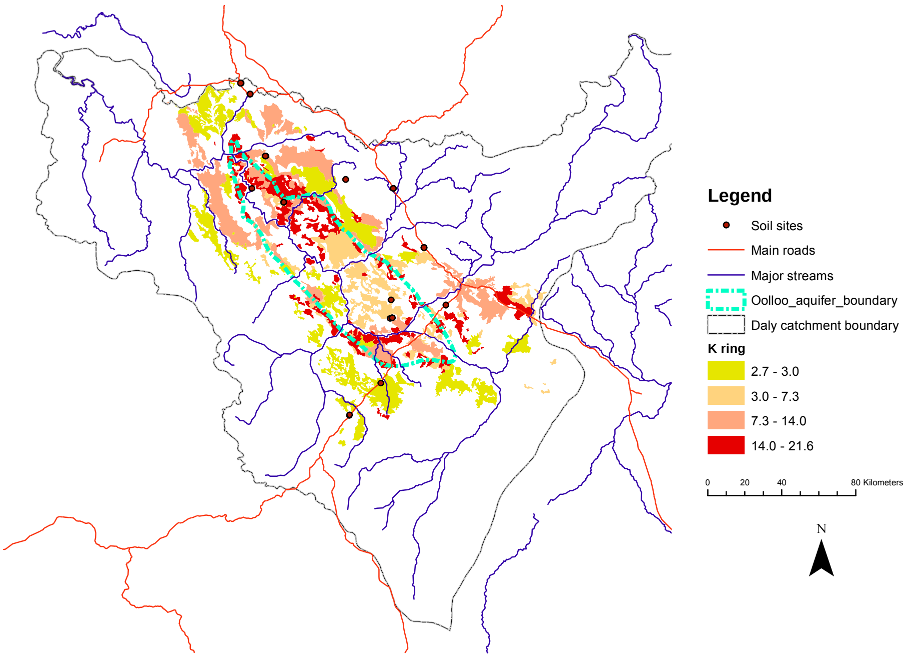


Figure 6-8 Spatial map of K_i for the Oolloo dolostone formation derived from ASRIS soil mapping of Figure 6-1 linked to estimates of K_i for measured soil types. Coloured legend represents rates of K_i in m d^{-1}.

6.2.5 Rainfall-runoff characteristics

The flume installed at the PCA site (Plate 6-4) provided data describing runoff for a given rainfall and antecedent soil moisture. The site featured shallow soils of the Woggaman order with ~10 per cent gravels by volume, ~ 10-15 per cent clay and ~80-90 per cent sand in terms of texture. Discrete rainfall and flow events were identified during the 2010-2011 Wet season and were matched with antecedent soil moisture. Events were captured from early December 2010 until the end of the Wet season in early April, 2011. Eighty events were captured spanning a soil moisture range of 0.04 to 0.45 m^3 m^{-3}. Runoff was calculated based on total flow volume (m^3) for an event as calculated from the 2 min water height above the V-notch using standard weir equations divided by the catchment area (2.75 ha). Moisture content at the beginning of an event (antecedent moisture content) was obtained from automated soil moisture sensors placed within the catchment. Over the period of measurements, volumetric soil water content ranged from 0.04 to >0.45 m^3 m^{-3} which is saturated water content for these soils, A typical event (9.6 mm over 1:45 h) is given in Figure 6-9 showing the rapid rise of V-notch water levels and slower recession post rainfall. Figure 6-10 describes the relationship between runoff and rainfall for all events where water height was within the V on the weir. The 2010-2011 Wet season was a record and a number of high flow events resulted in water levels at the peak or higher than the top of V notch, making discharge estimates unreliable. These high flow events were also associated with higher than expected levels of runoff and were excluded from analysis. Reliable events (43) were captured over the peak Wet season months of December to the beginning of April and represented 244 mm of rainfall for a total runoff of 113 mm, or 46 per cent of rainfall. The mean runoff fraction when averaged these events was 37 per cent. Figure 6-11 provides a surface plot of discharge as a function of antecedent soil moisture and event rainfall using a fitted quadratic equation to generate the surface (R^2=0.94, P<0.001).

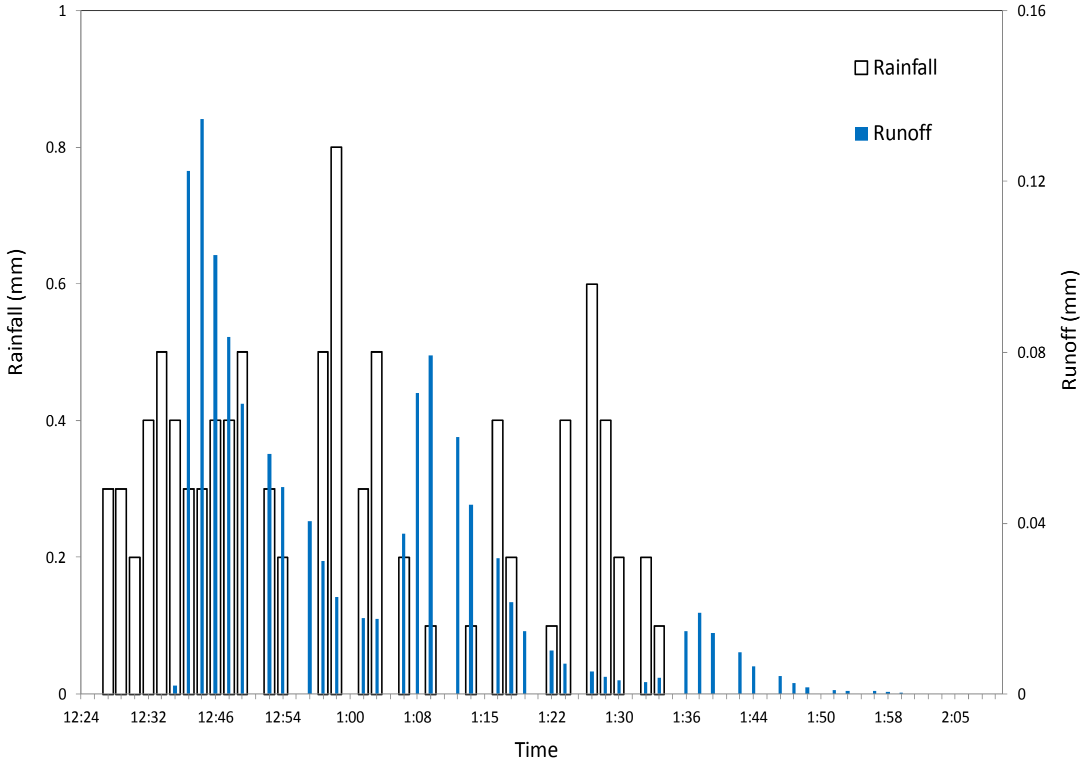


Figure 6-9 Typical low flow runoff event from the PCA flume on 7 December 2010. The total rainfall was 9.6 mm falling over a 1 h:46 min period which yielded 1.2 mm of runoff. Antecedent surface soil moisture content was low at 0.04 m^3 m^{-3}.

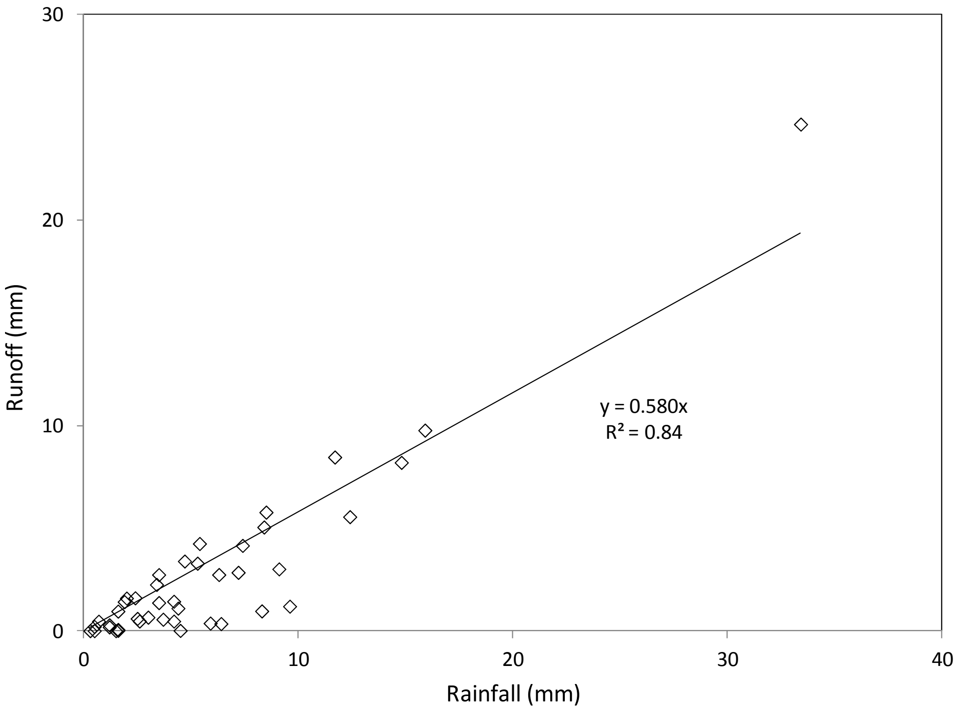


Figure 6-10 Runoff vs rainfall for 42 events for rainfall less than 40 mm.

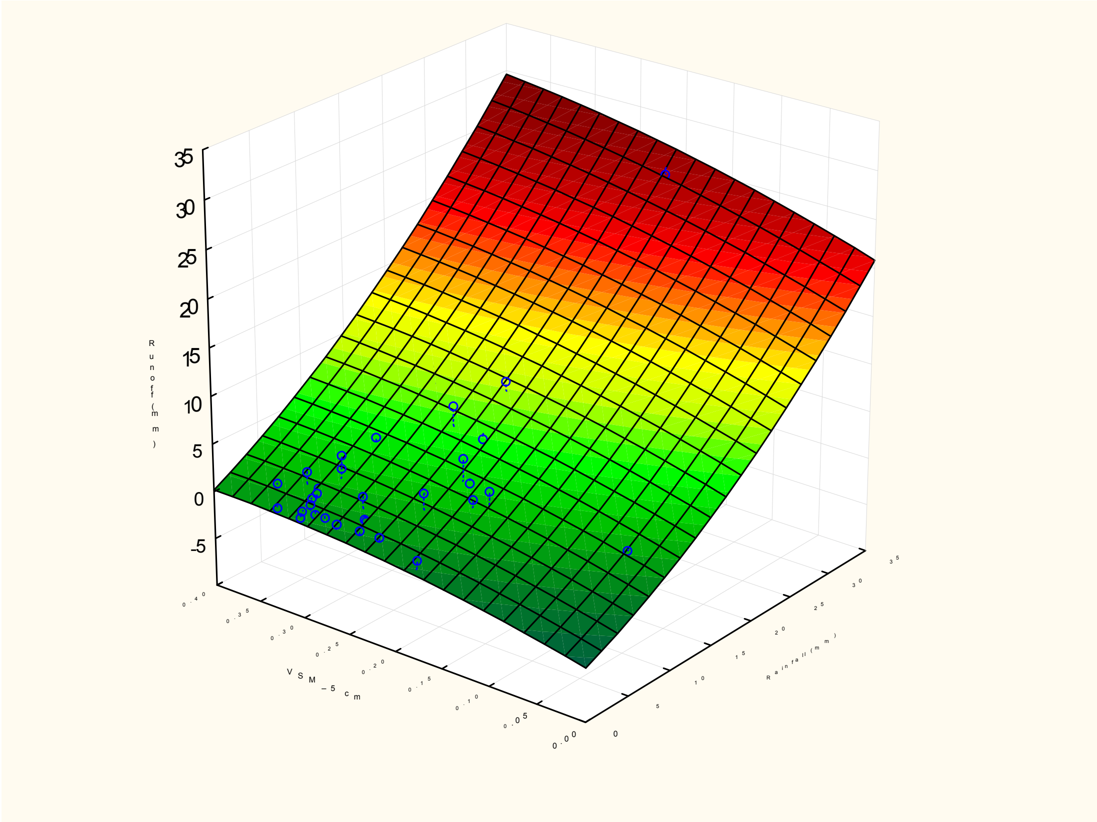


Figure 6-11 Runoff (mm) as a function of antecedent soil moisture at 5 cm depth and rainfall for all 80 events from the PCA flume. Katherine. The fitted surface is given by a quadratic equation with an r^2= 0 and was a significant fit (P<0.01).

6.3 *Discussion*

One approach to understanding surface water – groundwater interaction is to develop well parameterised SVAT models that partition rainfall into ET, runoff and deep drainage / recharge (see SWAT modelling, Chapter 7). This estimation of water flowing from the upper 5 m is partitioned into stream flow via lateral through flow or surface runoff or as recharge to surface aquifers. Essential to this understanding is robust descriptions soil hydraulics, in particular saturated and unsaturated hydraulic conductivity and soil water release characteristics that are central to modelling runoff, infiltration and water movement through soils plus uptake by vegetation. Spatial extrapolation is problematic and relies on spatial aggregation of properties derived from pedotransfer models (e.g. ASRIS Level 4 soil physical properties). These are derived from bulk density or texture classes and/or single values of soil matric potential at wilting point or field capacity (McKenzie *et al.* 2005). The ASRIS Level 4 data have a 1 km mapping window and is useful to describe groupings of geomorphologic related soil systems suitable for catchment planning rather than hydrological modelling (McKenzie et al 2005). For the Daly catchment and the Oolloo region, this level of data is not available. As such, management planning based on Level 4 data is problematic, and providing more precise hydrological characterisation of soils will result in improved estimations of recharge.

Across the Daly catchment, pedotransfer functions have been developed and applied to the entire catchment based on five or six sampling sites in agriculturally important soils only (Blain, Oolloo, Tippera, e.g. Day 1977). Previous measures of soil physical properties involved extensive disruption of soil structure via sieving and grinding prior to laboratory analysis which also adds uncertainty. Contemporary analysis is conducted on carefully extracted intact cores.

In this chapter, the properties of a wide range of soils have been presented for both agricultural and the non-agricultural soils. Texture ranged from sands to sandy clay loams and sand and silt fractions, as opposed to clay content, correlated well with water release parameters such as Campbell's *B* parameter (Figure 6-5) and van Genuchten *n* parameter, which describes particle size distribution. Such correlations are useful for the development of pedotransfer functions, which soil hydraulic properties to be inferred from simple measures such as soil textural analysis.

Across the soil types sampled, two distinct groups were evident (Figure 6-3) based on the slopes of their water release characteristics. Agricultural soils Blain and Oolloo were grouped and were significantly different to non-agricultural soils such as Cully, Bend, Birrimbah, Beemla, Dashwood and Kimbyan. Infiltration and Kus were an order of magnitude greater on the Blain and Oolloo soils (Table 6-6), with double the water holding capacity of the heavier textured, non-agricultural soils. The deep (2-10 m) Blain soils provide available water of up to 0.32 m^3 m^{-3} and when integrated over several meters of profile, provide a significant storage of available moisture (500-700 mm). Over 2 m depth, heavier soils such as Dashwood would only store ~300-400 mm. These soils are associated with headwater land systems (see Figure 6-1, Figure 6-7,Figure 6-8) with shallow profiles (< 1m depth Figure 7-11). They also contain higher clay and rock/gravel fractions than lowland, agricultural soils. Such differences significant influence rainfall-runoff functions (link to rainfall-runoff curve) and water release properties.

In the Oolloo region the non-agricultural soil types occupy 60 per cent of the, yet pedotransfer functions developed for these soils are not derived from any measurement in these land systems. As such, SWAT models calibrated using generic soil functions will not accurately capture runoff or drainage fluxes at these scales. This may be problematic when these models are used for scenario analysis to estimate impacts from climate change (shifts in evaporation, evapotranspiration, shifts in rainfall distribution and intensity) or land use change.

Water balance modelling for the Daly catchment has recently been undertaken by Creswell et al. (2011) via the Tropical Rivers and Coastal Knowledge Research hub (TRaCK). This modelling was aimed at quantifying catchment water balance as well as examining spatial and temporal patterns of water balance and shifts due to land use change (clearing). Of interest was changes in runoff and recharge as a function of vegetation change from deep-rooted, evergreen *Eucalyptus* dominated savannah to improved pasture. The SVAT model WAVES (Zhang and Dawes 1998) was used to simulate one-dimensional flow through the soil-canopy-atmosphere system. WAVES is a process-based model that integrates soil, canopy-atmosphere fluxes with a consistent level of process detail. The model is well suited to investigations of hydrological and ecological responses to changes in land management and climatic variation. It operates on a daily time step and is based on five balances: energy balance, water balance, carbon balance, solute balance and a balance of complexity, usefulness, and accuracy.

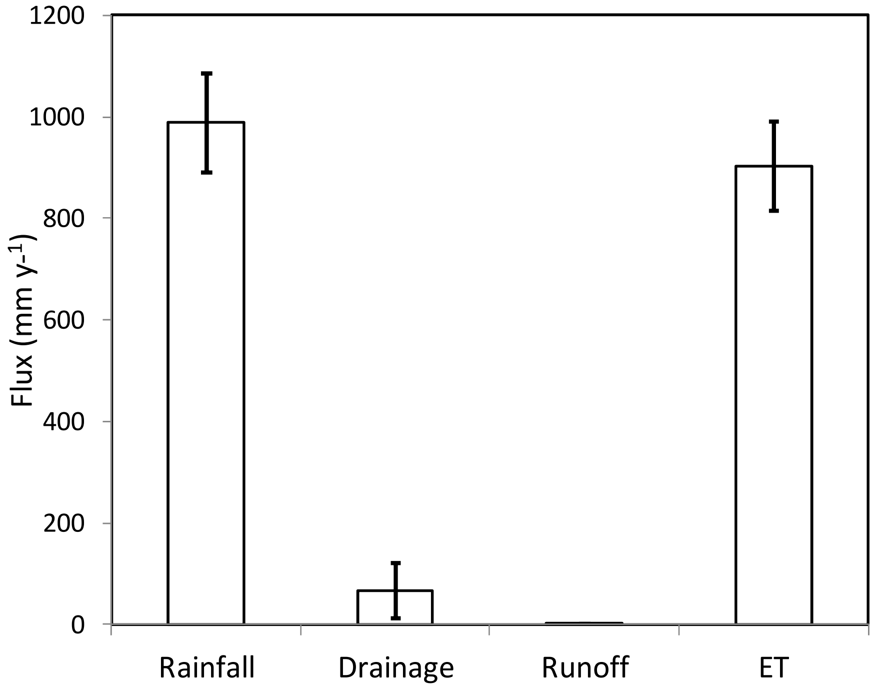


Figure 6-12 Simulated water balance components for land units of the Oolloo region using the WAVES SVAT model (derived from Creswell et al. 2011). Values are means and standard deviation for a 100 year simulation.

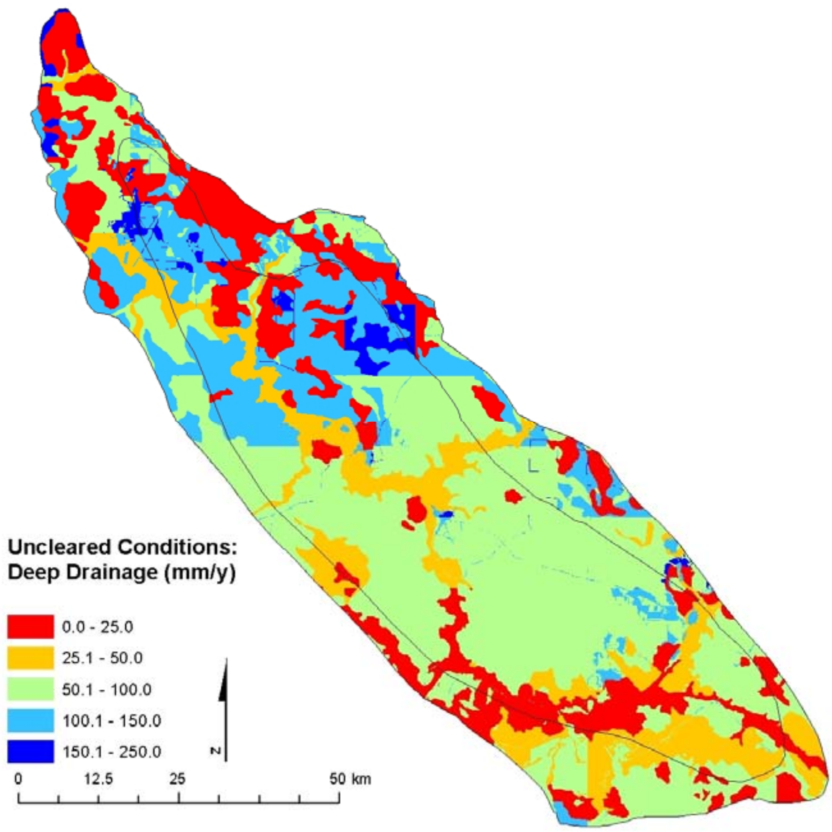


Figure 6-13 Spatial patterns of modelled deep drainage (mm y^{-1}) for land units of the Oolloo region using the WAVES SVAT model.

