COONDEWANNA FLATS ECO-HYDROLOGY REVIEW AND CONCEPTUAL MODEL

Prepared for

BHPB IRON ORE

January 2015

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1 Background

1.1 Introduction

Coondewanna Flats (the Flats) is a broad, flat lying area some 10 km south-west of Mining Area C (MAC). The Flats host two unusual Western Coolibah (*Eucalyptus victrix*) woodland vegetation communities, that are listed as Priority Ecological Communities (PEC) by the Department of Parks and Wildlife (DPaW 2014).

BHP Billiton Iron Ore (BHPB) have current and future mining areas in proximity to the Flats: Mudlark and Tandanya to the west and South Flank Valley and MAC to the east. Accordingly, BHPB is undertaking eco-hydrological studies and monitoring to develop an understanding of how the PECs function, to determine their environmental water requirements (EWR) and (if required) identify suitable management measures to maintain the persistence of the PECs as mining develops. To date, detailed eco-hydrological studies have been undertaken in phases, and have separately studied the vegetation, soil and hydrological characteristics of the Flats. This report describes the integration of previous work and monitoring data to develop a conceptual eco-hydrological model.

1.2 Scope

AQ2 previously developed a high-level conceptual model of the eco-hydrology of the Flats (as a specialist sub-consultant to RPS (2014)). Since then, additional data have been collected and BHPB have now engaged AQ2 (in conjunction with Equinox Environmental) to undertake a review and integration of all work to date. The scope is summarised below:

- Review and summarise data collected to characterise the ecohydrology of the PECs at Coondewanna Flats;
- Summarise the key findings and highlight linkages between vegetation, soil and groundwater;
- Confirm or update the existing conceptual eco-hydrological model;
- Semi-quantification of the key features and linking processes in the eco-hydrological model; use this where possible to develop thresholds for management; and
- Identify critical gaps and uncertainties and recommend studies and on-going monitoring to address these gaps.

This report presents a review of previous work and the data collection that underpinned it, integrates the data to define the main elements of the eco-hydrological system and processes that link these elements, describes a semi-quantified eco-hydrological conceptual model and highlights key data gaps and areas of uncertainty (with recommendations to address these gaps).

1.3 Physiography

The location and setting of Coondewanna Flats is summarized in Figure 1.

1.3.1 Setting

The Flats are located in the Hamersley Ranges in the Central Pilbara Region of Western Australia, approximately 100 km north-west of Newman and 10 km south-west of Mining Area C (MAC). The area is located close to the North Flank Valley (which includes MAC), South Flank Valley, Tandanya and Mudlark mining areas. The Flats are wholly contained within the Juna Downs pastoral station. Current land-uses are grazing and mineral exploration.

1.3.2 Topography

The Flats comprise an inter-montane alluvial plain bound by hills of Mt Robinson and The Governor to the east and south respectively, and by Packsaddle and Mt Meharry to the north and west respectively. The surrounding hills rise to over 1200 mAHD.

The Flats themselves have little relief and drainage across them is indistinct. Topographic elevations range between 690 m AHD near the margins of the Flats to 686 mAHD at the lowest points.

1.3.3 Climate

The Pilbara region is characterised by an arid-tropical climate, influenced by tropical maritime and tropical continental air masses. Tropical cyclones cross the coast on average 7 out of 10 years, typically between November and March (Golder, 2013) and bring heavy, intense rainfall with individual event totals commonly in the range 100 – 200 mm. With the exception of these large events, rainfall is highly variable, localised, and dominated by short duration, high intensity thunderstorm activity. Long-term average annual rainfall in the Coondewanna Catchment is 328 mm, based on SILO data (from DSITIA) (RPS 2014).

The Pilbara region has an extreme temperature range, rising up to 50 degrees Celsius (°C) during the summer, and dropping to approximately 0°C in winter (BOM).

The mean annual pan evaporation rate at Newman is 3,733 mm (Department of Agriculture, 1987), which exceeds mean annual rainfall by approximately 3,400 mm. Average monthly pan evaporation rates for Newman vary between a minimum of 173 mm in June and a maximum of 466 mm in December.

As annual average potential evaporation is far in excess of the annual average rainfall, there is commonly a large moisture deficit in the environment. Mean rainfall and potential evaporation are summarised in Table 1.