This approached featured the use of long-term (three year) observations of evapotranspiration and soil moisture dynamics from contrasting land use types in the Daly catchment linked to gridded climate, soils, terrain and slope models. Modelled water balance components of rainfall, drainage from the root zone, runoff and actual evapotranspiration (ET) for grids associated with the Oolloo region are given in Figure 6-12.

The ASRIS Level 4 soils mapping product was used to provide soil physical properties to drive modelling of recharge processes. Mean annual rates of deep drainage across the catchment for natural vegetation were highly variable, ranging from 0 to 150 mm+ y^{-1} (Figure 6-13) with a mean deep drainage of ~67 mm y^{-1} or 7 per cent of mean annual precipitation. If native vegetation was cleared converted to improved land types this term increased by 25 mm y^{-1}. This result change was highly spatially variable and was associated with a degree of uncertainty largely due to the paucity of soil hydraulic properties and runoff data across the catchment. Of particular uncertainty is the partition of excess water into either a drainage or runoff term.

The SWAT model as described in Chapter 7 also simulated ET and runoff for the Oolloo region and predicted an ET of 566 mm for the water year 1993/1994 for a rainfall of 1112 mm, a significantly lower ET for this amount of rainfall when compared to the WAVES output for the region (ET=993 mm). Over a two year period, the SWAT model predicted runoff during months with significant rainfall (>70 mm) as 15 per cent of rainfall for this region, double the estimate obtained from the WAVES modelling. However, when calculated for all months with rainfall, runoff as percentage of rainfall is 7.6 per cent. These broad scale estimates are significantly lower than headwater landforms with runoff 37 per cent observed at PCA flume site (Figure 6-11). During the Wet season runoff events from the PCA flume were up to 77 per cent of rainfall when intensity and antecedent soil moisture were high. Given the monsoonal rainfall and shallow soils, such runoff coefficients are possible for these land systems (Cook *et al.* 1998). For the Oolloo region, WAVES modelling estimated runoff as a percentage of annual rainfall at 0.7 per cent, suggesting this term has been underestimated which may mean an overestimate of deep drainage. These differences are significant and introduce some uncertainty into the estimates of runoff and thus drainage based on SVAT models. As such, models need to be parameterised with improved soil hydrologic properties, soil depth, rooting depth and topography and constrained using independent estimates of recharged based on groundwater geochemistry and isotopes (Chapters 4 & 5).

7 Rainfall Runoff Partioning

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7.1 *Summary*

USDA SWAT model was parameterised for early to mid 1990s for simulating surface runoff, soil profile water redistribution and evapotranspiration (ET) in the Oolloo region of the Daly River Catchment. The parameterisation relied on hydrological data and knowledge gained from the LAMSAT project and other historic research studies and monitoring programs within and outside the region, operational over this period.

Results show that SWAT is a very capable modelling system for modelling surface runoff, soil profile water redistribution and ET in the study area. Analysis of SWAT outputs, in terms of range and distribution, show good fits against observed data from disparate periods divorced from the period of model parameterisation. Observed data was obtained from the CERP project (1986/87) and from a Charles Darwin University project measuring ET and soil profile water (2008 to present).

The results provide a reasonable degree of confidence in the use of the model, as parameterised, over the entire region. A temporal and spatial sequence of surface runoff, ET and soil profile water, at a monthly time-step and sub-catchment scale, is presented in this report.

7.2 *Project Background*

The Department of Natural Resources, Environment, The Arts and Sport has been funded by the National Water Commission (NWC) to enhance current knowledge of the Oolloo-Dolostone groundwater system, its connectivity and interaction with stream flow processes, identify risks to groundwater and river water quality due primarily to the application of agrochemicals and to facilitate capacity building for effective management of the water resource for setting allocations within sustainable limits. Figure 7-1 shows the location of the region.

The purpose of this component of the project was to:

- parameterise the USDA-Soil and Water Assessment Tool (Neitsch *et al*. 2004 and 2005 and Winchell *et al*. 2007);
- model surface runoff for the Oolloo region using the USDA Curve Number Method (CNM; Dilshad and Peel*,*1994); and
- evaluate, where possible, model outputs against observed data and outputs of other physically sound models of collaborators (e.g. Charles Darwin University, and CSIRO) and other projects in the area.

The CNM is described in detail by Dilshad and Peel (1994) and Neitsch *et al*. (2005). A simple overview is provided later in this publication. Research conducted in the 1990s in the Daly River Catchment (refer: Dilshad and Peel 1994; Dilshad *et al.* 1995 and1996b; Motha *et al*. 1994, 1995a; and Motha and Dilshad 1997b), has shown that the CNM is highly useful in determining runoff from croplands, pastures and native vegetation. This research was conducted on experimental catchments on

Red Earths (Lucas 1984, Lucas *et al*. 1987), in the Douglas River district of the Daly R. Catchment (Dilshad and Jonauskas 1992; and Dilshad *et al.* 1996a).

A catchment/regional scale understanding of rainfall-runoff partitioning and water balance, in general, requires a spatial and temporal extrapolation of work such as those, above. The SWAT model provides the modelling framework to undertake such a regional/catchment scale extrapolation.

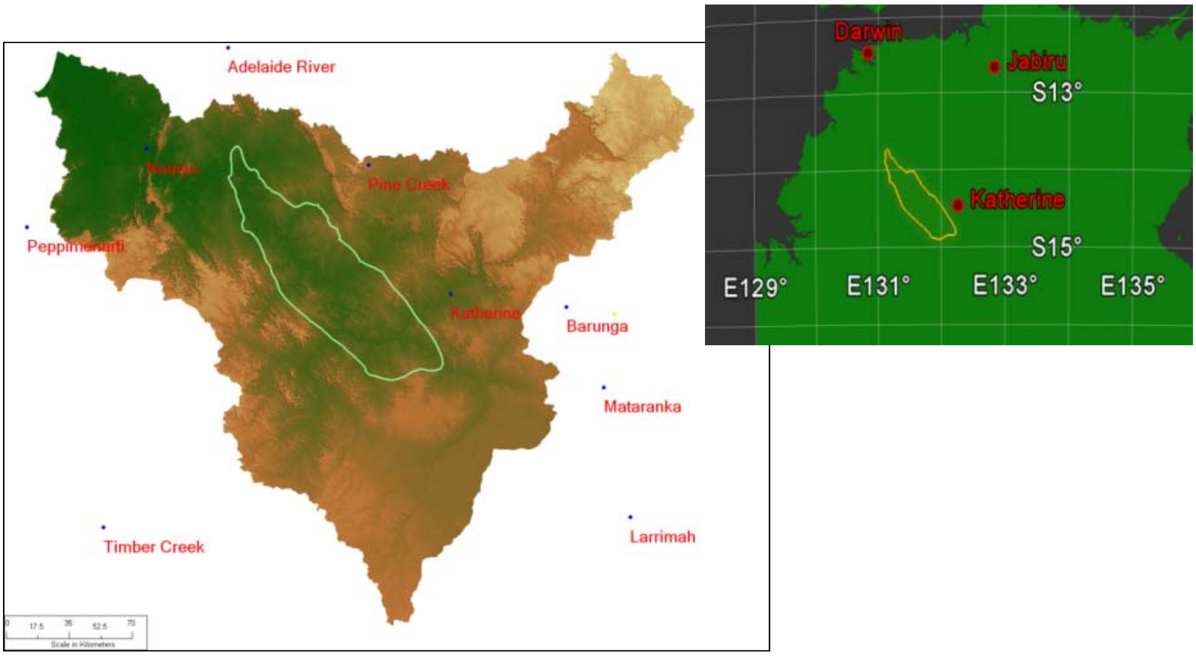


Figure 7-1 Oolloo region location within the NT context and boundary outline of the region overlain a 3 second digital elevation model of the Daly River Catchment

7.3 Background to the SWAT Model

The SWAT model is described in great detail in the approximately 1,500 pages of end-user documentation on the structure of the model, data input requirements, description of processes modelled, and operational manuals. Only a brief description is, therefore, provided in this publication.

7.3.1 Model Genesis

The SWAT model was developed at the Soil and Water Research Laboratory of U.S. Department of Agriculture (USDA, Arnold *et al*.1998; Neitsch *et al*., 2004). The genesis of SWAT lies mainly in the SWRRB (Simulator for Water Resources in Rural Basins; Arnold et al., 1990) model and contains features from ROTO (a continuous water and sediment routing model; Arnold *et al*., 1995), GLEAMS (Groundwater Loading Effects of Agricultural Management System; Leonard *et al*., 1987), QUAL2E (Enhanced Stream Water Quality Model; Brown *et al*.1987), CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems; Knisel, 1980), and EPIC (Erosion-Productivity Impact Calculator; Williams *et al*., 1984).

7.3.2 Model Framework and Capabilities

SWAT is a physically based model and can assist natural resources managers in assessing and predicting the impact of urban and rural land uses and management on the water balance and stream flow, sediment loads and nutrient and pesticide yields in large ungauged catchments with varying soils and physiography (Winchell *et al*. 2007). It allows for a number of physical processes to be simulated (Figure 7-3, Figure 7-4 and Figure 7-5).

The first task SWAT requires, before any modelling is undertaken, is the division of the studied catchment into sub-catchments. Each sub-catchment is then further divided into Hydrological Response Units (HRUs;Figure 7-2), based on sub-catchment slopes, soils, and land cover/management. In other words, HRUs identify areas within the sub-catchment which are similar or dissimilar in their hydrological response. It is at this HRU level that SWAT computes the daily water balance and integrates for the whole catchment (Figure 3). A sub-catchment is commonly divided into 5 to 12 HRUs.

The major components within SWAT are: climate, hydrology, land cover/plant growth, erosion and sedimentation, nutrients and pesticides, and management (Winchell *et al*. 2007). It uses physically-based inputs (e.g. soil characteristics for up to 10 layers, topography, land use, management, precipitation, air temperature, solar radiation, wind speed, and relative humidity) and is intended for continuous long-term simulation usually on a daily time step. (SWAT includes options for the Green and Ampt infiltration equation using rainfall input at any time increment and channel routing at an hourly time step; Winchell *et al*. 2007).

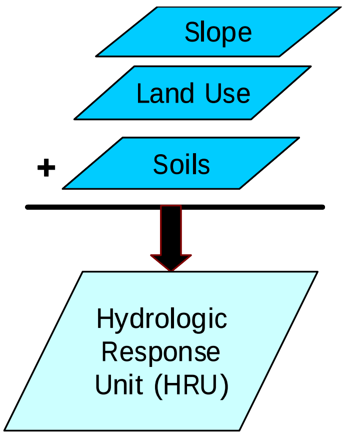


Figure 7-2. The makeup of Hydrological Response Units (HRUs).

7.3.3 Water Balance

Water balance is the driving force in SWAT model simulation, no matter what is being modelled. To accurately predict any process (e.g. movement of sediment), the hydrological cycle is modelled and must conform with what is happening in the catchment (Neitsch *et al*. 2004 and 2005; Winchell *et al*. 2007).

SWAT defines, on a daily basis, the hydrology by a specific list of processes and parameters, including: interception, evapotranspiration, surface runoff, lateral flow, soil moisture redistribution, return flow, percolation to shallow aquifer and ground water flow as well as river routing processes. SWAT hydrology is split into a land phase (see Fig. 3) and a routing phase (Figure 7-4). Figure 7-5 illustrates the schematics of pathways available for water movement in SWAT.

The land phase modelling simulates and models the process identified in Figure 7-3 and defines (controls) the amount of water, sediment, nutrient and pesticide loading to the main reaches (channel) in each sub catchment (Neitsch *et al.* 2004 and 2005).

The routing phase defines the movement of water, sediments, nutrient and pesticide in through the channel network of the catchment (and impoundments), to the outlet. Routing phase simulation is beyond the scope of this project and the rest of the report will be restricted to the land phase modelling, particularly surface runoff, evapotranspiration and soil profile moisture.

7.3.4 Land Phase of the Hydrological Cycle

The various inputs and processes involved in the land phase of the hydrological cycle includes: climate (e.g. precipitation, air temperature, solar radiation, wind speed, and relative humidity); hydrology (e.g. canopy storage, infiltration, redistribution, evapotranspiration, lateral subsurface flow, surface runoff, ponds and lakes, tributary channels, return flow); land cover/plant growth (e.g. potential growth, potential and actual transpiration , nutrient uptake, growth constraints); erosion; nutrients; pesticides; and land use\management.

The user documentation for SWAT describe all processes and inputs in detail. In this report, a brief summary of runoff, evapotranspiration and soil profile moisture inputs and processes is provided.

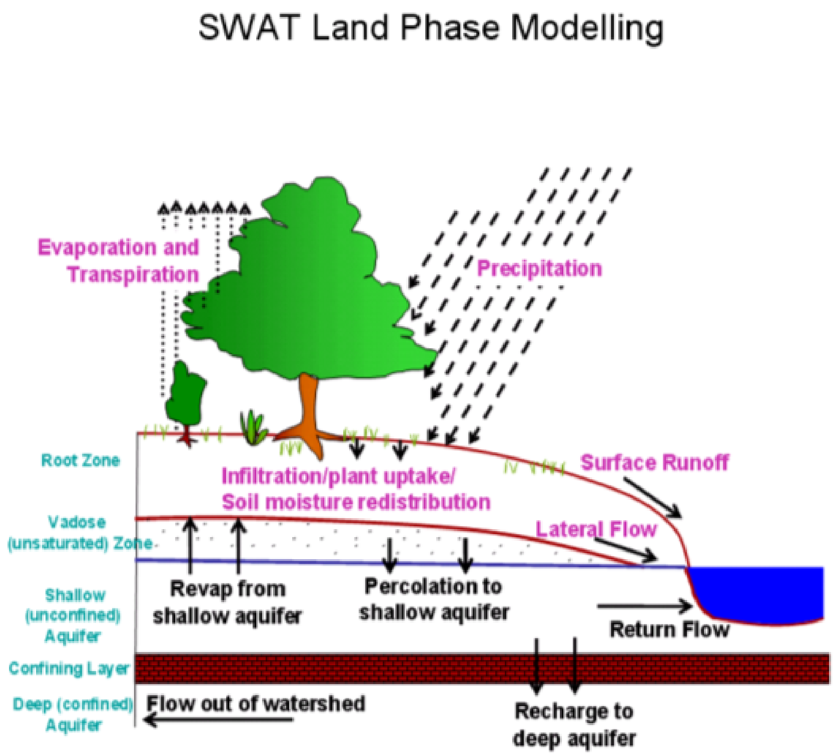


Figure 7-3. Terrestrial processes that can be modelled with SWAT (Adapted from the USDA-SWAT user manual)

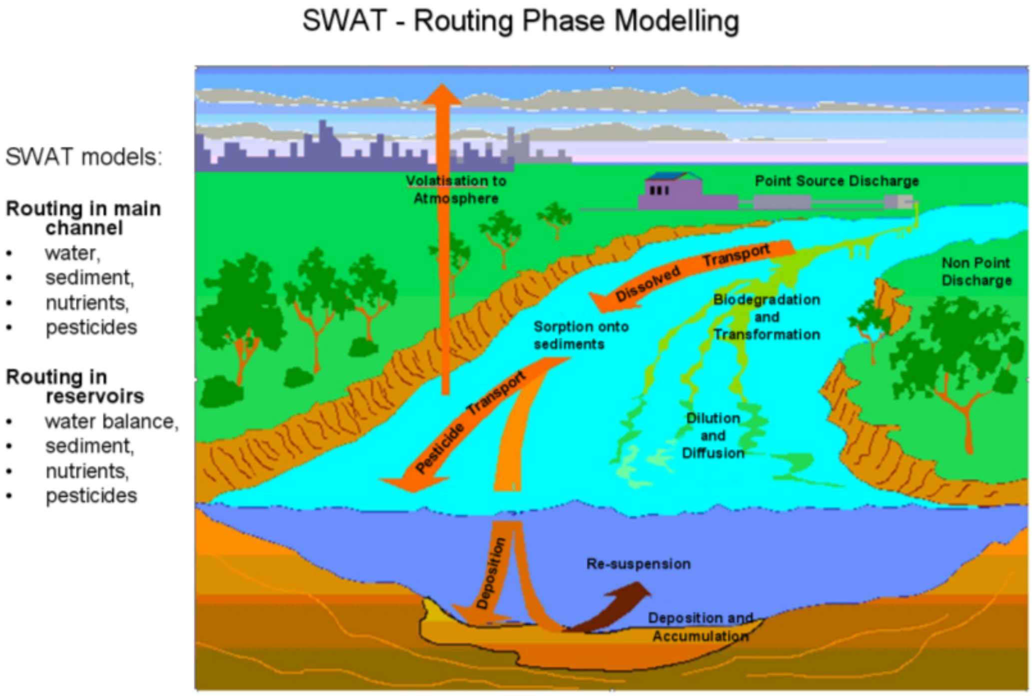


Figure 7-4. Routing Phase modelling in channels and impoundments that can be undertaken with SWAT. (Adapted from the USDA-SWAT user manual).

7.3.5 Surface Runoff

SWAT provides two methods for estimating surface runoff, at the HRU level, namely: the USDA Curve Number Method (CNM, Dilshad and Peel 1994) and the Green and Ampt Infiltration Equations (Green and Ampt 1911).

The CNM, described in detail by Dilshad and Peel (1994) and Neitsch *et al*., (2005), has been extensively studied and used for modelling purposes in the Douglas River sub-catchment of the Daly River (refer: Dilshad and Peel 1994; Dilshad *et al.* 1995 and1996b; Motha *et al*. 1994, 1995a; and Motha and Dilshad 1997b). These studies have been undertaken by the author for cropland, pastures and native woodland, conditions. The version of CNM studied in this region include the original which utilises five day antecedent rainfall as an index of antecedent soil moisture and improved versions which allow for daily soil profile moisture with varying daily vegetation cover (refer: Motha *et al.* 1995a and Motha and Dilshad 1997b). The latter improved version of CNM is used for SWAT modelling in this study.

The CNM operates on a daily time step and utilises non linear curves dependent on antecedent soil moisture, retention parameter (based on changes in soils, land use, management, slope), daily rainfall, and initial abstraction (storage interception, and infiltration prior to runoff) and are used to determine surface runoff from ungauged catchments. Essentially as soil moisture drops and approaches wilting point, the Curve Number (CN) approaches 0. The CN approaches 100 as moisture approaches saturation. (Winchell *et al*. 2007).

The Green and Ampt Infiltration Equations can operate at very short time step (e.g. sub-hourly) and requires rainfall input at that relevant time-step. It calculates infiltration as function of a wetting front matric potential and hydraulic conductivity.

Water that does not infiltrate becomes runoff (Neitsch *et al*. 2005). Peak runoff rate is computed using a modification to the Rational Formula or using the TR-55 method (refer: Neitsch *et al*. 2005).

7.3.6 Evapotranspiration

Evapotranspiration is a collective term which includes evaporation (from soils, water bodies, vegetation surfaces) and transpiration (evaporation from within the leaves of plants (Neitsch *et al*. 2005).

SWAT calculates potential evapotranspiration (PET) using one of three methods, namely: Hargreaves (Hargreaves and Samani. 1982), Priestley-Taylor (Priestley and Taylor 1972), and Penman-Monteith (Monteith 1965). Actual evapotranspiration is determined from PET, as reviewed by Neitsch *et al*. 2004 and 2005 and Winchell *et al*. 2007. The Penman-Monteith method was used for this study.