Figure 1: Location and setting of the Coondewanna Flats (reproduced from URS 2014)

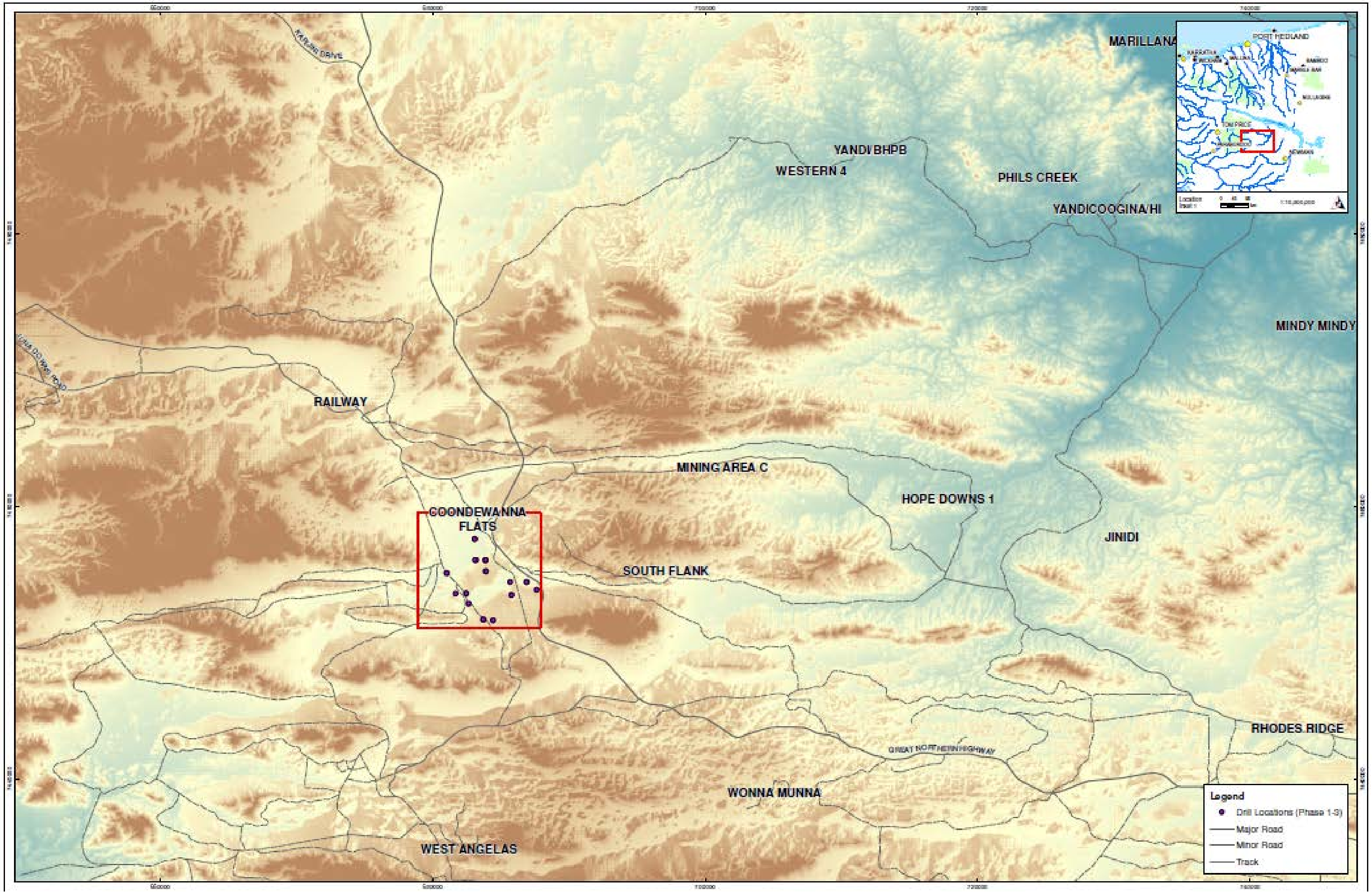


Table 1 Mean rainfall and evapotranspiration at locations near the Coondewanna Flats

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Marillana Creek - average rainfall (mm)	69	72	49	23	21	19	14	6	3	5	9	27	**317**
Newman - potential evaporation (mm)	461	369	343	290	174	173	199	193	264	377	424	466	**3733**

Marillana Creek rainfall is used in the table above, as the catchment is in proximity to Coondewanna Flats and hosts the Flat Rocks flow gauge (the closest DoW gauge to Coondewanna). Newman is the closest ET station to Coondewanna.