SWAT first evaporates any canopy storage and then determines maximum transpiration and maximum evaporation. The maximum ET is determined using functions related to the leaf area index (Neitsch *et al*. 2005). Actual ET is determined using adjusted maximum transpiration (for water and plant growth constraints) and adjusted maximum evaporation (for shading effect, plant water use etc, Neitsch *et al*. 2004).

7.3.7 Soil Water

Water that infiltrates soil may redistribute by a several pathways, including plant uptake and evaporation (i.e. the ET component), percolation past the root zone and ultimately becoming aquifer recharge, or moving laterally and becoming stream flow. Generally the ET accounts for the bulk of the soil water redistribution.

The SWAT theoretical documentation (Neithsch *et al.* 2005) provides the detailed mathematics describing the above processes. In essence, SWAT uses routing techniques to predict percolation through each soil layer. Water is allowed to percolate if water content of the layer exceeds field capacity and the layer below is not saturated. SWAT also uses “cracked flow” (“bypass”) model which allows percolation of infiltrated rainfall through cracks and macro pores, even in situations where soil water content is less than field capacity. Research has shown bypass flow to be an important percolation and recharge process in the Daly River catchment (Wilson *et al.* 2006). The bypass model option was utilised for this study.

The portion of soil water that does not percolate out of the layer becomes part of layer stored water and cannot percolate until storage exceeds field capacity (Neithsch *et al.* 2005).

Lateral subsurface flow in SWAT is computed using the kinematic storage model (Sloan *et al.* 1983). The model accounts for variation in conductivity, slope, soil water content, and allows flow upward to surface.

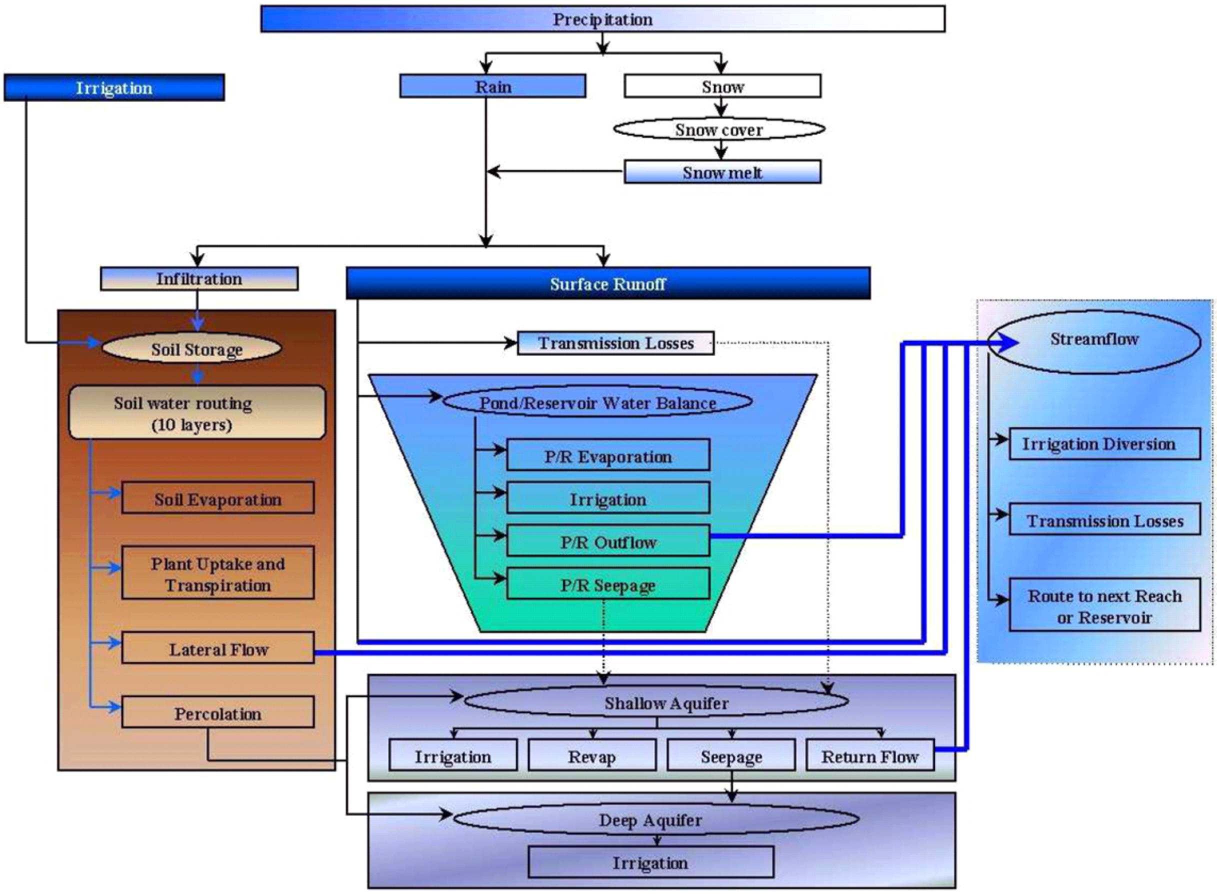


Figure 7-5 Schematics of pathways available for water movement in SWAT. Source: USDA_SWAT user manual.

7.4 *Methodology*

The broad methodology for this project is identified below:

- A "hydrologically conditioned" three second Shuttle Radar Topographic Mission (SRTM) DEM (Dilshad 2007), was processed for the Oolloo region in order to define the stream networks and delineate sub-catchments;

- Existing physiographic and landuse\cover data was collated into a form appropriate for defining the Hydrological Response Units (HRUs; landscape classification at a level lower than sub-catchments) of the Oolloo region;

- Curve Numbers, based on previous work and new or external data, were determined for the HRUs;

- The USDA-SWAT was parameterised using available data and knowledge gained from past work (refer: Dilshad and Peel 1994; Dilshad *et al.* 1994, 1995 and1996a & b; Motha *et al*. 1994, 1995a; Motha and Dilshad 1997a and b; and Peel *et al.* 1994 and 1996);

- The parameterised model was run to determine surface runoff, ET and soil profile moisture at the HRU level; and

- Model outputs were evaluated against observed data and model outputs of collaborating researcher (Charles Darwin University, see chapter 6 and CSIRO) and other projects in the region.

7.4.1 Model Data Preparation and Input

Comprehensive SWAT documentation on model input identifies detailed input data requirements for the model (refer: Neitsch et al. 2004). The MS/SWAT version (Leon 2009) was used for this project.

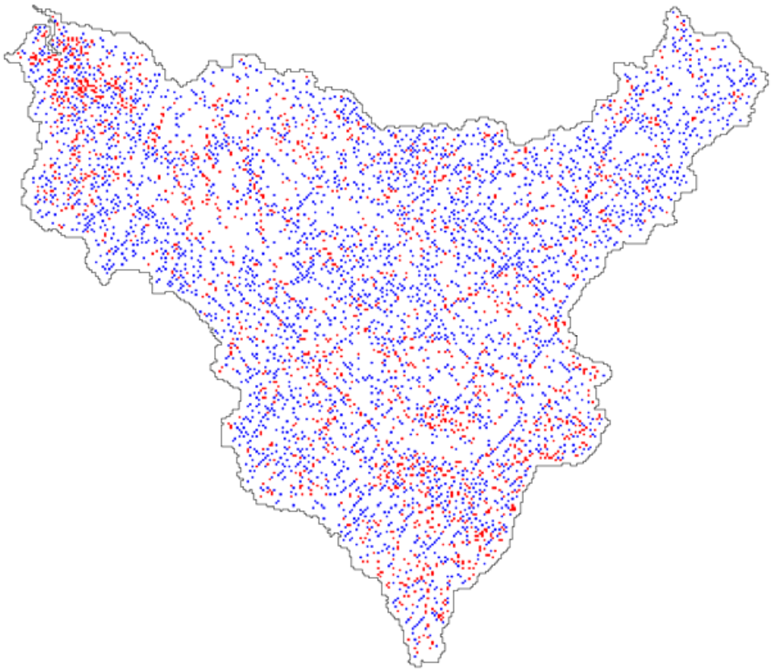


Figure 7-6. Data anomalies (red and blue dots) within the three second SRTM DEM. These anomalies were rectified for use of DEM for hydrological purposes by Dilshad (2007).

7.4.2 Digital Elevation Model (DEM)

Central to the operation of the SWAT model is a stream network defined from a DEM. A subset of the “hydrologically conditioned” three second (90m pixels) SRTM DEM (Figure 7-6 and Figure 7-7; refer: Dilshad 2007) was used for this project. The GeoScience Australia delineated river network at 1:250000 scale was used for “stream burning” and subsequent river network generation and sub-catchment delineation for the Oolloo region (Figure 7-8).

Based on previous work and literature (Refer Dilshad 2007) and the DEM resolution, a drainage area threshold of 35 km^2 was used for beginning the river network. D8 flow accumulation algorithms were used for catchment delineation and river network generation. The intent was to create a sufficiently detailed river network, representing all larger streams, whilst limiting the number of links across the area of interest. First order link length less than 2 km have not been included in the catchment delineation and river network generation. This resulted in 101 sub-catchments (Figure 7-8). Frequency distribution for sub-catchment area groups is displayed in Figure 7-9.

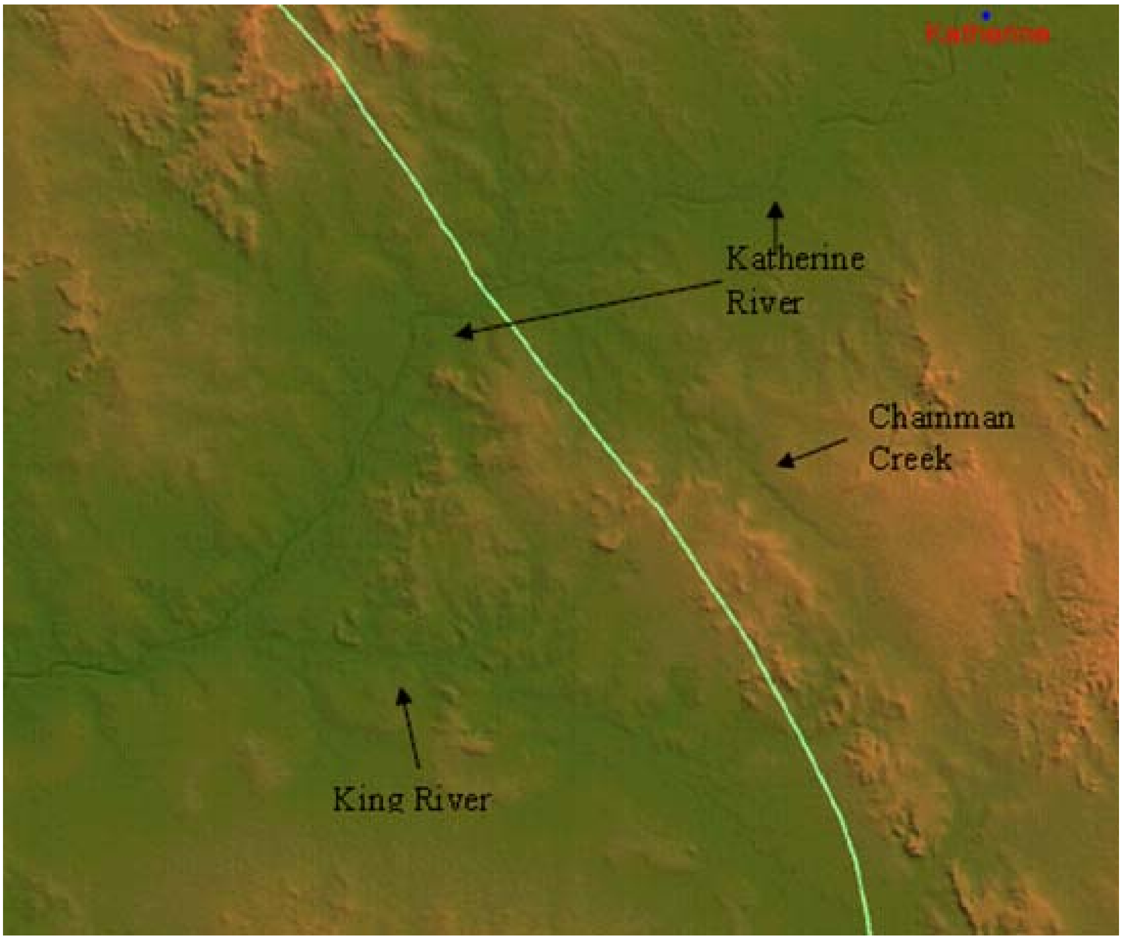


Figure 7-7. "Hydrologically conditioned" three second DEM showing the outline of the Katherine and King rivers and Chainman Creek.

7.4.3 Land Use

The latest landuse data for the Oolloo Region was used for this project. It was clipped from the larger Daly River Catchment dataset (Figure 7-10). The clipped data was then coded in a form appropriate for SWAT.

7.4.4 Soils

Soils input requirements for SWAT can include up to ten layers of profile description for the physical and chemical characteristics of a soil (Neitsch *et al*., 2005). For this study, the relevant soils data was obtained from published surveys and reports, NT and Commonwealth Government databases and from expert knowledge. This data was collated, analysed and compiled in a form suitable for SWAT.

Figure 7-11, for example, shows the median soils depth for the region, determined from the above disparate sources. Soil depth forms an important input to hydrological modelling. Detailed description of the processes in developing such spatial inputs is beyond the scope of this paper and will be reported in subsequent publications.

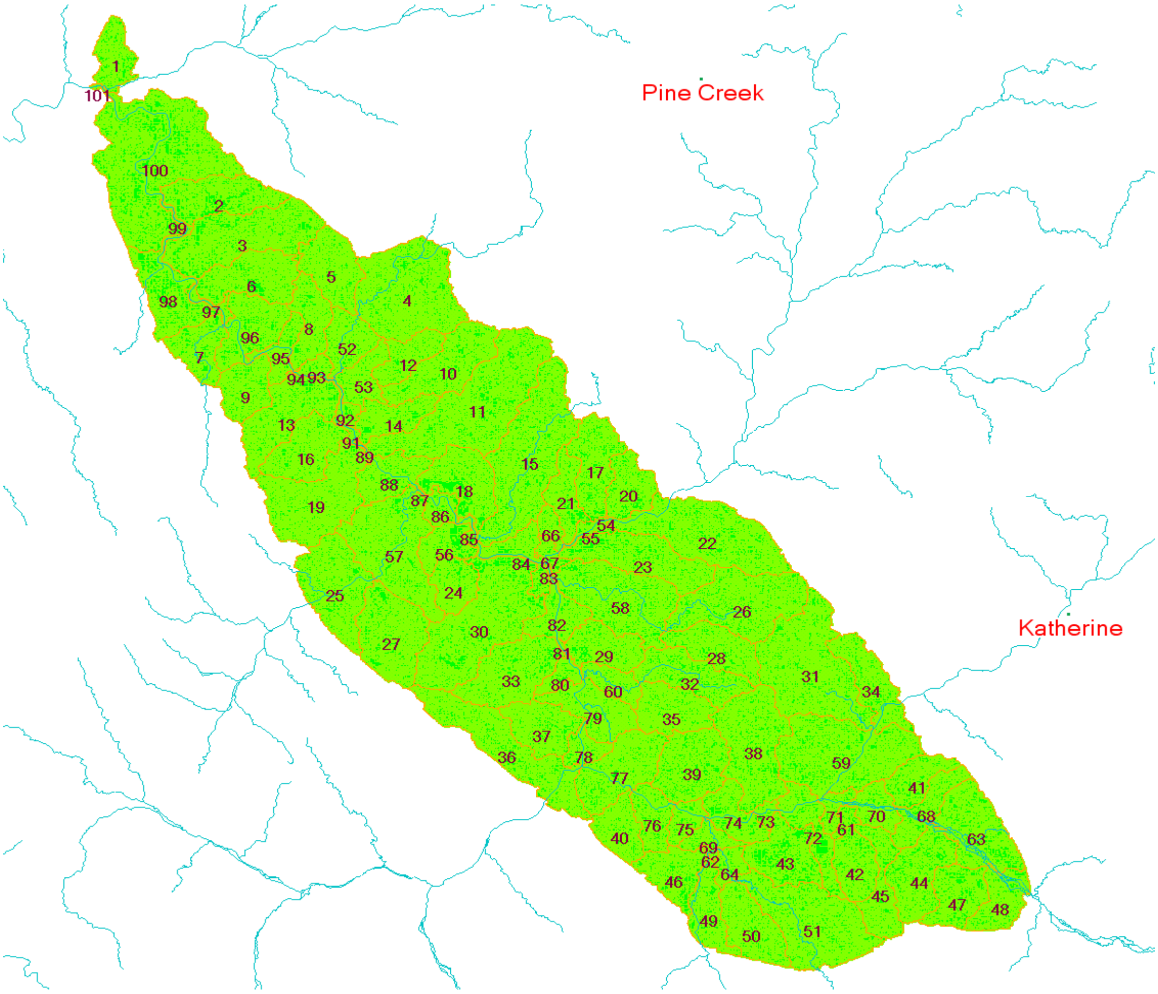


Figure 7-8. The Oolloo region was “discretised” (divided) into 101 sub-catchments.

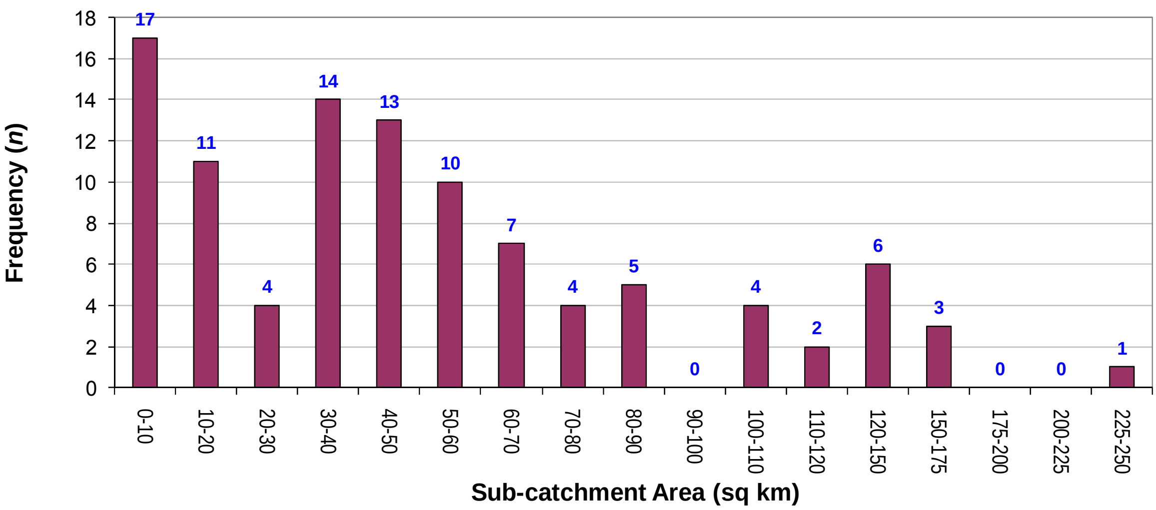


Figure 7-9 Frequency distribution of the discretised catchment area (km2). Frequency numbers also approximate percentage of total number of catchments as total number of sub-catchments equals 101.

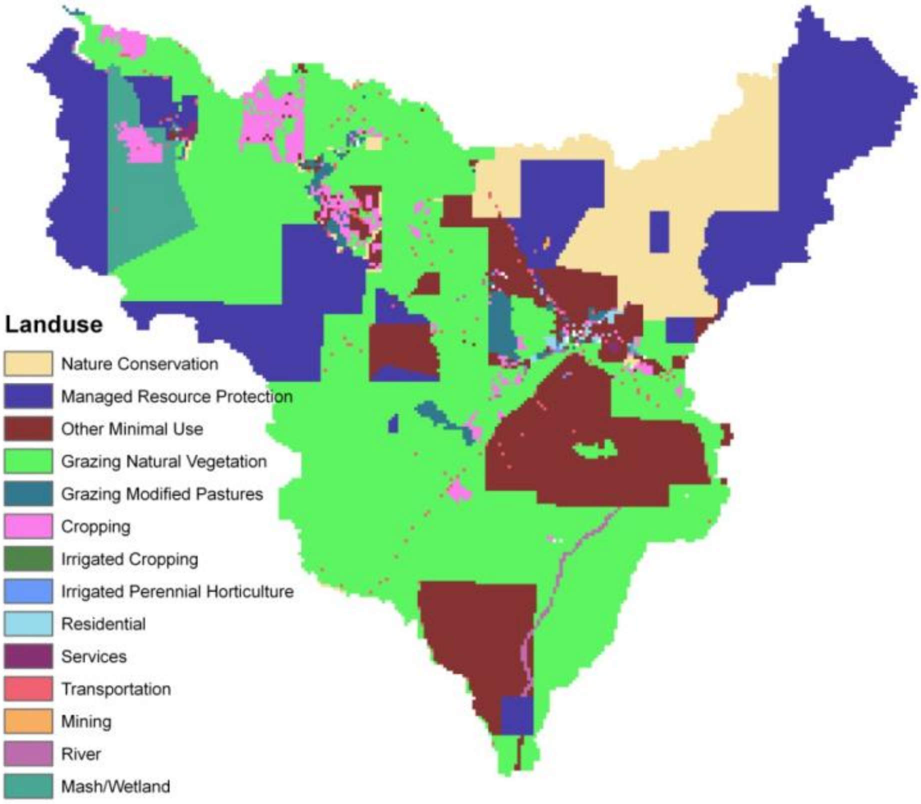


Figure 7-10. Land use in the Daly River Catchment (2006 Data) – supplied by NRETA Land Use Mapping Program.

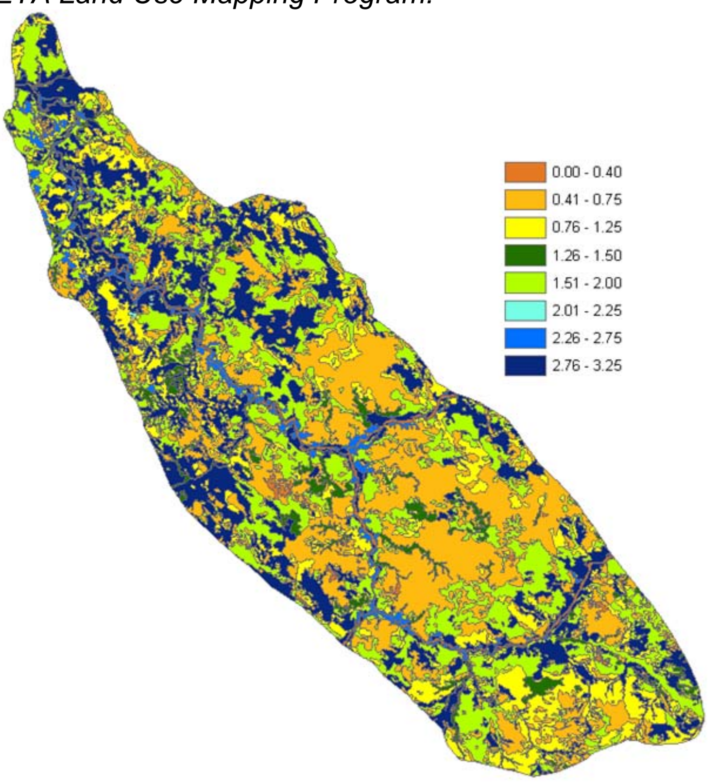


Figure 7-11. Median soil depth (m) for the Oolloo region – an input into hydrological modelling. Data collated and extrapolated as part of this project.

7.4.5 Climate Data

SWAT utilises climate data (rainfall, maximum/minimum air temperature, solar radiation, wind speed, and relative humidity) for its simulation. SWAT contains a powerful climate data generator for simulating climate data at sub-catchment\HRU level and generating missing data.

Techniques developed by Motha and Dilshad (1996) were used to infill missing climate data for Douglas River and Katherine weather stations before modelling commenced. Observed climate and rainfall data was obtained from various stations in the region (Figure 7-12). Bureau of Meteorology (BOM) generated daily climate data ("drill" data) was also available for the study area. However, preference was given to observed and infilled missing data where available, with BOM drill data being used as a last resort.

The way MS-SWAT operates is that for each of the five categories (precipitation, temperature, solar radiation, relative humidity, and wind speed), if there are no data tables (relational database) in that category, the category is simulated using a weather generator. Otherwise each sub-catchment will use observed data from the table where the weather station is the closest amongst those stations having tables in that category (Leon 2009).

For example, if there are weather stations with identifiers A, B and C, and tables Apcp, Bpcp, Atmp, Btmp, and Cslr, then the result will be:

- For precipitation: sub-catchments will use observed data from Apcp or Bpcp, according to whether station A or B is closer;
- For temperature: sub-catchments will use observed data from Atmp or Btmp, according to whether station A or B is closer;
- For solar radiation: all sub-catchments will use observed data from Cslr;
- For relative humidity: all sub-catchments will use simulated data; and
- For wind speed: all sub-catchments will use simulated data (Leon 2009).

This makes it possible to combine observed data from a number of sources. It is also possible to combine simulated and observed data for different sub-catchments. For example, if all the values in Apcp are -99 (unknown, missing data), while Bpcp is observed data, then sub-catchments closer to station A will use simulated precipitation data and those nearer to B will use observed data (Leon 2009).

7.5 *Hydrological Response Units (HRUs)*

The Hydrological Response Units (HRU's) of the Oolloo region were identified. This is essentially a process of landscape classification at a level lower than sub-catchments.

7.5.1 Input Thresholds

An input threshold, defined as percentage of sub-catchment area (e.g. 10 per cent), was set for the variables used (soil type, slope bands and landuse\vegetation) for delineating the HRUs. This weighting allowed for any potential HRU to be ignored for which the landuse, soil or slope was less than the selected threshold. The areas of HRUs that were ignored were redistributed proportionately amongst those that were retained. This is a good way of handling poor quality data at the project scale of operation.

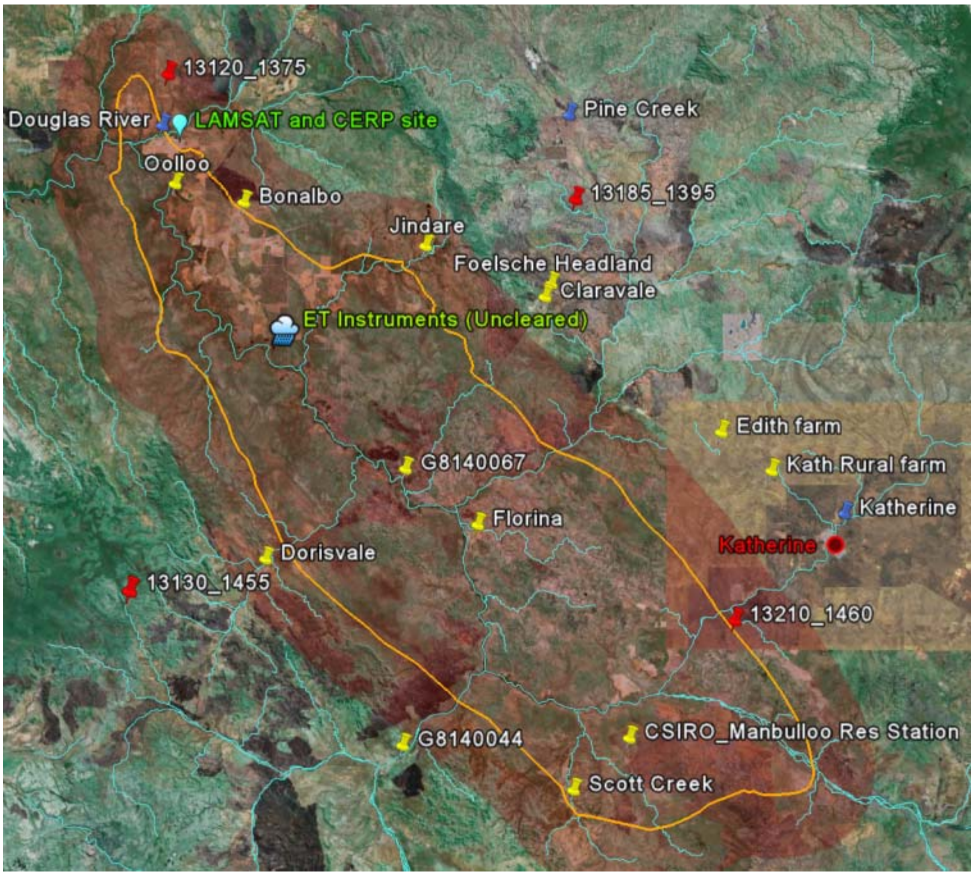


Figure 7-12. Location of observed climate stations (blue pins) and observed rain gauges (yellow pins) in and around the Oolloo region. Location of Bureau of Meteorology (BOM) generated daily climate data sites are represented by red pins. LAMSTA/CERP and CDU ET instrumentation sites are also highlighted. Satellite image sourced from Google Earth.

7.5.2 HRU Delineation and Distribution.

The 101 sub-catchments of the Oolloo region (Figure 7-8) were subdivided further into just under 600 HRU's. HRU classification provides a very useful way of classifying the landscape. Figure 7-13 shows an example of the spatial distribution of an HRU within sub-catchment 8, which is located near Stray Creek. Sub-catchment 8 has an area of 4260ha and occupies 0.8 per cent of the Oolloo region (study area = 530,438ha).

This HRU identified in Figure 7-13, occupies 323ha (7.5 per cent of sub-catchment and 0.06 per cent of the region). The identifier box in the map shows the unique landuse, slope band and soil combinations of the HRU. This HRU has an agricultural landuse (data can be drilled down to the cropping activity), is on a 0-2per cent slope and has soils which are predominantly sandy red earths (Lucas *et al*. 1987)

In simplistic terms, the hydrological response of all the bits within this HRU of sub-catchment 8 (Figure 7-13) should be identical but different from other HRUs of this sub-catchment. SWAT produces very useful statistics for describing the catchment, sub-catchments and HRUs characteristics.

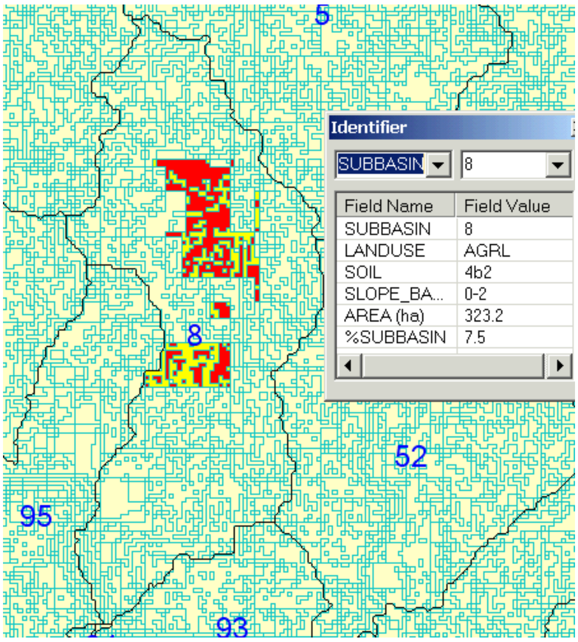


Figure 7-13. Layout of HRU AGRL/4b2/0-2 on sub-catchment 8 (Stray Creek area) and basic statistics.

7.6 *SWAT Model Run for this Study*

The model was parameterised and run over the period 1991/92 to 1994/95 to "link" with hydrological studies conducted just outside the Oolloo region, namely the Land Management Strategies for the Semi Arid Topics (LAMSAT) project (Dilshad *et al.*1996a, refer Figure 7-12).

SWAT was parameterized using data and knowledge gained from LAMSAT and other studies within and outside the region. Once parameterized, it was intended to validate the SWAT model outputs against 1986/87 measured runoff data from CERP (Dilshad and Jonauskas 1992; refer Figure 7-12) and against ET and soil profile data observed by Charles Darwin University (CDU) and CSIRO researchers over the last 3 years (Anon. 2010), as part of the Charles Darwin University led Tropical Rivers and Coastal Knowledge (TRACK) program.

Figure 7-14 shows aggregated annual northern Wet season rainfall for Northern Australia sourced from the BOM. The SWAT model was run over a relatively dry period for Northern Australia, with the three year annual running averages below the long term mean annual rainfall for the region. Two years individually, however, were above the long term mean. The period over which CDU collected ET and soil moisture data (2008 to present) is from well above mean annual rainfall. The 1986/87 season, the period for observed runoff, was well below average season.

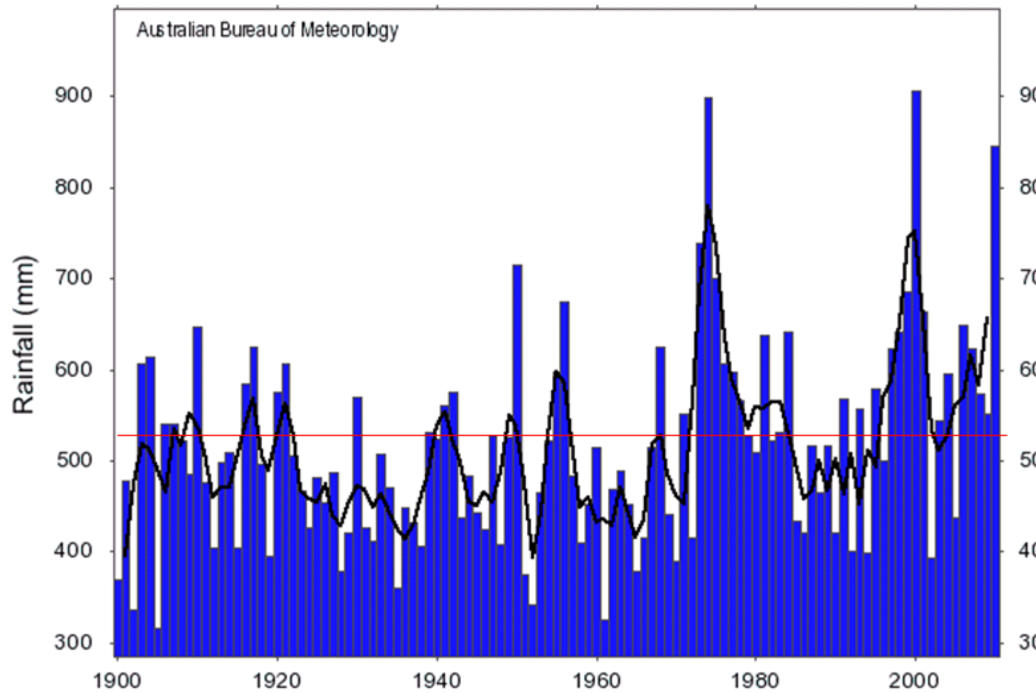


Figure 7-14. Aggregated northern Wet season rainfall for Northern Australia. Source: BOM. Black and red lines represents 3 year running averages and annual average over the period 1900-2010, respectively.

7.7 *Results and Discussion*

7.7.1 Whole of Catchment Results

Table 7-1 shows total monthly outputs for surface runoff, evapotranspiration, and soil profile water for the whole of the Oolloo region over the period December 1992 to December 1994. It also shows percent rainfall converted to runoff. Figure 7-16 expresses this output, along with rainfall, as a mean daily per month value (mm/day).

SWAT modelling outputs show a monthly conversion rate of rainfall to runoff, on a lumped catchment basis, of between 0 to 25.8 per cent for the period December 1992 to December 1994 (Table 7-1). The figures were 0 to 19.6 per cent when averaged over the entire duration of modelling run (Figure 7-15).

The runoff values are similar in range to field observations reported by Dilshad and Jonauskas (1992), whose results showed a conversion rate of 0.03 per cent to 24.9 per cent of rainfall to runoff over a three year period, reflecting various management. Review of data for the broader Timor Sea drainage division by Eamus *et al.* (2006) shows similar conversion rates (upper limit = 21.5 per cent). Hence these results provide a reasonable degree of confidence in the spatial extrapolation of runoff over the entire Oolloo region.

Table 7-1- Lumped observed rainfall and modelled output (monthly time-step) of key variables for the whole of the Oolloo region over the period: December 1992 to December 1994. The table also shows conversion of total monthly rainfall to total monthly runoff (%)

Month/Yr	Rain (mm/month)	Runoff (mm/month)	Runoff (% of Rain)	Soil Profile Water (mm/day/ month)	ET (mm/month)
Dec-92	190	19.8	10.4	160	130
Jan-93	460	118.5	25.8	225	118
Feb-93	356	59.1	16.6	205	105
Mar-93	73	0.01	0.0	163	103
Apr-93	1	0.0	0.0	134	28
May-93	1	0.0	0.0	123	14
Jun-93	0	0.0		117	6
Jul-93	0	0.0		108	9
Aug-93	0	0.0		83	25
Sep-93	0	0.0		59	23
Oct-93	7	0.0	0.0	46	23
Nov-93	112	0.7	0.6	134	62
Dec-93	331	79.1	23.9	199	80
Jan-94	147	0.6	0.4	182	91
Feb-94	217	22.4	10.3	205	89
Mar-94	294	60.9	20.7	147	80
Apr-94	4	0.0	0.0	131	21
May-94	0	0.0		123	8
Jun-94	0	0.0		117	6
Jul-94	0	0.0		103	14
Aug-94	0	0.0		81	22
Sep-94	0	0.0		65	16
Oct-94	0	0.0		44	21
Nov-94	69	0.0	0.0	107	49
Dec-94	202	12.9	6.4	186	82

Point based studies in Stray Creek region by CDU, located within current study area, (Figure 12, Anon. 2010) has shown a Wet season ET range (within one standard deviation) of approximately 1 to 7mm/day for uncleared and regrowth native vegetation and pastures and a Dry season range of approximately 0.01 to 2 mm/day. SWAT model outputs for ET, averaged over the entire Oolloo region, shows a very similar range and trend to that of the observed point data (Figure 7-16). There is a dearth of observed soil profile data to test SWAT model outputs against at the broad catchment level. Soil profile model outputs will be examined at a finer resolution, below, against recently collected CDU data.

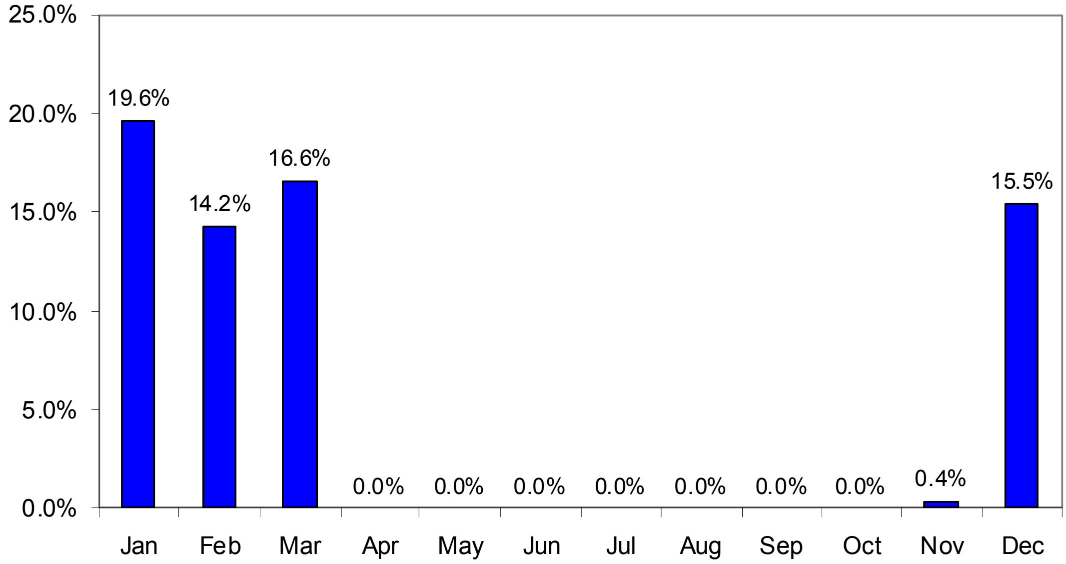


Figure 7-15. Rainfall converted to runoff, averaged over the entire Oolloo region for the total duration of model run (1991/92 to 1994/95).