1.3.4 Hydrology

Although the Flats are considered to be in the Ashburton River Basin, they are internally draining. Surface water runoff from the surrounding catchments is focused onto the Flats and then either infiltrates (to the soil-moisture or groundwater) or evaporates. There is no surface water outflow. The surface water catchment-area is 860 km^2.

Due to the large moisture deficit in the environment, runoff is only generated when rainfall exceeds a threshold value of around 20 mm (Golders 2013). Consequently:

- flow to the Flats is ephemeral; significant runoff occurs to the Flats every 3 in 4 years (RPS 2014);
- diffuse recharge to the regional groundwater system occurs at very low rates; and
- groundwater recharge occurs preferentially during the largest rainfall-runoff events along the major creeks and other areas of surface water concentration/inundation such as the Flats (notably Lake Robinson).

The hydrostratigraphy of the Flats includes low to moderate permeability Tertiary detritals overlying an unconfined aquifer comprising calcrete and dolomite. The water table is approximately 20 mbgl. Groundwater level gradients across the Flats are low and groundwater flow is to the east.

1.3.5 Vegetation

Vegetation on the Flats comprises Coolibah (*E. victrix*) and Mulga (*A. aptaneura*) woodlands with associated under-storey vegetation including lignum and tussock grasses. The PECs[1] at the Flats specifically comprise:

- **Priority 1**: Coolibah woodlands (*E. victrix*) over lignum (*Muehlenbeckia florulenta*) over Swamp Wanderrie (*Eriachne benthamii*). Lake Robinson in the northern portion of the Flats is the only known occurrence of this community in the Pilbara region; and

[1] A Priority Ecological Community (PEC) is an ecological community that does not meet survey criteria for 'threatened' status or that is not adequately defined, and is considered by the DPaW to require further survey or ongoing monitoring to ensure their security does not decline. PECs are listed under one of five categories ranked in order of priority.

- **Priority 3**: Coolibah and Mulga woodland over lignum and tussock grass on clay plains. Examples of this community have only been identified at Coondewanna Flats and Wannamunna Flats (approximately 40 km to the southeast).

Flooding events are important drivers for the function of riparian vegetation in semi-arid environments (Eamus et al. 2006). Flood frequency has been correlated with tree health (McGinness et al. 2013); and has also been linked to recruitment (Jensen et al. 2008). In this regard, the distribution of Coolibah in the Central Pilbara is often correlated with floodplain environments.

Lignum is common in Australia's arid zone wetlands and prefers ponding of water for several months every 1–3 years, but is able to tolerate inundation for up to 12 months and dry periods of up to 10 years (Roberts & Marston 2011). The presence of Lignum on the Coondewanna Flats suggests a variable flooding regime with significant inter-annual variability.

Mulga (*Acacia aneura* and closely related taxa) is generally shallow-rooted (likely < 5 m depth), can extract water from very dry soils, and is able to maintain very low rates of water use during extended drought to survive (Page and Grierson 2010).

2 Review of Literature and Data Collection

2.1 Background Work and Literature

2.1.1 Previous Studies at Coondewanna Flats

A number of studies addressing aspects of the ecohydrology of Coondewanna Flats have been completed in the past decade. Additionally, over the last two years, a considerable volume of monitoring data has been collected.

Four monitoring bores were installed by Aquaterra (2005) as part of a regional monitoring network for BHPB. Mineral exploration in the area was carried out by UMC (2009) and 45 RC exploration holes were drilled. These two studies provide good geological control and groundwater level data.

URS (2012) and SKM (2012) undertook the first phase of a hydro-environmental assessment that included drilling (11 bores) and the assessment of soil-water and groundwater chemistry, including stable isotope chemistry. These studies aimed to determine the extent of ecosystem groundwater dependence and as part of this work tree-water chemistry and leaf water potential (LWP) were also measured (Astron 2012).

Regular monitoring has been undertaken in the regional monitoring bores installed by Aquaterra since 2004. Data loggers were also installed in six of the bores drilled by URS (2012). In combination, these data sets provide an indication of water level change at Coondewanna Flats.

A review and integration of all previous work until 2012 was undertaken by RPS (with AQ2 as specialist) (2014), as part of the process of developing an ecohydrological conceptual model for the Central Pilbara Region (CPR) to support BHPB's Strategic Environmental Assessment (SEA). Key points of this integrated conceptual model were:

- Surface water runoff from the surrounding catchments is attenuated in the internally draining low-relief landscape of the flats, principally accumulating in the Lake Robinson area but extending more widely across the flats in very large and infrequent flood events.
- Beneath the Flats is an unconfined aquifer comprising calcrete around 5-10 m thick occurring at a depth of ~20 mbgl. This is overlain by low to moderate permeability Tertiary detritals and underlain by low to high permeability basement of the Wittenoom Formation.
- Groundwater level gradients across the flats have a general west-east direction. However, gradients are low and little groundwater flows into the area from the west. Consequently recharge derived from ponding of surface water runoff is the major source of groundwater replenishment in Coondewanna Flats.
- Recharge occurs predominantly as infiltration from surface water in the Lake Robinson area. Recharge events have a return period of approximately four years and although recharge is highly variable over time, annual average recharge rates are approximately 6,500 kL/d at Lake Robinson and 11,000 kL/d over the broader Coondewanna Flats area. The latter represents approximately 75% of total recharge to the down-gradient Weeli Wolli (groundwater) Catchment.

- Notwithstanding that recharge occurs every four years on average, surface water flows typically reach Coondewanna Flats three out of every four years and replenish soil moisture in the unsaturated profile, even when groundwater recharge does not occur.
- A southwest-northeast trending dyke acts as a partial (low flow) groundwater flow barrier at the eastern end of Coondewanna Flats; as indicated by a steep groundwater gradient.
- Groundwater levels are around 20 mbgl on the Flats, whilst downstream (south and east of the dyke) groundwater levels are around 50 mbgl.
- Groundwater discharge occurs as outflow to the South and North Flank Valleys, thus connecting the Coondewanna and Weeli Wolli Catchments from a groundwater perspective. Coondewanna Flats is the major source of groundwater throughflow that ultimately reaches Weeli Wolli Spring. Although a 60%:40% allocation of flow to the North and South Flank valleys respectively has been provisionally adopted in recent work, on the basis of relative hydraulic gradients, the actual distribution of groundwater flow between the valleys is uncertain.
- Vegetation of the Lake Robinson area includes Western Coolibah (*E. victrix*) woodlands over open shrub land of Lignum (*M. florulenta*) and tussock grassland growing on orange brown loamy clay.
- Vegetation of the slightly more elevated flats surrounding the Lake Robinson area includes open forest of Mulga (*A. aptaneura* and closely related taxa) with occasional *E. victrix* over sparse Lignum and tussock grasses growing on red brown clay loam.
- The Western Coolibah trees on Coondewanna Flats rely on stored soil moisture to meet water requirements. Studies indicate they are able to obtain water for prolonged periods from deeper layers in the unsaturated zone above the water table (pre-dawn leaf water potentials of at least -4,000 kPa have been measured after prolonged dry conditions). There is no evidence to suggest that they use groundwater. The surface water regime of regular soil water replenishment (around 3 out of 4 years) to the deep unsaturated sediments maintains sufficient soil moisture to support these trees.
- Mulga and under-storey vegetation obtain water from the upper 5 m of soil profile while the Coolibahs may obtain water from depths of up to 15 mbgl.
- The surface water dynamics of Coondewanna Flats are likely to influence Western Coolibah bud-set, flowering, seed production and seedling recruitment.
- The Lake Robinson water body is ephemeral but may persist for several months after large catchment runoff events.

A key conclusion from the RPS work was the lack of evidence to suggest groundwater dependency in the vegetation community; rather that there was sufficient soil water available to support the communities through extended periods of drought. A simple 1-D model (using Hydrus[2]) was also constructed to further test this conclusion. The model showed that the unsaturated profile can store large volumes of plant available water (PAW), and that even after 10 years of extreme drought there

[2] Details of Hydrus available at http://www.pc-progress.com/en/Default.aspx?hydrus-1d

would be minimal flux from the water table into the unsaturated zone when tree-roots were simulated to a depth of 18 mbgl.