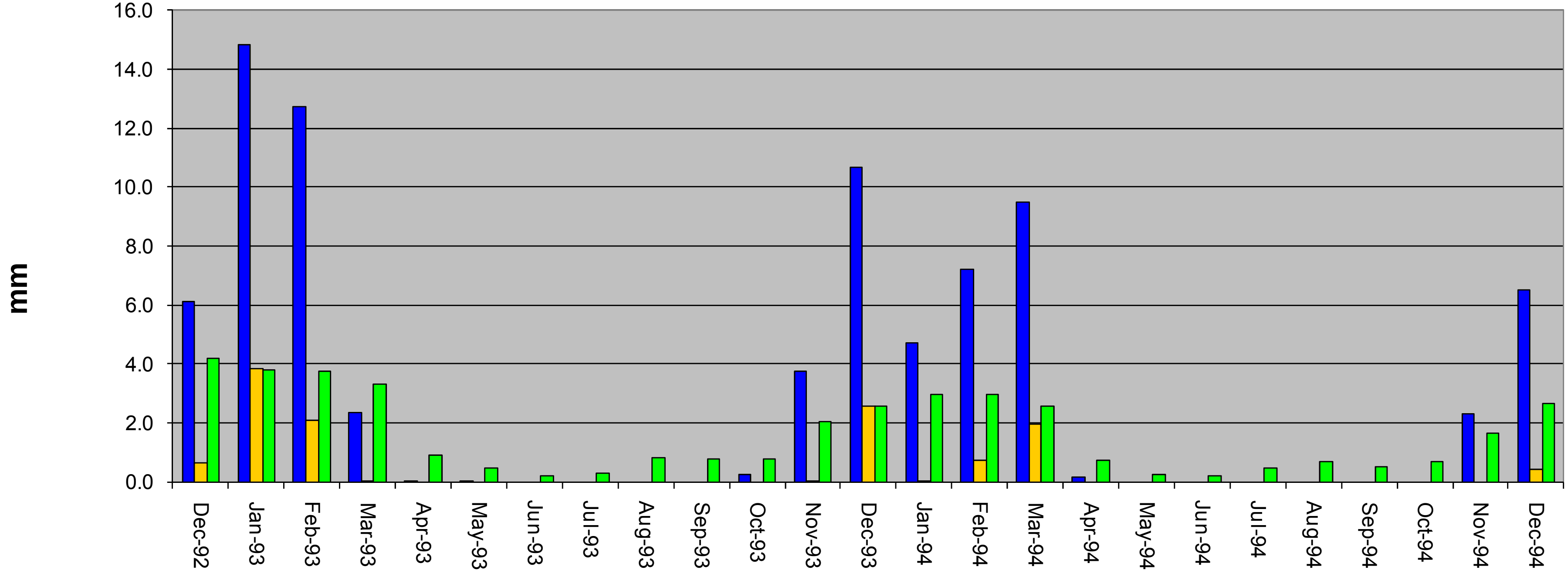
7.7.2 Sub-Catchment and HRU Results

7.7.2.1 Evapotranspiration (ET).

Figure 7-17 and Figure 7-19, show the uncleared native vegetation ET observed by CDU researchers in the Stray Creek region (Lat: 14.1592 S Long: 131.3881 E; Figure 12, Anon. 2010), located within the current study area. This observation period, early 2008 to mid 2010, was a period of above average Wet seasons (Figure 7-14).

Figure 7-17 shows SWAT output for the period December 1992 to December 1994, a period of below average Wet seasons. Data describing the distribution of soil types used for SWAT modelling was based on soil surveys conducted at a 1:50000 scale (Lynch *pers. com.*, 2011). Figure 7-18 provides SWAT modelled ET response on dominant soils upon which the CDU ET instrumentations are located and near vicinity (HRU 46 and HRU 44; sub-catchment 8), and their mean. The LAMSAT site used for SWAT parameterisation is located approximately 40 km away from the CDU site.

Whilst there is a temporal difference of nearly 15 years between the two periods, the SWAT modelled ET outputs have “almost identical” range and distribution to those observed in the field by CDU. This is the case when modelled output is expressed at a daily time step (Figure 7-20) as well as when summarised as mean daily per month (mm/day, Figure 7-18). Whilst the SWAT modelling and CDU field work periods represent below and above average rainfall periods, respectively, it would seem that for both periods soil profile moisture was sufficiently available to allow for similar evapotranspiration (see Figure 7-21 and Figure 7-22).



	Dec-92	Jan-93	Feb-93	Mar-93	Apr-93	May-93	Jun-93	Jul-93	Aug-93	Sep-93	Oct-93	Nov-93	Dec-93	Jan-94	Feb-94	Mar-94	Apr-94	May-94	Jun-94	Jul-94	Aug-94	Sep-94	Oct-94	Nov-94	Dec-94
Rainfall	6.1	14.8	12.7	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.2	3.7	10.7	4.7	7.2	9.5	0.1	0.0	0.0	0.0	0.0	0.0	0.0	2.3	6.5
Runoff	0.6	3.8	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.6	0.0	0.7	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4
ET	4.2	3.8	3.8	3.3	0.9	0.4	0.2	0.3	0.8	0.8	0.8	2.1	2.6	2.9	3.0	2.6	0.7	0.2	0.2	0.5	0.7	0.5	0.7	1.6	2.6

Figure 7-16 Mean daily per month observed rainfall and SWAT model outputs for evapotranspiration (ET) and surface runoff for the whole of the Oolloo region, over the period December 1992 to December 1994

Rigorous statistical analysis between SWAT modelling and CDU observed data cannot be undertaken at present. SWAT modelling needs to be expanded to include a modelled output for the same period as the CDU research. This entails the incorporation of soil characterisation based on detailed point data descriptions of soil profiles obtained by CDU. There is also, at present, no observed climate data available in the SWAT required format for the CDU research period.

The “drilled” BOM climate data that is available for this validation period, whilst, statistically correct over long term, does not lend itself for model testing and evaluation against observed field data over one or two seasons. This is primarily due to misalignment of generated climate data with real climate characteristics of the day and the resultant hydrological response. Observed data needs to be utilised for this validation work, with missing climate data in the “in filled” using various techniques, such as those described by Motha and Dilshad (1996).

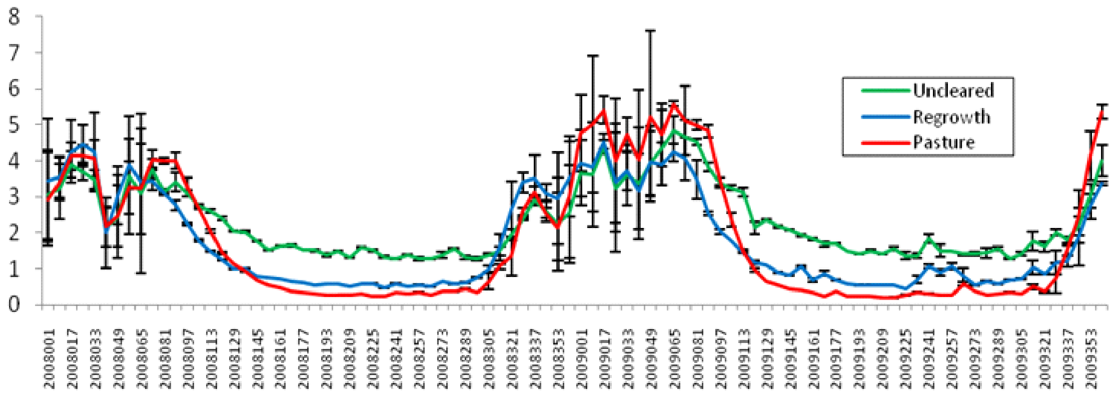


Figure 7-17. CDU/TRACK evapotranspiration observations from Stray Creek region of the study area over 1 two year period starting 1 January 2008. Date is in Julian format e.g. 2008365 = 31 December 2008. Note Day 33 = 2 February, Day 65 = 6 March, day 97 = 7 April, Day 193= 12 July, Day 241= 29 August, Day 289= 16 October, Day 337 = 3 December.

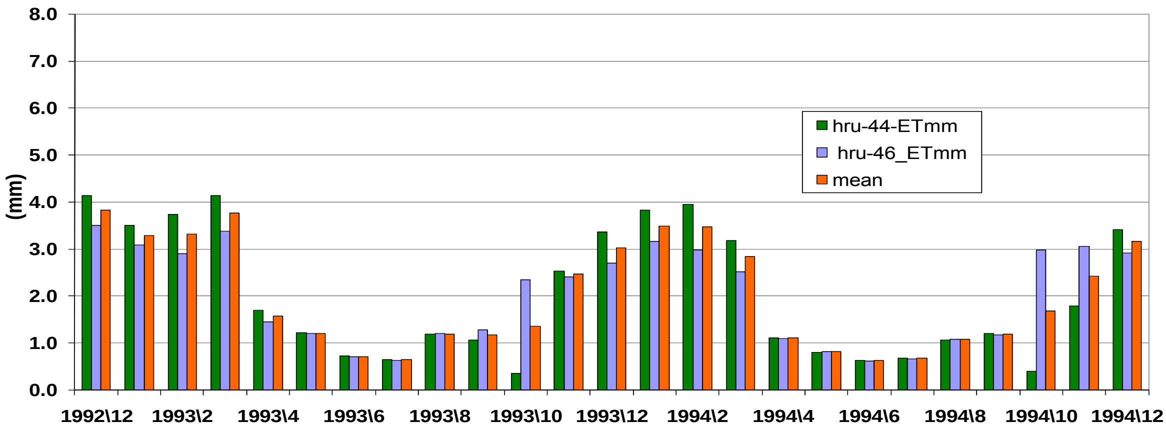


Figure 7-18 SWAT predictions for mean daily per month (mm/day) ET outputs for uncleared vegetation for the HRU upon which CDU instruments are located and for near vicinity (sub-catchment 8, HRU 44 and 46), and their mean.

7.7.2.2 Soil Water

Figure 7-21 shows observed and modelling results from CDU project over the period September 2008 to June 2010. SWAT model outputs for the period December 1992 to December 1994 are presented in Figure 7-22

For the bulk of the Dry season, CDU observations suggest a stabilisation at near 0.12m. SWAT model outputs range between 0.1 and 0.2m, with soil profile water dipping below 0.1m for a few weeks at the very end of the Dry season. CDU modelling shows a sharp drop in soil profile moisture in the transition from wet to Dry season. The SWAT modelling output indicates a more gradual drop.

The differences in the Dry season soil profile moisture could be due to the fact the SWAT modelling period was for below average Wet seasons and CDU observations were made in above average Wet season. Modelled and observed ET range and distribution for both SWAT and CDU periods were, however, very similar. In other words profile soil moisture did not seem to be a limiting factor for the ET response for both the above and below average Wet seasons. The differences in Dry season soil profile water could simply be a reflection of these factors.

These differences could also be due to SWAT model parameterisation of key factors such as soil characteristics and rooting depth and density. The CDU report describes the soils at their ET instrumentation site, located on HRU46, as a deep red sandy loam. This description is based upon results of point based surveys. Land unit survey, undertaken at 1:50000 scale and used for SWAT modelling, identifies the dominant soils at the ET instrumentation site as comprising of sands in the top layer (500 mm) and changing into a loam down the profile.

Rigorous statistical analysis between SWAT and CDU outputs can only be taken following the collation of in filled observed SWAT suitable climate data over the CDU observation period and minor re-parameterisation of SWAT to reflect CDU point based soils descriptions and a reassessment of rooting depth and density. The SWAT model, if so required, can be further calibrated following this work.

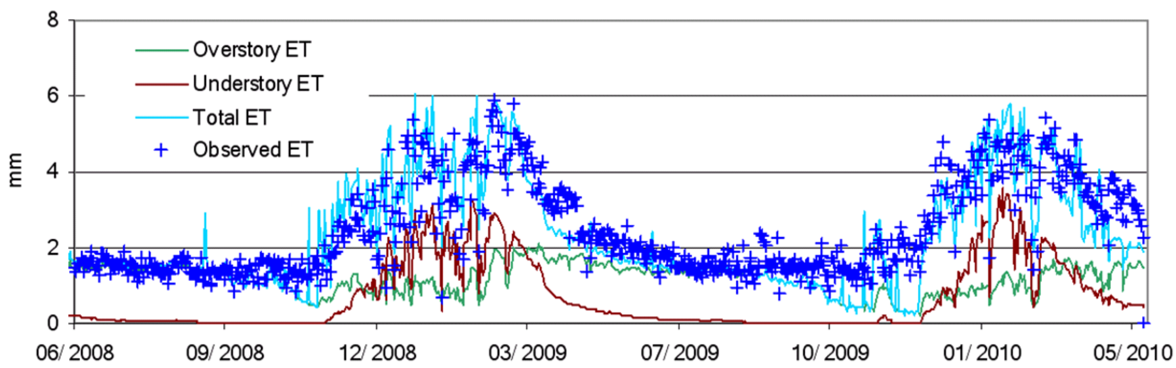


Figure 7-19 CDU/TRACK observed and modelled daily total ET for uncleared native vegetation. Solid light blue line represents modelled output.

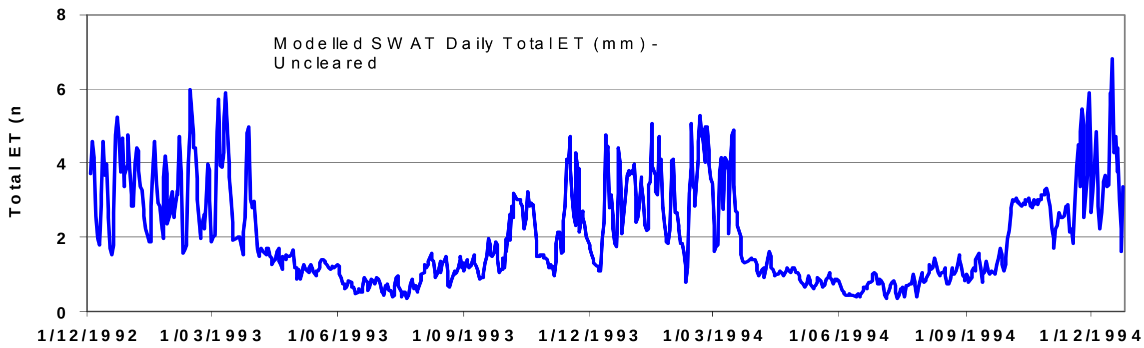


Figure 7-20 SWAT ET output presented as a 3 day running average of daily ET outputs for uncleared native vegetation on HRU 46, upon which the ET instruments for native woodland are situated.

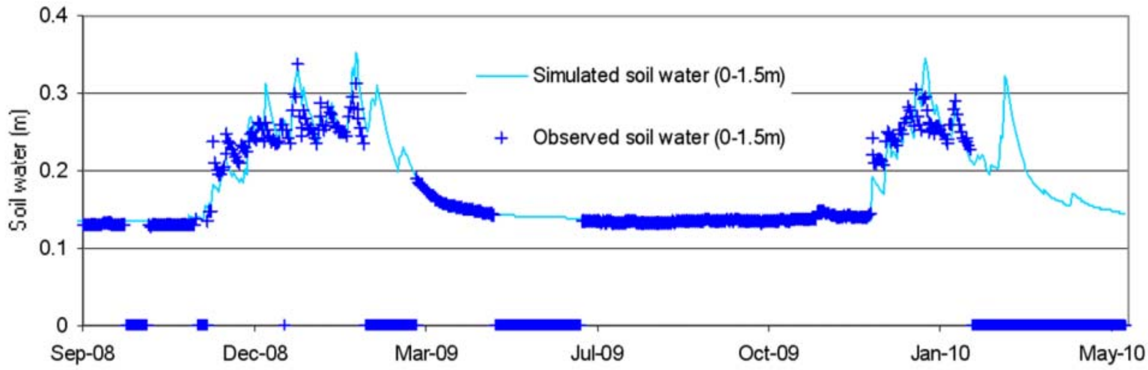


Figure 7-21 CDU/TRACK observed and modelled soil profile water (m)

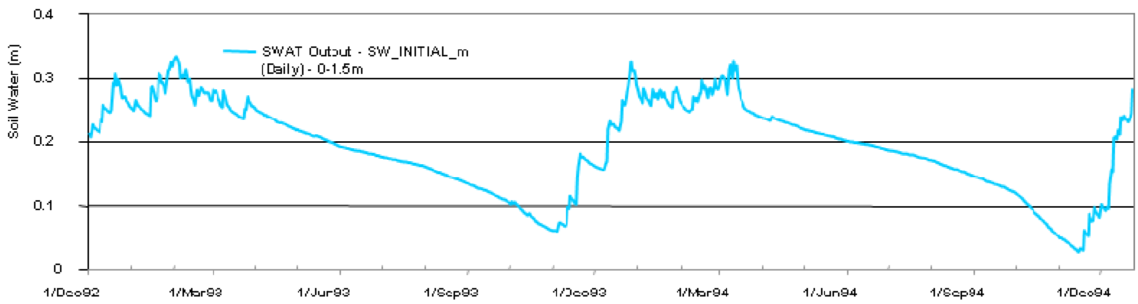


Figure 7-22 SWAT modelled outputs for soil profile water for the top 1.5m at start of each day over the period 1 December 1992 to 31 December 1994.

7.7.2.3 Runoff

Figure 7-23 shows the total seasonal rainfall input and runoff responses from the CERP project (Dilshad and Jonauskas 1992), for the 1986/87 Wet season for conventionally tilled maize crop (Motha *at al*. 1995b and 1995c). It also shows SWAT model output for the 1992/93 Wet season, about six years later, for sub-catchment 2, HRU6. The LAMSAT site used for SWAT parameterisation is located approximately 16 km away from HRU6.

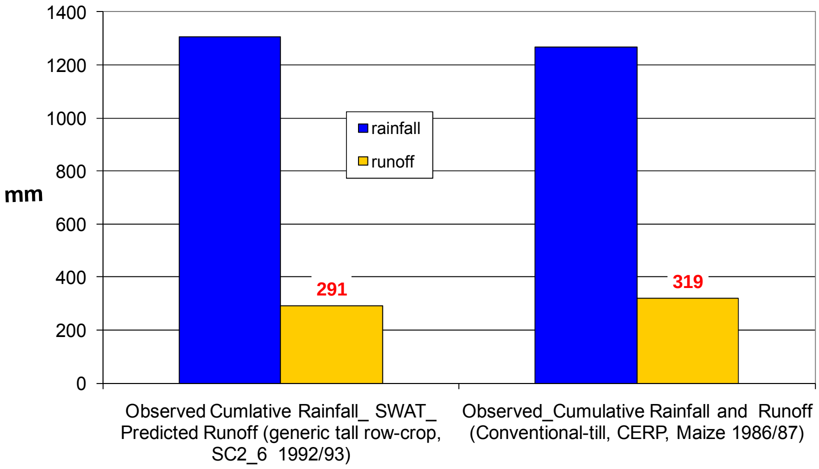


Figure 7-23. Total observed rainfall and runoff for 1986/87 and modelled SWAT runoff outputs for 1992/93. Rainfall for 1992/93 was observed.

HRU6 was identical to the CERP site in terms of slope range and management. The CERP soils (see Lucas 1984 and Lucas *et al.* 1987), whilst not identical, were similar to those on HRU6. The total observed rainfall for both seasons are similar (see Figure 7-24), with only a 3 per cent difference between seasons. Total difference between the observed (1986/87) and modelled runoff season (1992/93) was 27 mm; under 10 per cent (8.8 per cent).