2.1.2 Other Relevant Literature

Groundwater recharge and discharge in semi-arid environments is strongly linked to vegetation cover, water table depth and surface water distribution/focusing (e.g. Wen et al. 2009, Nimmo et al. 2002, Walvoord et al. 2002, Scanlon et al. 2003, 2005, Walvoord 2004, Sandvig and Phillips 2006, Miller et al. 2012 *inter alia*). With the exception of shallow water table environments, much of the infiltration from incident rainfall is captured in the upper 5 m of the soil profile owing to the strongly negative matric potential of this layer (Allen and Anderson 1993, Walvoord et al. 2002). Stored soil water is subsequently used by vegetation in addition to evaporating directly from the soil surface. This water capture, storage and release mechanism restricts deep percolation and is associated with the accumulation of chloride at and below the vegetation root zone.

Where soil profiles have very high water storage capacity (i.e. deep soils in the absence of preferential flow paths) relative to rainfall inputs, there may be effectively no groundwater recharge (Walvoord et al. 2002). However, where surface water is focused in channels or ponds, the larger volumes of infiltrating water may be sufficient to overcome the soil-moisture-deficit and facilitate recharge on a periodic basis (Nimmo et al. 2002). The recharge process can transport accumulated chloride into deeper unsaturated layers and groundwater systems. The type of vegetation cover has a key influence over the timing and extent of deep infiltration (Walvoord and Phillips 2004, Sandvig and Phillips 2006); for examples as influenced by vegetation root depth, water use strategies and water use regulation mechanisms.

Water use strategies vary between tree species (O'Grady et al 2009). Notwithstanding, considerable convergence in unit-rates of water use between species have been demonstrated under similar water availability regimes (Hatton and Wu, 1995; Hatton et al. 1998; Zeppel and Eamus 2008; Zeppel 2013). In the Pilbara region and other semi-arid environments in Australia, typical rates of tree-water use range between 100 and 300 L/tree/day for mature riparian *Eucalyptus* species (Pfautsch et al 2011; Pfautsch et al 2014).

Some plant species are able to access groundwater as well as soil-water to meet their water use requirements; these are referred to as phreatophytes (Thomas 2014). Access to groundwater may be temporary or permanent, with the level of reliance on groundwater varying between species and growing environments for the same species. In some cases vegetation may be reliant on permanent access to groundwater, particularly where the water table is less than 10 mbgl (Eamus, et. al., 2006); whilst in other cases groundwater is used opportunistically, most typically when other water sources become difficult to access or unavailable (Eamus, et. al., 2005). As has been demonstrated in numerous studies globally, the majority of phreatophytes use a combination of groundwater and soil-water from the unsaturated zone (Thomas 2014, O'Grady, et. al., 2011). Simultaneous use of different water sources means that trees that use groundwater may still maintain low stem water potentials (≥ -4,000 kPa) at least during some periods (Gou and Miller, 2013).

Mt Bruce Flats is approximately 100 km west of Coondewanna Flats and comprises an analogous geomorphology and vegetation community. Rio Tinto has undertaken extensive investigation of many of the factors outlined above at Mt Bruce Flats (e.g. Rio Tinto 2011). Key conclusions from this work are:

- Based on soil chloride profiles, stable isotope signatures and groundwater chemistry recharge occurs on the Mt Bruce Flats periodically after large rainfall runoff events (i.e. when the focusing of surface water is sufficient to overcome soil moisture deficit); the water table is 17-20 mbgl and the unsaturated profile can store considerable quantities of plant available water.
- Mature *E. victrix* trees on Mt Bruce Flats use on average 115-135 L/d of water. At a vegetation stand level, total woodland water use is around 250 mm/year. Annual average rainfall at the site has been estimated as 402 mm, and average annual evaporation (from a free water surface) is approximately 1840 mm.
- On the basis of soil-chloride profiles and stable isotopes in soil water and tree-water, *E. victrix* accesses water from the unsaturated zone to depths of up to 11 mbgl and is predominantly reliant on deeper soil moisture rather than groundwater during prolonged dry periods.

2.1.3 Implications of Previous Studies for Coondewanna Flats

The following can be gleaned from a synthesis of the available information:

- Salient points from a broader literature review are consistent with previous data collected from Coondewanna Flats, suggesting the existing hydro-ecological conceptualisation outlined by RPS inter alia is above is reasonably robust.
- Coondewanna Flats exists in a water-limited semi-arid environment characterised by large moisture deficits. The vegetation community is likely to play an important role in establishing equilibrium water fluxes in the eco-hydrological system of Coondewanna Flats.
- On average soil-water is likely to be replenished 3 in 4 years, whereas, groundwater recharge will only occur 1 in 4 years following events that are large enough to overcome the soil moisture deficit.
- Broadly, where there is no surface water focusing, groundwater recharge is likely to be negligible. Notwithstanding the return period of larger events on Coondewanna Flats, it is likely to be an area of enhanced groundwater recharge due to the focusing and retention of surface water runoff in the area.
- The hydrogeological system on the Flats is well understood although some uncertainty remains with respect to allocation of groundwater outflow between the North and South Flank valleys (and hence the integration of the flats with the broader regional system).
- *E. victrix* and *A. aptaneura* are the main woodland species; it is likely they will have differing water-use strategies to co-exist side by side although may tend to similar overall water consumption at a stand-level.
- From similar woodland communities elsewhere, water use by mature individuals of *E. victrix* is likely to range between 100 L/d and 300 L/d. The water use of mature individuals of *A. aptaneura* is likely to be less than this.

- The depth to water, at 20 mbgl, provides a large soil-water store which is replenished regularly and which will afford considerable quantities of plant available water.
- The area is analogous to the Mt Bruce Flats where extensive work by Rio Tinto provides strong evidence that the *E. victrix* woodland community is not groundwater dependent.
- The above findings in combination with soil-chloride profiles, the negative leaf water potentials and previous isotope studies suggest Coondewanna Flats is unlikely to be groundwater dependent.

2.2 Summary of Recently Completed Work

Recent work was completed by Astron (2014) and URS (2014). The objective was to provide additional data to complement the studies completed in 2012 and outlined above. Comprehensive presentations of the data collected are provided in the respective URS (2014) and Astron (2014) reports; the data are not replicated here. A summary of the measurements and data collected is provided in Table 2 and discussion follows.

2.2.1 URS Phase 2 and 3 Eco-hydrological Investigations - 2014

The URS (2014) reports describe the installation of additional soil and groundwater monitoring bores to complement work undertaken during their Phase 1 assessment (URS 2011) and the results from which used in the work outlined above. A total of 13 groundwater monitoring bores were installed across a dry season and wet season campaign. Data collected during the drilling of each bore are summarised in Table 3.

URS installed crest-gauges on some of the channels flowing into Coondewanna Flats from the Tandanya mining area. Loggers associated with these were also downloaded during the most recent field work with a view to showing surface water flow on the Flats during the 2013/2014 wet season.

Additionally, in November 2014, soil-moisture probes were installed in shallow bores at 5 locations. At each location, three soil moisture sensors were installed to 0.4 m, 1 m and 4 m depth. Due to failure of some loggers, data was only recorded at 3 locations.

The location of the data collection points are shown on Figure 2.

The URS investigations adopted a well thought-out approach and used generally appropriate methods of data collection. The reports present a compendium of robust raw data.

This current report seeks to use this raw data to improve the eco-hydrological conceptual model and integration between the surface, soil and ground water and vegetation elements of the ecohydrological system.