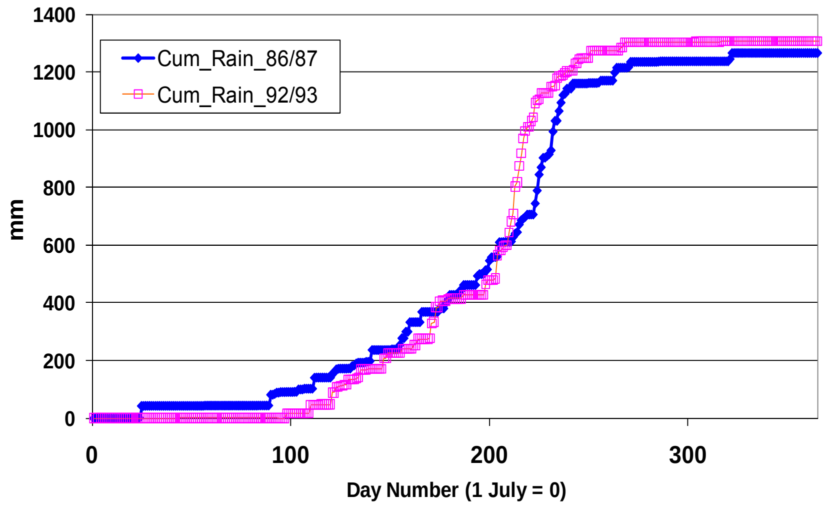


Figure 7-24 Cumulative daily rainfall (mm) for the 1992/93 and 1986/87 Wet seasons. Data source: Douglas Daly Research Farm. Day 100 = 8 October, Day 150, Day= 27 November, Day 200=16 January, Day 250= 7 March, Day 300=26 April.

Rainfall for the two seasons, whilst very similar, was not identical. Figure 7-24 highlights the obvious differences in the daily rainfall patterns between the two seasons. For example, 1986/87 had an earlier Wet season than 1992/93. 1986/87 had received nearly 100mm of rain before first rainfalls were received for the same period for the 1992/93 season.

Figure 7-25 shows the cumulative runoff for the two periods. The requirement for the work being reported was to compare the relative response of two seasons, six years apart. Therefore, for the purposes of this exercise, the time lines differences for the start of runoff for the two seasons has been removed and set to be the same (i.e. set to t=0) to allow for easier comparison. (For the 1996/97 Wet season, surface runoff began about three weeks before the first runoff for the 1992/93 season).

It should be noted that for this modelling work, growth parameters for a generic tall row crop were used for SWAT modelling. Cultivar specific parameters for maize for the region (identified by Motha *et al.* 1995a and 1995b) are expected to provide a better modelled runoff output. However, despite these handicaps of using simplified crop growth parameters, and those due to climatic variability between the two seasons at daily time-steps, the modelling outputs are reasonably close to observed values and provide a good gauge as to how well the SWAT model may be predicting runoff for the entire Oolloo region. These outputs provide reasonable confidence in the goodness of model prediction for the rest of the Oolloo region.

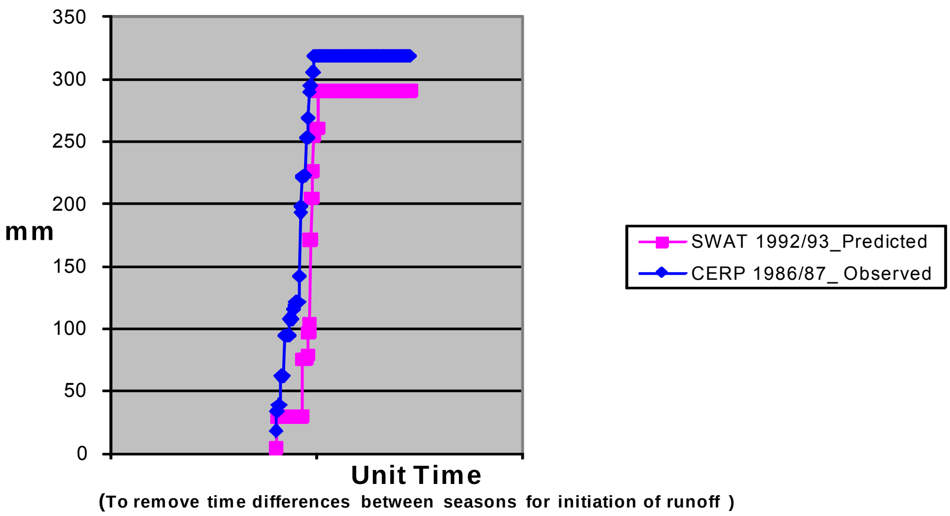


Figure 7-25. CERP observed runoff (cumulative daily; mm) for 1986/87 Wet season and SWAT modelled runoff for the 1992/93 Wet season (sub-catchment 2 HRU6). CERP was conventionally tilled with maize.

A generic relationship between monthly rainfall and runoff for the Oolloo region, for operational purposes at a coarse planning scale only, is provided in Figure 7-26. It should, however, be noted that as with modelling outputs for soil profile moisture and ET, rigorous statistical analysis to explain the variability between the two seasons is only possible when differences in climatic conditions (e.g. rainfall, humidity, radiation, wind speed), soils, and plant growth parameters have been taken into account. This requires observed climate data for 1986/87, in filled for missing data, being available in SWAT required format and the model better parameterised for crop growth.

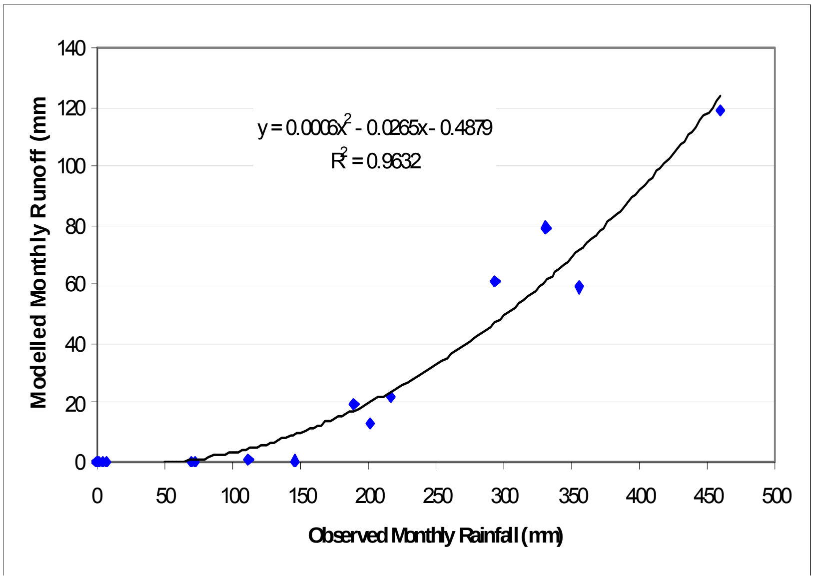


Figure 7-26. Modelled runoff and observed rainfall relationships for the entire Oolloo region (monthly time step).

7.8 *Time Series-based Spatial Model Outputs*

SWAT was parameterized using hydrological data and knowledge gained in the early 1990s from LAMSAT and other studies within and outside the region. The above analysis of SWAT outputs, indicates favourable comparisons against observed data from discrete periods outside the early 1990s, within a two decade span. Getting reasonable fits in terms of range and distribution of ET, surface runoff and soil moisture gives a degree of reasonable confidence in the use of the model, as parameterised, over the entire region.

A temporal sequence of surface runoff, ET and soil profile water at a sub-catchment scale for selected months, as examples, is presented below (Figure 7-27 to Figure 7-29).

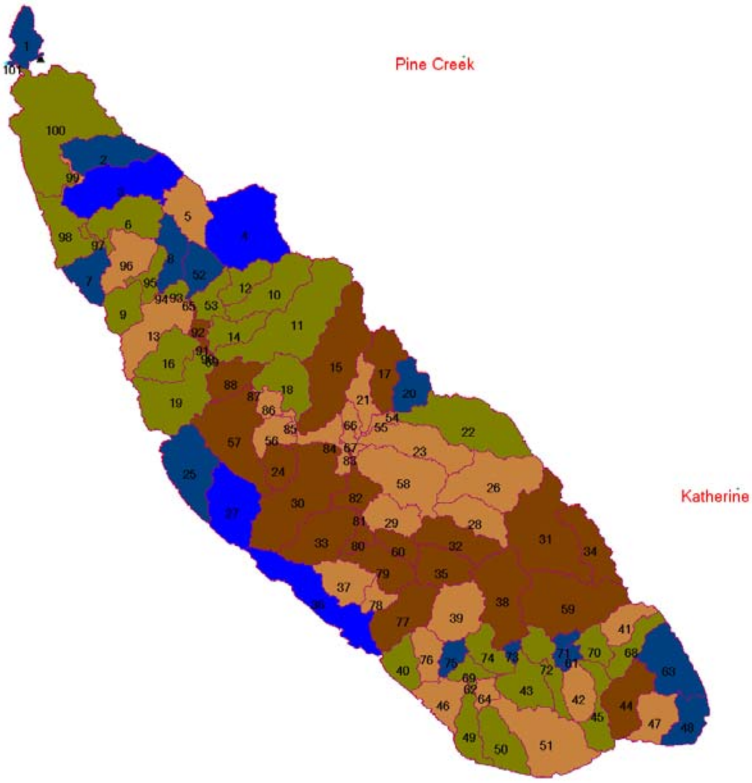
7.9 *Conclusion and Recommendations*

SWAT appears to be a very capable modelling system for simulating surface runoff, soil profile water redistribution and evapotranspiration in the Daly River Catchment of the NT. Model outputs are similar in terms of range and distribution against the limited observed data available. Despite the region being relatively “data poor” with respect to the current study, this work can be further enhanced by:

Collating, in a form suitable for SWAT, observed climate data and infilling missing values for periods where there is observed data for model testing, particularly for periods of CERP and CDU evapotranspiration studies; and improving the parameterisation of the SWAT where better soils, plant growth, and root depth and distribution data is available.

This above work is strongly recommended. Undertaking the above tasks will allow for rigorous statistical testing of SWAT outputs against observed data.

Soil Profile Moisture - Spatial and Temporal Distribution



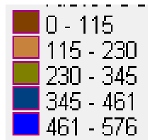


Figure 7-27a. SWAT modelled soil profile moisture (mm) in the Oolloo region - January 1993

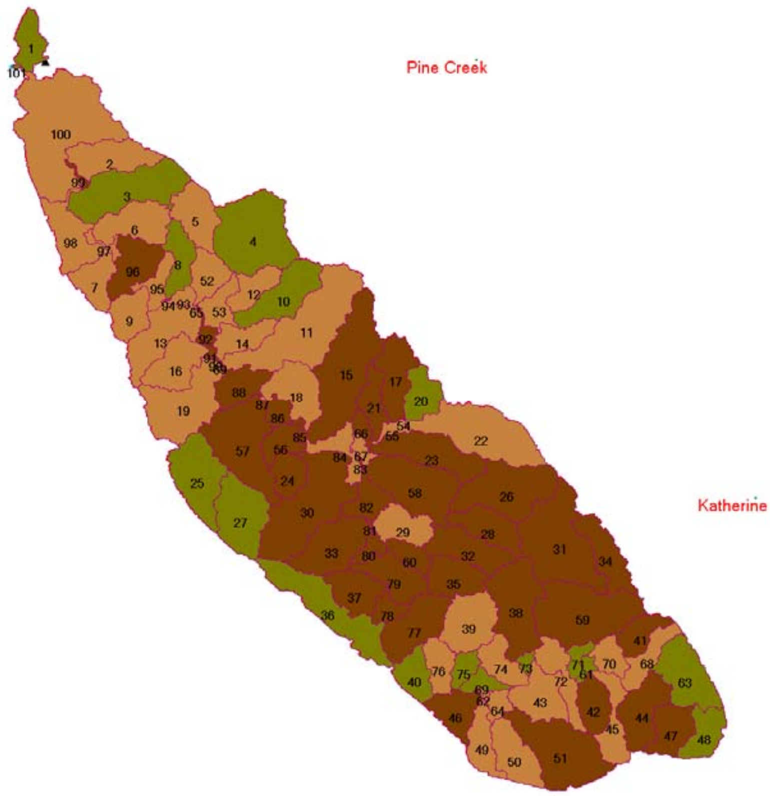
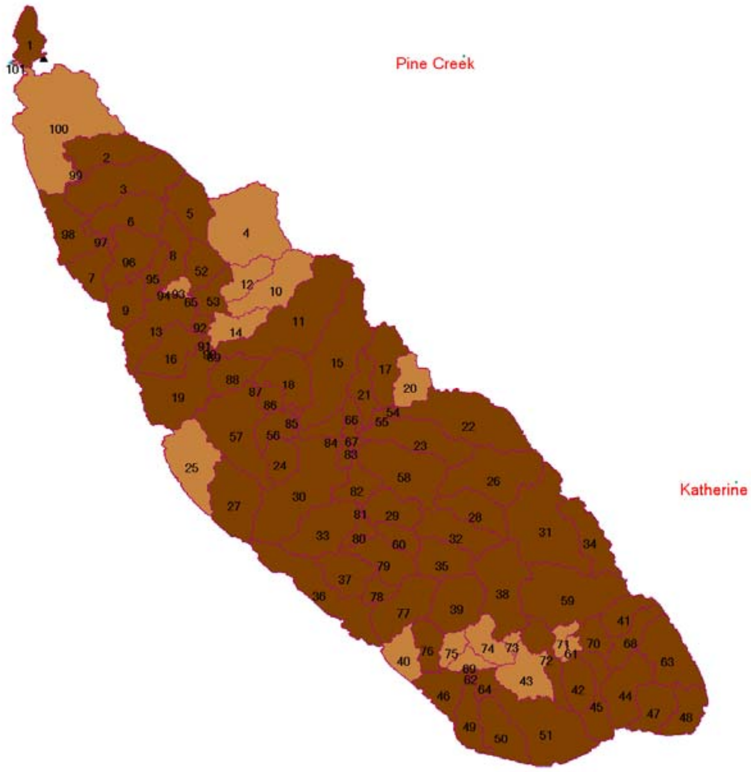


Figure 7-27b. SWAT modelled s*oil profile moisture (mm) - April 1993*

Soil Profile Moisture - Spatial and Temporal Distribution



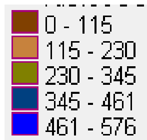


Figure 7-27c. SWAT modelled s*oil profile moisture (mm) - October 1993*

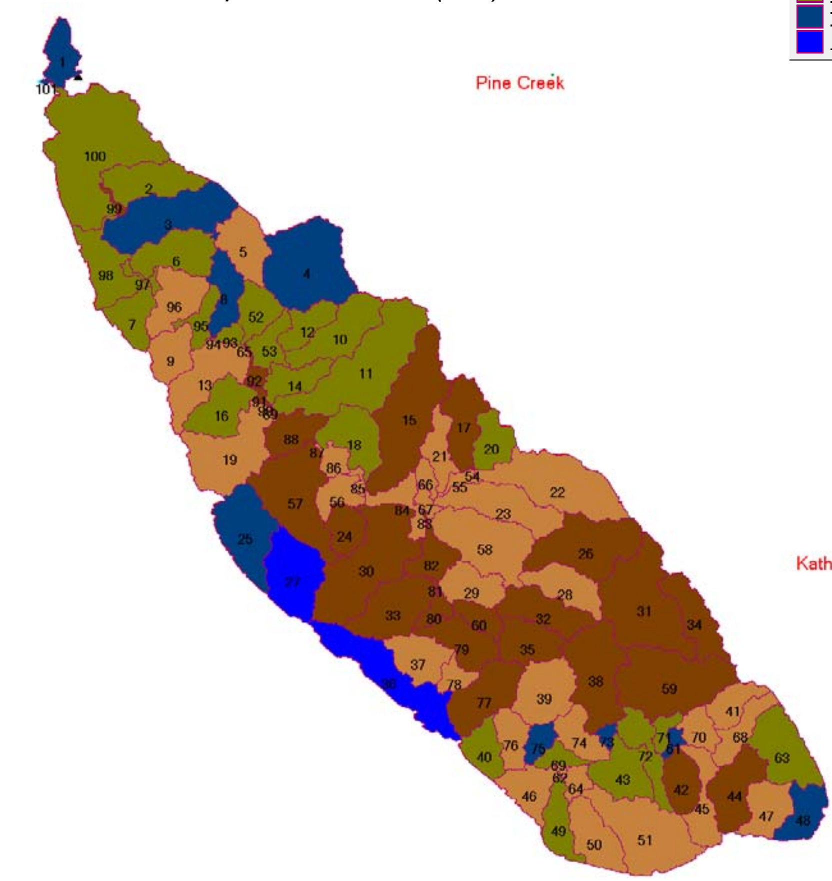
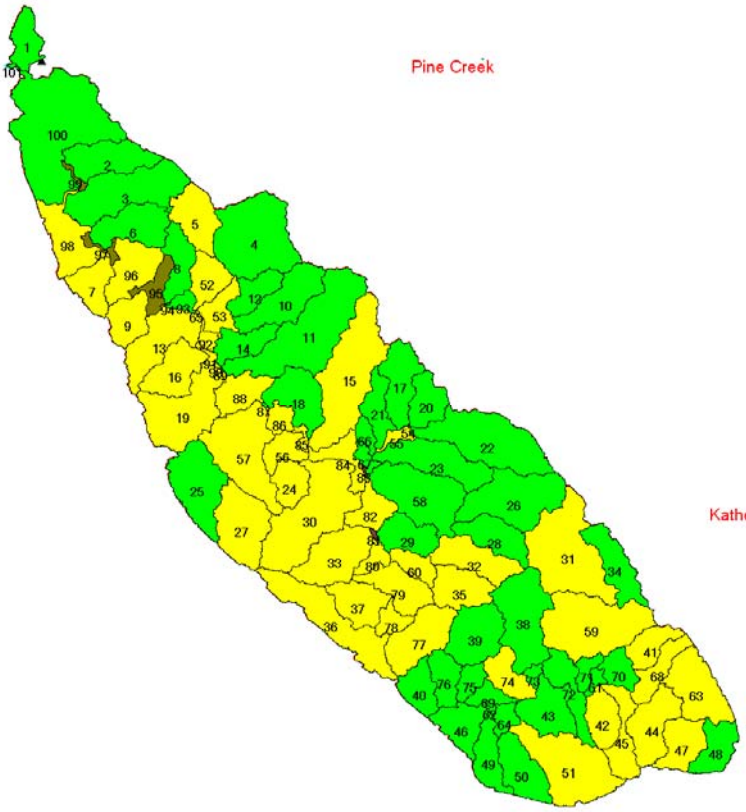


Figure 7-27d. SWAT modelled s*oil profile moisture (mm) - December 1993*

ET - Spatial and Temporal Distribution



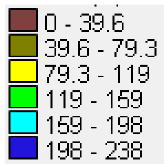


Figure 7-28a SWAT modelled ET - January 1993 (mm/month)