Table 2 Summary of recently completed work by Astron and URS

Measurement / Metric	Timing / Frequency	Source	Application / Focus
Counts of live and dead trees, saplings and seedlings of E. victrix and A. aptaneura within circular plots (25 m radius) proximal to the target drill pads[1]. Visual estimates of the percentage understorey cover (to the nearest 5%) of native plants, weeds, litter and bare ground were also made.	Apr-14	Astron	Riparian Vegetation Community
Descriptive plant traits including stem diameter, crown dimensions and height for each 'focus' plant.	Measured once in either November 2013 and April 2014	Astron	Riparian Vegetation Community
Health status of 'focus' plants based on visual assessment techniques suitable for each species.	November 2013 and April 2014 for each 'focus' plant	Astron	Riparian Vegetation Community
Sapwood samples were obtained from a separate group of six *E. victrix* trees and five *A. aptaneura* trees sampled from random locations adjacent to access tracks across the study site. This provided the basis for developing an allometric relationship between sapwood area and DBH over bark for each species.	Apr-14	Astron	Riparian Vegetation Community
Projected foliar cover (PFC) of *E. victrix* and *A. aptaneura* was measured using the digital canopy photography (DCP) method of MacFarlane et al. (2007a; 2007b). Photo points were permanently marked with capped steel pegs to allow repeated measurements.	November 2013 and April 2014 for each 'focus' plant.	Astron	Riparian Vegetation Community
Leaf water potential was measured at predawn and midday using a pressure chamber. Three subsample measurements were obtained for each plant from separate shoots (containing 3 to 10 leaves) severed from the mid-canopy.	November 2013 and April 2014 for each 'focus' plant.	Astron	Riparian Vegetation Community
Leaf turgor loss point was also determined for *E. victrix* and *A. aptaneura* from the analysis of pressure volume (PV) curves, from a separate set of trees sampled at the study site.		Astron	Riparian Vegetation Community
Sap flow was measured in eight *E. victrix* and seven *A. aptaneura* trees using the Heat Ratio Method (HRM) of Burgess et al. (2001). This was used in combination with sapwood area estimates to calculate sap flux density (SFD, $cm^3\ cm^{-2}\ h^{-1}$)	Continuous (half hourly). Trees at pads 11, 12, 13, 14, 16, 20 and 22 were instrumented in June 2013, while trees at pads 15 and 17 were instrumented in November 2013. Data presented in the Astron (2014) report is from the dates of installation until 22 April 2014.	Astron	Riparian Vegetation Community
Stable isotopes in plant stem tissue water. This complemented the sampling of groundwater, rainwater and soil for stable isotopes by URS (2014) (refer to Section 2.2.1).	14 November 2013 and 27 April 2014	Astron	Riparian Vegetation Community
Physical properties of soil/geology. Drilling 13 monitoring bores to provide geological descriptions of saturated and unstarurated zones. Analysis of selected samples for Particle Size Distribution and Bulk Density. Samples cored with Sonic Rig	2 Campaigns: November 2013 (7 bores) and May 2014 (6 bores)	URS	Soil and Groundwater Reservoirs
Soil Chemsitry - major ions and salinity	2 Campaigns to identify seasonal change: Dry season - November 2013 (7 bores) and Wet season - May 2014 (6 bores)	URS	Soil Water Reservoir
Soil Water Chemistry - major ions and stable isotopes from samples extracted during drilling.	2 Campaigns to identify seasonal change: Dry season - November 2013 (7 bores) and Wet season - May 2014 (6 bores)	URS	Soil Water Reservoir
Soil Moisture Content - measured in the field on selected samples during drilling using Decagon soil moisture probe; selected samples subject to laboratory measurement; measured in-situ soil moisture sensors installed in bores 9 bores at 3 sites - 3 at each site between 0.4 and 4m depth	2 Campaigns to identify seasonal change: Dry season - November 2013 (7 bores) and Wet season - May 2014 (6 bores). Installed soil moisture probes continuous data 11/11 - 4/14	URS	Soil Water Reservoir
Soil Matric Potential based on 'filter paper method' on selected samples collected during drilling	2 Campaigns: November 2013 (7 bores) and May 2014 (6 bores)	URS	Soil Water Reservoir
Groundwater Levels - installation of additional loggers and collection of data from loggers installed in existing bores		URS	Groundwater Reservoir
Groundwater Chemistry - major ions and stable isoptopes from samples collected during drilling and testing	2 Campaigns: November 2013 (7 bores) and May 2014 (6 bores)	URS	Groundwater Reservoir
Aquifer hydraulic properties - slug tests on groundwater monitoring bores.	2 Campaigns: November 2013 (7 bores) and May 2014 (6 bores)	URS	Groundwater Reservoir

Table 3 Summary of groundwater monitoring installation and collection between November 2011 and April 2014.