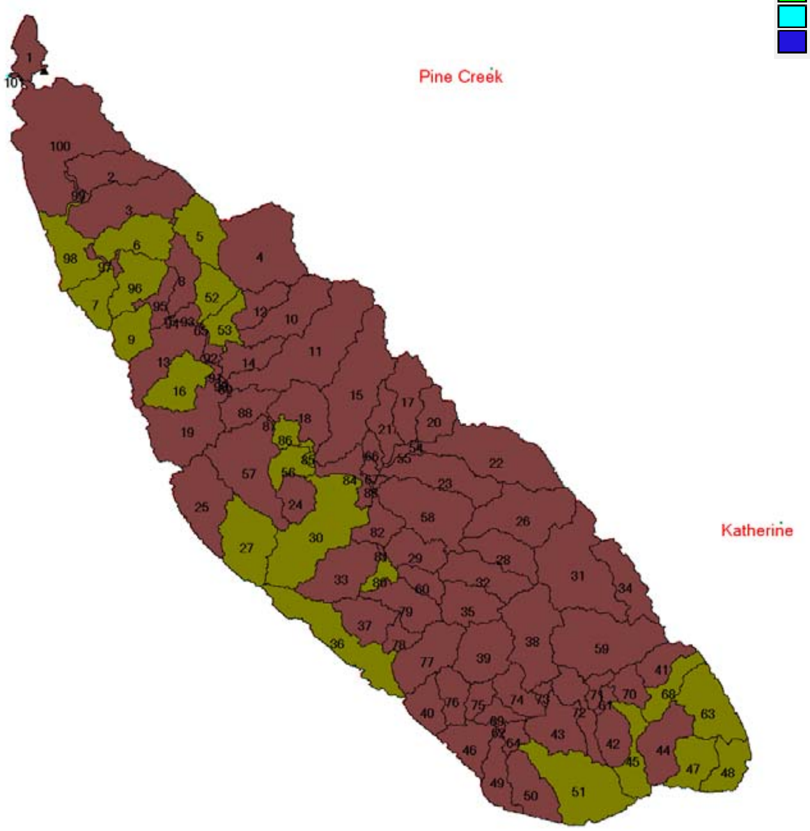
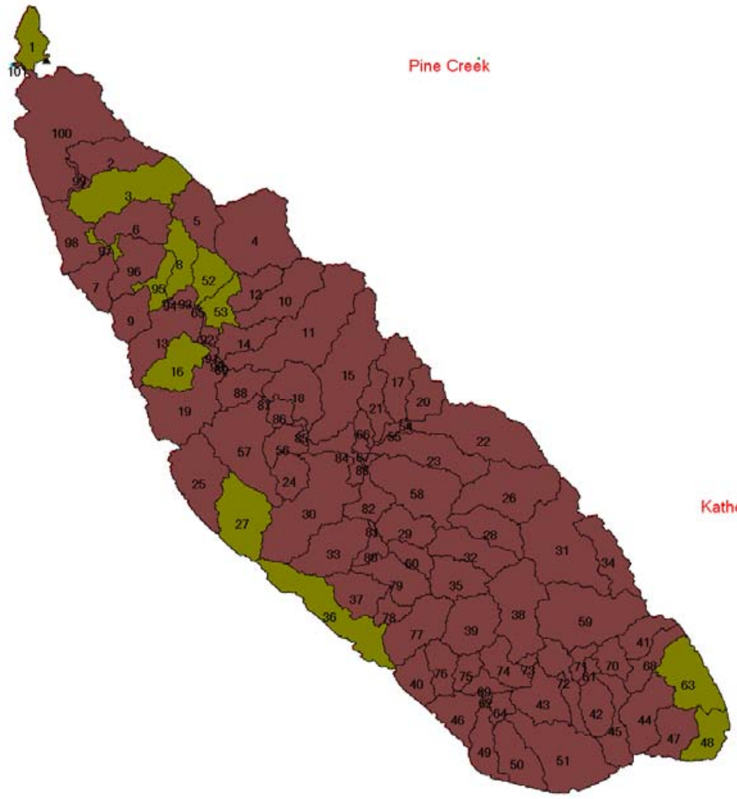


Figure 7-28b SWAT modelled ET - April (mm/month)

ET - Spatial and Temporal Distribution



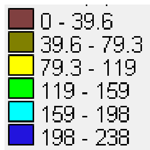


Figure 7-28c SWAT modelled ET - October 1993 (mm/month)

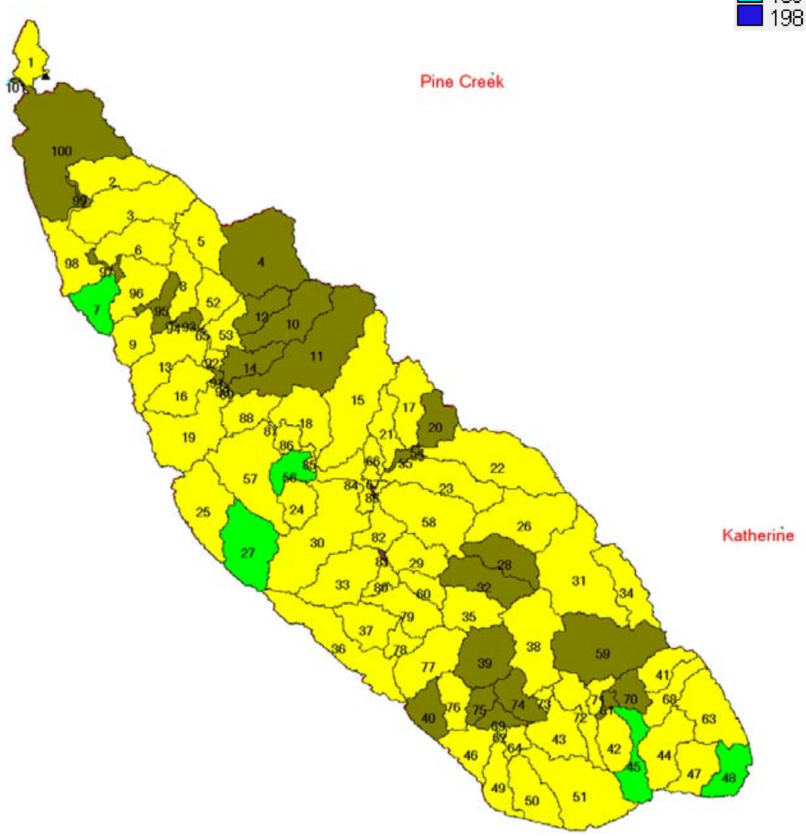


Figure 7-28d SWAT modelled ET – January 1994 (mm/month)

Runoff - Spatial and Temporal Distribution

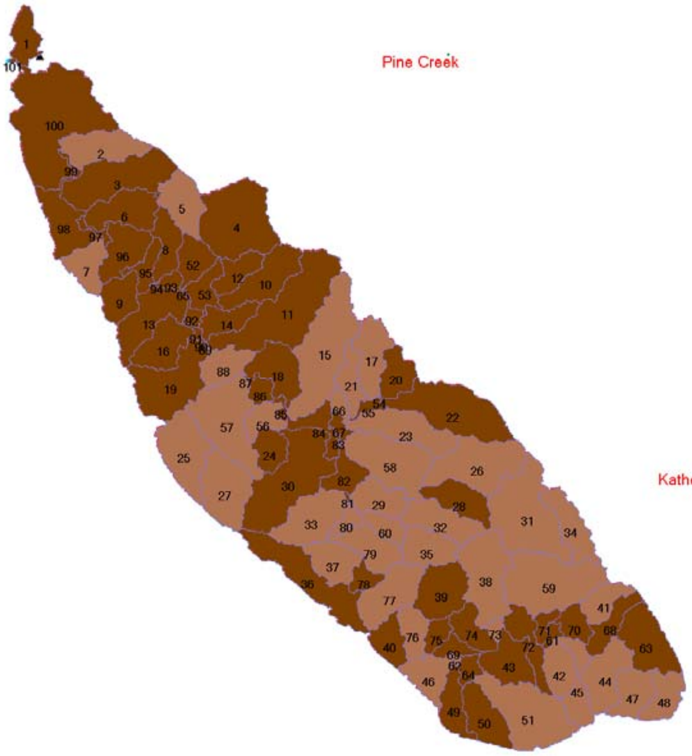


Figure 7-29a SWAT modelled runoff (mm)- December 1992

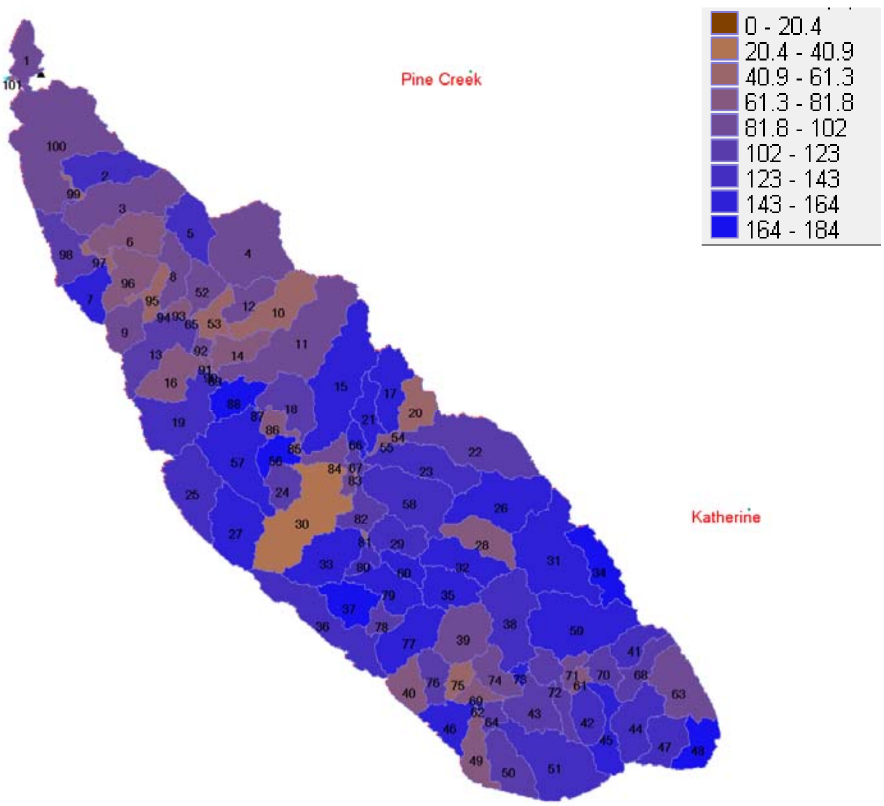


Figure 7-29b SWAT modelled runoff (mm)-- January 1993

Runoff - Spatial and Temporal Distribution

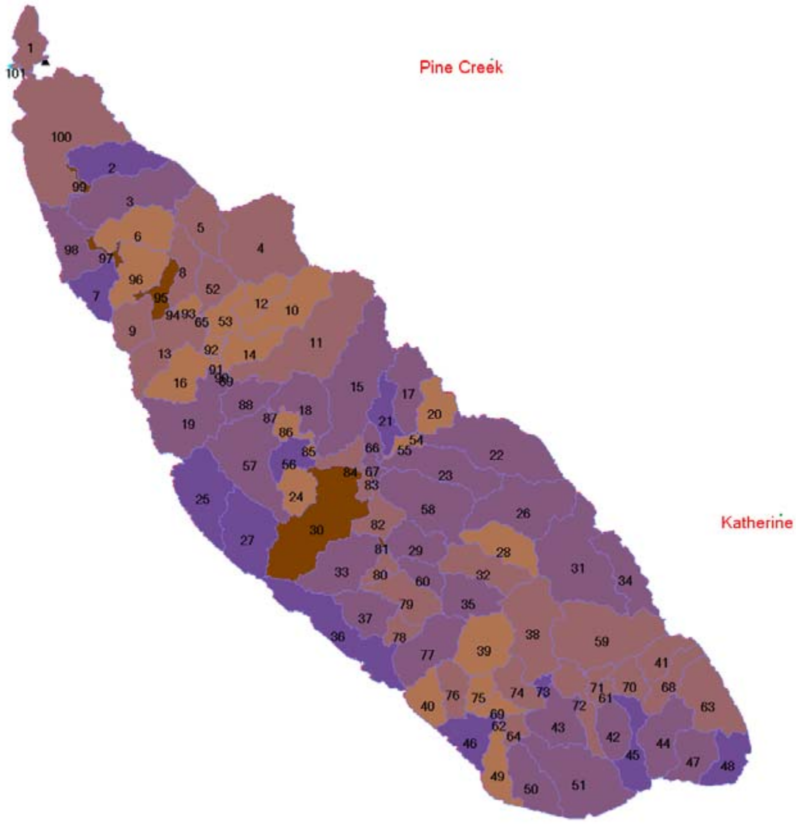


Figure 7-29c SWAT modelled runoff (mm) - February 1993

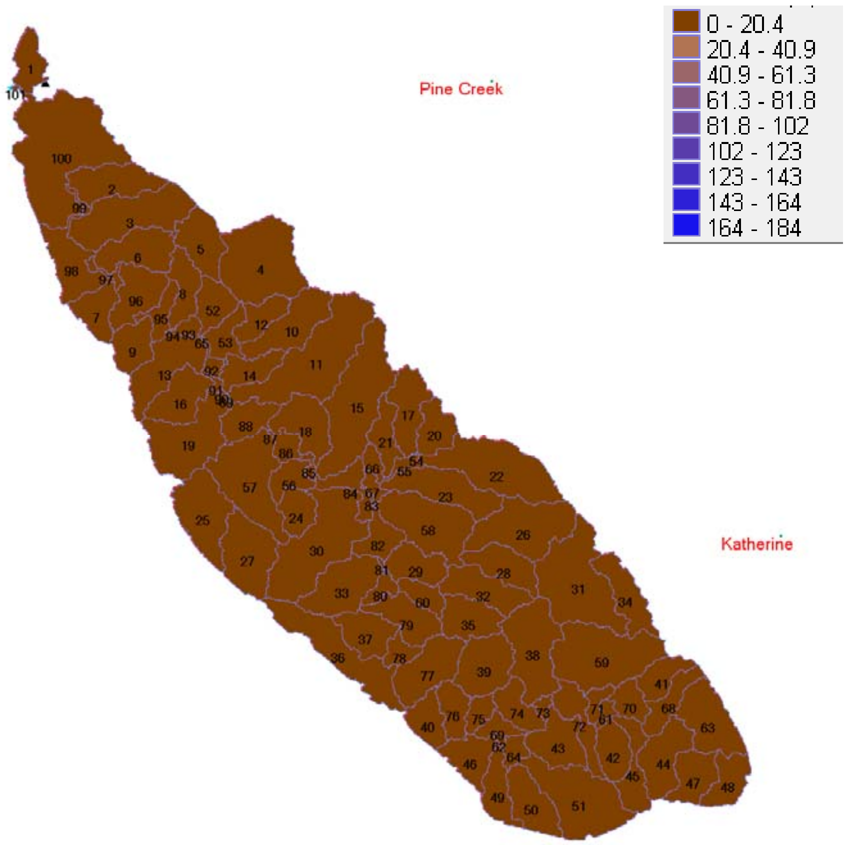


Figure 7-29d SWAT modelled runoff (mm) - March 1993

8 Discussion

The overall aim of the work is to support the soon to be established water allocation plan for the Oolloo aquifer developed by NRETAS. This will be achieved by applying improved scientific knowledge about the aquifer, springs and the mechanics of the water cycle that involves the aquifer and the river that has been developed during this and other projects over the last decade. The results will now be discussed in terms of the five specific aims originally set for the project. The bulk of the effort was directed towards studying aspects of the water balance. The remaining aims have been addressed mainly as a result of that work.

8.1 *Water balance investigations*

“Undertake research to fill key knowledge gaps concerning the water balance components of the system.”

Key aspects of the water balance affecting the Oolloo aquifer have been examined during this study, in particular groundwater recharge, runoff and groundwater discharge. A water balance can be calculated at sub-catchment scales, or in this case, for an aquifer. This is a summary of water entering and leaving the aquifer over a specified time. The spatial distribution, size and spatial variation of hydraulic properties of aquifer means that no individual technique yields definitive results in terms of understanding flows and their drivers. Rather, a range of possible values becomes better defined via the use of multiple approaches and methods, providing a robust estimate of fluxes and associated errors, critical for sustainable management of the resource. A diverse range of techniques have been used to estimate all water balance components and values are given in Table 8-1. Values are provided for the Douglas-Daly catchment as a whole, the Stray Creek sub-catchment as well the Oolloo region. Measurements and modelling also span a range of time periods as well and a wide range of estimates result. In terms of resource management, recharge processes need to be well understood and runoff, aquifer recharge estimates are of considerable interest. Across the Douglas-Daly catchment rainfall ranges from 1300 to 800 mm, with ET ranging from 1500 to 600 mm per annum depending on rainfall, vegetation type, soil and topography (Creswell *et al.* 2011). Within the Oolloo study this range is reduced.

The first attempt at a water balance was undertaken by Jolly (2002) for the whole of the Daly River catchment. Its main components included rainfall, runoff, recharge and ET. Runoff and groundwater discharge were determined from stream gauging records with recharge assumed to equal discharge plus ET. Of the total runoff of 220 mm, 90 mm was attributed to groundwater discharge. ET was estimated from other studies of savannah vegetation water use in the Darwin and Katherine regions namely Cook *et al.* (1998), O’Grady *et al.* (1999), Hutley *et al.* (2001). Bore hydrographs were used to determine two recharge zones to the Oolloo aquifer. Where there is no cover of Cretaceous rocks, recharge was estimated to be 150 mm y^{-1}, but where they are present; the recharge was estimated to be 40 mm.

Wilson et al. (2006) focused on sites within the Stray Creek sub-catchment (within the Oolloo region) and estimated ET, deep drainage beyond the root zone (~5 m soil depth) and groundwater recharge to the Oolloo Dolostone using a combination of micrometeorological, soil water balance plus isotope and tracer methods. They compared these components on uncleared land and cleared land and deep drainage was estimated to be approximately 50 to 200 mm/year and 300 to 540 mm/year respectively under each land type. Deep drainage was estimated by difference from direct measures of ET and changes in soil moisture storage and assumed runoff of 10 per cent of rainfall. Observations were only available from the end of the Dry season the end of a single Wet season (six months). Given the short period of estimates, an assumed runoff and with observations at two sites only, considerable uncertainty is associated with deep drainage estimates derived from the water balance calculations. However this study demonstrated the significant differences between cleared and uncleared vegetation. Clearing of deep-rooted, evergreen trees resulted in reduced extraction from deep within the soil profile, increasing drainage. Rates of ET were high in the Wet season but dropped significantly in the Dry, whereas native uncleared vegetation used water all year.

The current study significantly extends the work of Wilson et al. (2006) and focused on surface water – groundwater interaction and recharge fluxes(Chapters 4, 5), drainage beyond the root zone (Chapter 6) and runoff (Chapter 6, 7). This study features more extensive spatial sampling of geochemistry, isotopes, a key complement of obtaining a far more reliable understanding and estimate of recharge. Four years of ET measurements within the Stray Creek catchment underpin far more robust estimates of ET, soil properties, deep drainage and modelling products of all water balance components to compare with improved recharge estimates based on isotopes, tracers and geochemistry.

Despite apparent variability, there is a convergence of estimates for the critical parameter, aquifer recharge, based on modelling, catchment scale water balance and geochemistry. Modelled and measured (using chloride) total recharge in the Stray Creek area was 69 and 60 mm y^{-1} respectively (Chapter 6, Wilson *et al.* 2006), similar to the estimate from geochemistry and water balance (Jolly, 2002) estimates with Cretaceous rock layer present. Without this rock layer, recharge more than approximately doubles to between 90 (Jolly, 2002) and 167 mm (Chapter 4) Runoff is a key variable that has been little studied except for the extensive studies of Dilshad and Peel (1994), although this work was conducted on agricultural soil types only. This study attempted to measure runoff on upland, skeletal soils with a significantly different hydrological properties and a far higher runoff coefficient is associated with such landforms (35 per cent rainfall). Runoff was highly variable across a number of studies collated in Table 7-1 and further work is required to refine current estimates. This in turn will improve modelled estimates of recharge, a critical variable in terms of understanding surfacewater-groundwater interaction.

Groundwater discharge occurs at two distinct areas along the Daly River (Chapter 2), in the form of (i) discrete point source seeps; (ii) broad exposed seepage zones; and, (iii) submerged (concealed) seepage zones. The net effect of groundwater discharge in a sub-catchment scale or aquifer water balance can be estimated from mapping increase in river discharge through stream gauging. Such an approach has been conducted in the Daly Basin since 2002 (Chapter 2) and couples well with synoptic sampling for environmental tracers that indicate groundwater discharge (e.g., Cook et al., 2003). In the current study (Chapter 4), groundwater discharge was estimated to be 10 m^3 day^{-1} per km of river for broad seepage zones downstream of Stray Creek and 180 m^3 day^{-1} per km of river where prominent springs discharge to the Daly River just upstream of Stray Creek.

Synoptic river sampling and groundwater sampling for environmental tracers has also started to reveal the source and potential age of groundwater discharge (Chapters 4 and 5). Whilst rates and locations of groundwater discharge to the Daly River are informative for water resource planning, the knowledge of source, mixing, and the potential age will advance conceptual models, which in turn underpin quantitative models. Interpretation of age tracers and groundwater modelling indicate two key findings for the Daly River: (i) where the river is incised into the Daly Basin bedrock formations a high water table limits the amount of groundwater interaction; and, (ii) water in the springs just upstream of Stray Creek is from a regional source. These findings portray groundwater discharge occurring at two distinctly differing spatial scales, which will respond to changes in distinctly differing timeframes.

Figure 8-1depicts groundwater interaction with the Daly River as a conceptual model. At the small scale, within 1 km of the river, the Oolloo aquifer is recharged by a combination of deep drainage and, to a lesser degree, from annual flooding and lateral flow into the aquifer. In the subsequent Dry season, discrete point source seeps provide relatively young water to the river. However, at the large scale, on the order of the Daly Basin, regional scale groundwater flow supplies water to major spring zones and most likely to submerged (concealed) seepage zones that extend downstream of Stray Creek.

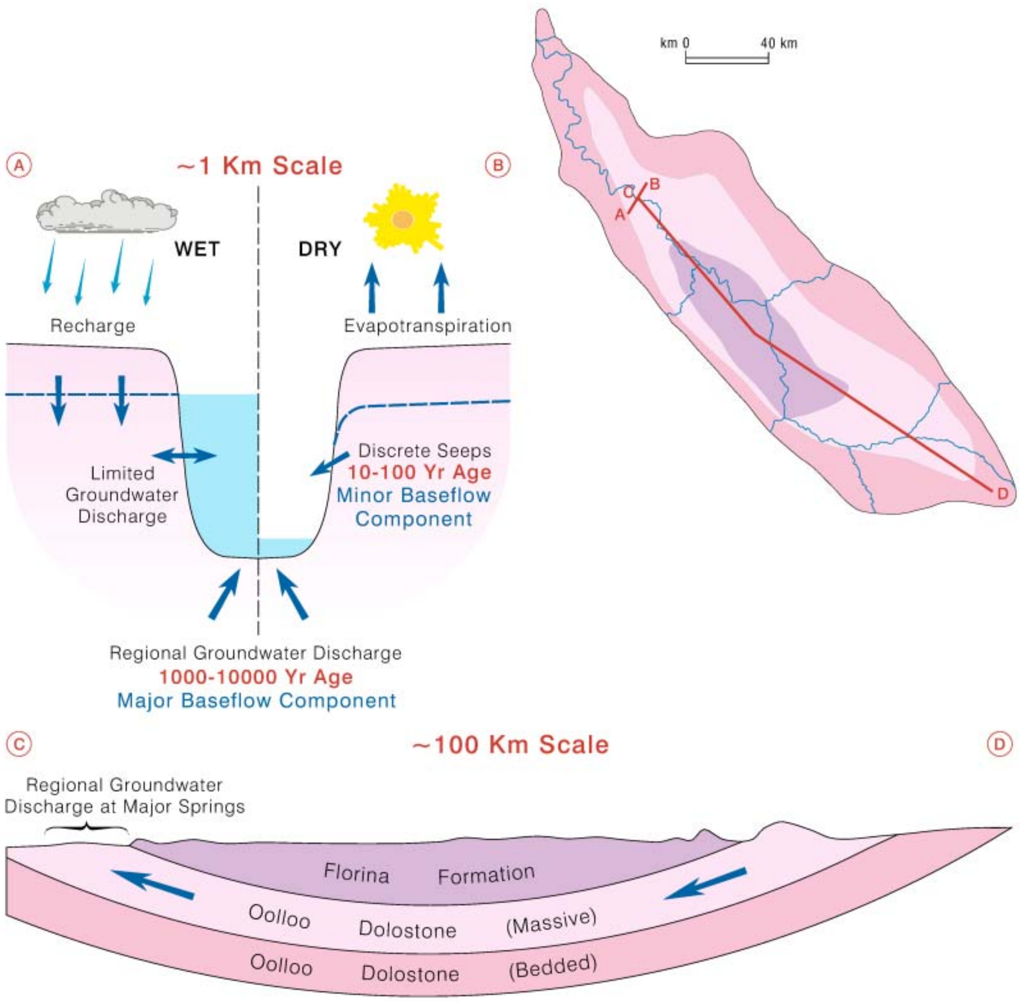


Figure 8-1 Conceptual model of basin-scale aquifer recharge, flow, age and discharge processes.

Table 8-1 Water balance parameters components, with this and previous studies within the Daly Catchment. These studies ranged from whole of catchment to sub-catchment. Estimates of water balance terms are mm per year. Rainfall has been derived over these catchments area using the long-term gridded rainfall product SILO (Bureau of Meteorology).

Rainfall	ET	Recharge	Runoff	Source	Catchment	Comments
970	660	90	220	Jolly (2002)	Douglas-Daly	Water balance for the entire Daly catchment, calculated from gauging
		40		Jolly (2002)	Douglas-Daly	Recharge where Cretaceous cover present
		150		Jolly (2002)	Douglas-Daly	Recharge where no Cretaceous cover present
1027	915	91	15	Creswell et al. (2011)	Douglas-Daly	Water balance components modelled using WAVES modelling extrapolated using HGUs, vegetation classification, ASRIS soil types.
1170*		50 to 200		Wilson *et al.* (2006)	Stray Creek	Deep drainage under native vegetation calculated from 10 month soil water balance
		300 to 540		Wilson *et al.* (2006)	Stray Creek	Deep drainage under cleared l, native grass pastures calculated from 10 month soil water balance
	870	3 to 35		Wilson *et al.* (2006)	Stray Creek	Deep drainage under native vegetation, determined by chloride concentrations. flow. ET scaled from wet and Dry season measurements
	500-600	40 to 200		Wilson *et al.* (2006)	Stray Creek	Deep drainage under cleared, native grass pastures determined by chloride concentrations
		60		Wilson *et al.* (2006)	Stray Creek	Total recharge to aquifer under native vegetation, determined by chloride concentrations
		18 / 42		Wilson *et al.* (2006)	Stray Creek	Deep drainage under native vegetation assuming 30% of recharge is diffuse, 70% bypass flow
1030**	902	116	7	Creswell et al. (2011)	Stray Creek	Point based estimates using WAVES model for native vegetation calibrated using on-site flux and soil moisture obs.
1030**	771	235	55	Creswell et al. (2011)	Stray Creek	Point based estimates using WAVES model for 30 yo. cleared improved pasture, calibrated using on-site flux and soil moisture obs.
1020		170		This study, Chapt 5	Oolloo region	Recharge where no Cretaceous cover present, approximately 17% of annual rainfall
1020		70		This study, Chapt 5	Oolloo region	Recharge where Cretaceous cover present, approximately 7% of annual rainfall
988**	903	67	1	This study, Chapt 6	Oolloo region	Sub-catchment scale estimate using HGU's integrated with WAVES model, native vegetation, using Creswell et al approach
988**	879	92	1	This study, Chapt 6	Oolloo region	Sub-catchment scale estimate using HGU's integrated with WAVES model, cleared pasture scenario, using Creswell et al approach
988**			71	This study, Chapt 6	Oolloo region	Sub-catchment scale, runoff from small upland, headwater area with rocky, skeletal soils, based on V-notch weir measurements, PCA flume site, Florina Rd, Katherine
1341	596		258	This study, Chapt 7	Oolloo region	SWAT modelling, Lumped outputs for 1993 (calendar year).

* SILO derived mean annual rainfall for Stray Creek sub-catchment, within the period of measurement, 2000-2008., ** SILO derived long-term mean annual rainfall for Stray Creek sub-catchment,1905-2010.*** SILO derived mean annual rainfall for Oolloo basin / sub-catchment,1905-2010.

8.2 *Monitoring infrastructure*

"Identify areas where development is likely to proceed and provide monitoring infrastructure to support future management needs."

The suitability of land for agriculture has been delineated by NRETAS (2010), based on soils and landform information derived from land unit mapping. Three general categories have been identified: arable with slight to moderate limitations, arable with severe limitations and non-arable. The former category occurs dominantly in areas where the Oolloo Dolostone is at or near the surface, identified here as the main recharge areas. The other two categories tend to correspond to areas where Cretaceous rocks or the Florina Formation are present, similarly identified here as areas receiving lesser or no recharge.

The monitoring bore network now gives a good coverage of the main areas where development is likely to occur, i.e. areas with few to moderate limitations to agriculture. There were some constraints however to the placement of monitoring bores. For example access to the western side of the Daly River is limited to later in the Dry season and some large tracts of land have no tracks suitable for a drilling rig.

The current coverage of monitoring bores is adequate for the purposes of detecting changes in the regional groundwater flow pattern and local influences due to pumping. Several of the bores have records dating back to the 1970s and 1980s. These provide a baseline to help differentiate climatic influences from human induced changes to groundwater levels.

8.3 *Adaptive management practices*

"Identify adaptive management practices that are compatible with the maintenance of spring dependent communities with healthy endemic populations."

Adaptive management is the setting of practices that manage water use to mitigate or adapt to any changes that could affect the sustainability of the resource. Examples of such changes could include natural events, such as change in rainfall regime. Human induced changes could include a widespread change to agricultural practice with different water use characteristics.

Adaptive management rules are included in the draft WAP. The plan uses a variable annual extraction limit to provide protection to riverine and riparian ecosystems that depend on discharge from the aquifer against the effects of extraction. Using this method of allocation, less water is allocated when rainfall is below average and more when rainfall is above average. This ensures that the Katherine and Daly Rivers do not cease to flow as a result of extractions from the aquifer. The lowest annual flow of the Daly River is maintained in line with current understanding and relevant research. Minimum flows have been set at two key gauging stations, G8140067 and G8140042 (Figure 8-2) to preserve environmental water requirements.

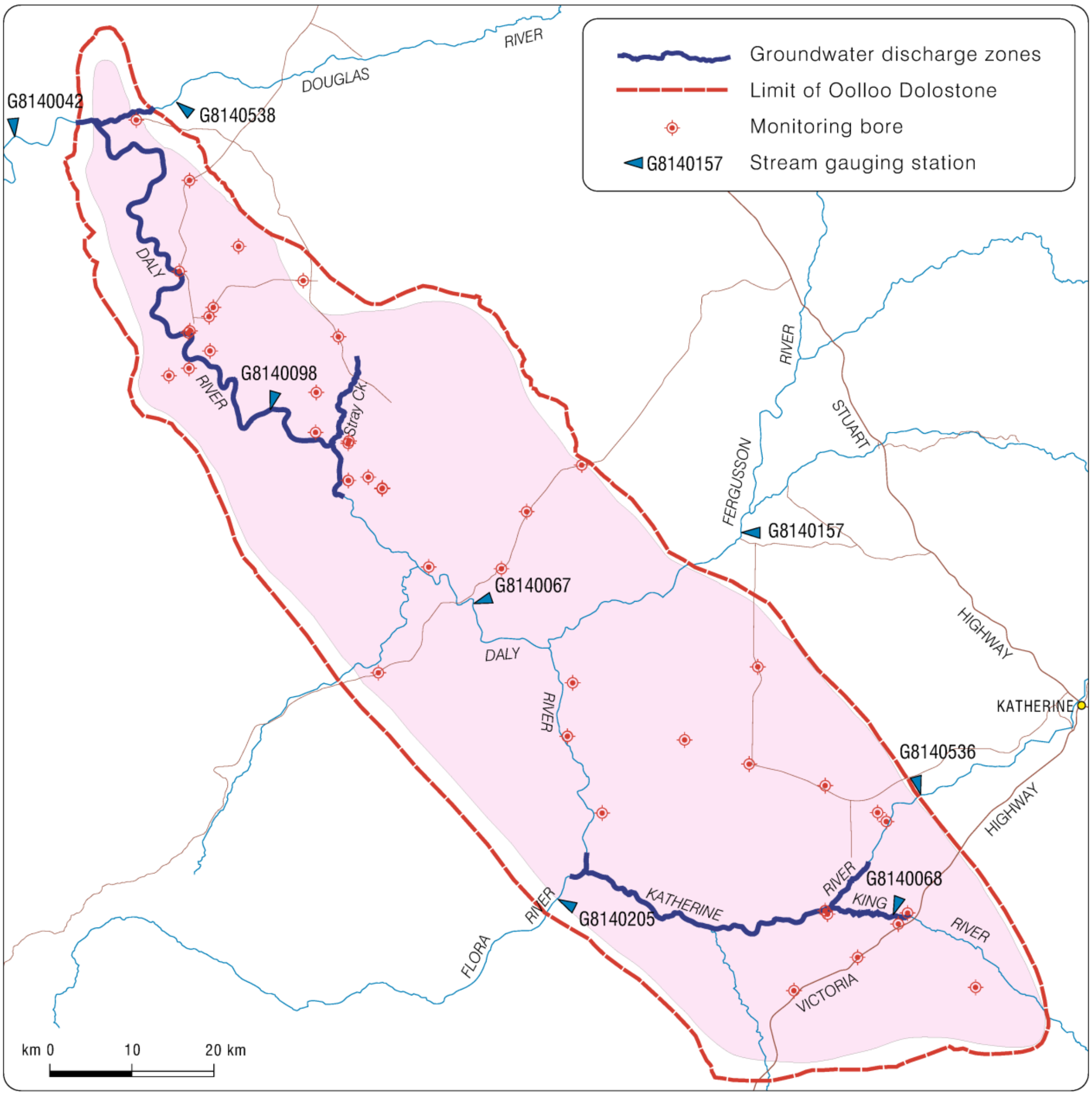


Figure 8-2 Monitoring bores and key gauging stations

8.4 Risks to springs

"Develop a robust workable system to identify measure and manage the risks to springs and dependent ecosystems caused by the allocation of water and land use changes in the region."

The discharge from the Oolloo aquifer comprises a multitude of individual springs and seepage zones spread out over many tens of kilometres along the river, mostly in inaccessible areas. The major portion of the discharge is unseen through the river bed. This means that in order to manage the springs they cannot be treated individually, rather they are best considered as broad zones along the rivers. Logical management zones would be the three delineated in Figure 2-8. They include the Katherine River, the Stray Creek and Daly River spring zones. The most significant in terms of discharge is the Stray Creek zone.

The management rules that specify minimum river flows at specified locations (Section 8.2) are designed to regulate the total amount of extraction permitted from the aquifer. The location of the bores is not however accounted for apart from two broad management zones defined in the WAP, a northern and a southern one, each with their respective water allocations.

In general all groundwater extraction will eventually result in a corresponding reduction in discharge from the aquifer. The time frame that this occurs over is the important factor for maintaining environmental river flows. The location of production bores can influence this time frame. For example if a certain volume of water is pumped from bores distant from a spring, their radius of influence will likely not reach the river over a single Dry season. If the bores were located close to the spring and the same volume was pumped, groundwater levels could potentially be lowered at the spring, reducing its flow within a short time frame (hours to months). The more distant extraction will also affect spring flows but over a longer time frame (years to decades or longer).

In order to avoid direct interference of springs it would be prudent to set buffer zones around the spring zones in which new bores would not be permitted or in which maximum pumping rates would be set. There is currently a one kilometre buffer applied around streams for any land clearing application in the Daly catchment but no such buffer exists for bores. Evans (2007) discusses methods for estimating impacts on springs from groundwater extraction. These are based on the Theis equation which assumes the aquifers are of the porous media type, homogeneous and isotropic. Evans (2007) notes that “due to the complexity and variability of the natural environment there is no single robust and technically simple tool for predicting the impact of groundwater pumping on stream flow”. This is particularly the case for the Oolloo aquifer which is karstic. That means that it contains macro-scale solution channels through which groundwater can move much more rapidly than through the micro scale network of pores and fractures. The use of the Theis equation is inappropriate in this case. For example if a high yielding bore tapped a major conduit its zone of influence on a spring would potentially be greater than that predicted using a method based on the Theis equation.

Despite the current lack of a rigorous scientific method for determining impacts of groundwater pumping on springs it would be prudent to set buffer zones as a precautionary measure. The nature of the three spring zones identified suggests that they can be treated differently in this regard. The main one, the Stray Creek spring zone contains individual springs with discharges up to 1 m^3/sec, suggesting that relatively large conduits are present in the aquifer. The other two zones are spread out along a much greater length of the rivers and are made up of many springs with small discharges. Groundwater levels measured on the Oolloo Crossing transect (Figure 8-3) give a broad indication of how groundwater pumping might affect the river. Under the present conditions groundwater flows towards the river where it discharges. The river is analogous to a pumping bore and the zone of significant influence on the watertable is of the order of 1,500 metres. In the absence of better information that distance could serve as a useful guideline for a buffer around the Daly River spring zone for production bores. Some large conduits almost certainly exist but a 1,500 metre buffer would protect the majority of springs and at the same time not be too greater hindrance to land owners. The Katherine River spring zone has similar characteristics so the same buffer could be applied.

The Stray Creek spring zone is more problematic because major conduits are certainly present. A buffer zone should therefore be greater than for the other two zones. The question is how extensive are large conduits? That is unknown but the current knowledge of the geology and of the distribution of caves and sinkholes suggests that large conduits are probably less common than those encountered in the nearby Tindall aquifer. Considering the importance of this spring zone it is proposed here to double the buffer distance in this case to three kilometres.

Continued monitoring of Dry season river flows and of groundwater levels is important as buffer distances may need to be reassessed as development proceeds. It should also be noted that the current climate is wetter than the average and this is reflected in above average spring discharges (Figure 1-2 and Figure 2-10). When rainfalls revert to below average levels, groundwater levels will fall and the effects of pumping on spring flows will be more critical.

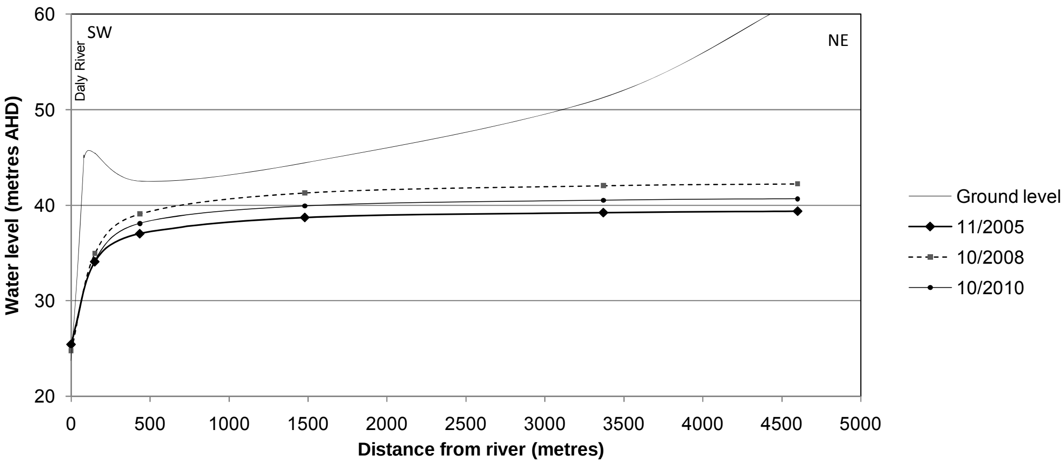


Figure 8-3 Groundwater levels at Oolloo Crossing, late Dry season, see Figure 4-1a for the location.

8.5 *Application of the study outcomes*

"Work collaboratively with water managers and industries that will depend on the water to ensure that the study outcomes are understood, relevant and applied."

The main purpose of the current study is to provide a better scientific basis for the Oolloo WAP. As such NRETAS the department responsible for managing the plan is the primary audience. The computer model used to determine water allocations has already been modified by some of the current findings. For example, the revised extent of the aquifer has been taken into account by the model.

It is anticipated that in the short term various others will also be incorporated. For example, the improved gauging data will constrain the current distribution of transfer rates used in the model. The environmental tracer data could be incorporated into the current coupled model as a comparison and validation. The new conceptualization of the aquifer (Figure 8-1) from equivalent porous media to dual continua may be implemented in the model. The assumption of little to no bank storage assumed by the current coupled model is validated.

In the longer term a soil-vegetation-atmosphere transfer (SVAT) model, such as SWAT (see: Chapter 7) could be used in combination with the current groundwater / surface water model. Previous groundwater flow modelling of the Oolloo Dolostone (Knapton, 2005; Knapton, 2006) identified that an improved estimate of recharge with respect to quantity and distribution would improve the physical basis for the model and the ability of the model to reproduce the observed groundwater levels and discharges. It has also been identified that a distributed model of the land component of the water cycle would eliminate discrepancies associated with the different methods used to calculate runoff and recharge implemented in the current coupled model (Knapton, 2010). Given the physically based nature of SVAT models and their ability to be parameterised and calibrated against actual observed data, it is considered that a SVAT model would provide a suitable framework from which to generate distributed recharge and runoff for the current coupled surface water / groundwater model. A SVAT model would also maintain conservation of mass between the different components. The SVAT model presented herein is seen as a basis for the realisation of distributed recharge and runoff in the coupled model.

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