BHID	EAST	NORTH	ELEV (tc)	DEPTH	Screened Geology	DATE	DRILL METH	DTW (mbtc)	WL mAHD	Remarks	Soil		Soil Moisture		Groundwater		
											Chemistry	Isotope	Sample	Matric Potential	Level	Aquifer Parameters	Quality
HCF0018	683189	7456051	686.6	47.1	TD2/Dolomite	30/10/2013	sonic	23.02	663.6	Phase 2	✓	✓	✓	✓	✓	✓	✓
HCF0019	681036	7455100	691.7	44.1	TD2/Dolomite	3/11/2013	sonic	18.80	672.9	Phase 2	✓	✓	✓	✓	✓	✓	✓
HCF0023	683720	7451697	682.0	84.3	TD2/Dolomite	8/11/2013	sonic	18.90	663.1	Phase 2	✓	✓	✓	✓	✓	✓	✓
HCF0027	682645	7452866	687.0	50.9	TD2/Dolomite	13/11/2013	sonic	23.50	663.5	Phase 2	✓	✓	✓	✓	✓	✓	✓
HCF0031	685808	7453503	687.3	21.5	TD3	16/11/2013	sonic	20.00	667.3	Phase 2	✓	✓	✓	✓	✓		✓
HCF0032	683103	7457610	692.6	62.7	TD2/Dolomite	21/11/2013	sonic	24.40	668.2	Phase 2	✓	✓	✓	✓	✓	✓	✓
HCF0036	684453	7451630	692.5	62.1	Dolomite	24/11/2013	sonic	47.40	645.1	Phase 2	✓	✓	✓	✓	✓	✓	✓
HCF0040	683098	7457605	688.2	35.0	TD3	24/04/2014	sonic	23.44	664.8	Phase 3, Elev. suspect	✓	✓	✓	✓	✓	✓	✓
HCF0041	683188	7456058	687.5	30.0	TD2	3/05/2014	sonic	22.82	664.7	Phase 3, Elev. suspect	✓	✓	✓	✓	✓		✓
HCF0042	687645	7453869	687.4	30.0	TD3	6/05/2014	sonic	23.90	663.5	Phase 3, Elev. suspect	✓	✓	✓	✓	✓	✓	✓
HCF0043	685811	7553503	687.1	53.0	TD3	20/05/2014	sonic	21.30	665.8	Phase 3, Elev. suspect	✓	✓	✓	✓	✓	✓	✓
HCF0044	683726	7451709	687.9	20.0	TD3	24/05/2014	sonic	18.70	669.2	Phase 3, Elev. suspect	✓	✓	✓	✓	✓		✓
HCF0045	681032	7455103	687.2	22.0	TD3	26/05/2014	sonic	18.08	669.1	Phase 3, Elev. suspect	✓	✓	✓	✓	✓	✓	✓
HCF0006	683910	7455241	687.1	61.3	Dolomite	3/11/2010	diamond	23.40	663.7	Phase 1					✓	✓	
HCF0007	686897	7454454	686.8	30.0	TD3	28/10/2011	sonic	Dry		Phase 1					✓		
HFC0008	686897	7454454	686.8	51.0	Dolomite	27/10/2011	sonic	Dry		Phase 1, Eco Hydro	✓	✓	✓		✓		
HCF0009	685696	7454445	686.8	25.0	TD3	29/10/2011	sonic	21.60	665.2	Phase 1, Eco Hydro	✓	✓	✓		✓	✓	✓
HCF0010	681700	7453599	686.8	22.0	TD3/Calcrete	31/10/2011	sonic	18.60	668.2	Phase 1, Eco Hydro	✓	✓	✓		✓		✓
HCF0011	682482	7453616	686.8	22.8	Calcrete	5/11/2011	sonic	20.80	666.0	Phase 1, Eco Hydro	✓	✓	✓		✓	✓	✓
HCF0012	683899	7456056	687.3	26.0	TD3	8/11/2011	sonic	23.53	663.8	Phase 1, Eco Hydro	✓	✓	✓		✓	✓	✓
HCF0013	683899	7456056	687.3	20.0	TD3	11/11/2011	sonic	Dry		Phase 1					✓		
HCF0014	683910	7455241	687.1	22.7	TD3/Calcrete	12/11/2011	sonic	21.31	665.8	Phase 1, Eco Hydro	✓	✓	✓		✓	✓	✓
HCF0015	682487	7453611	686.8	15.5	TD3	13/11/2011	sonic	Dry		Phase 1					✓		
HCF0016	683899	7456056	687.3	38.0	Calcrete	19/11/2011	sonic	22.76	664.6	Phase 1					✓	✓	

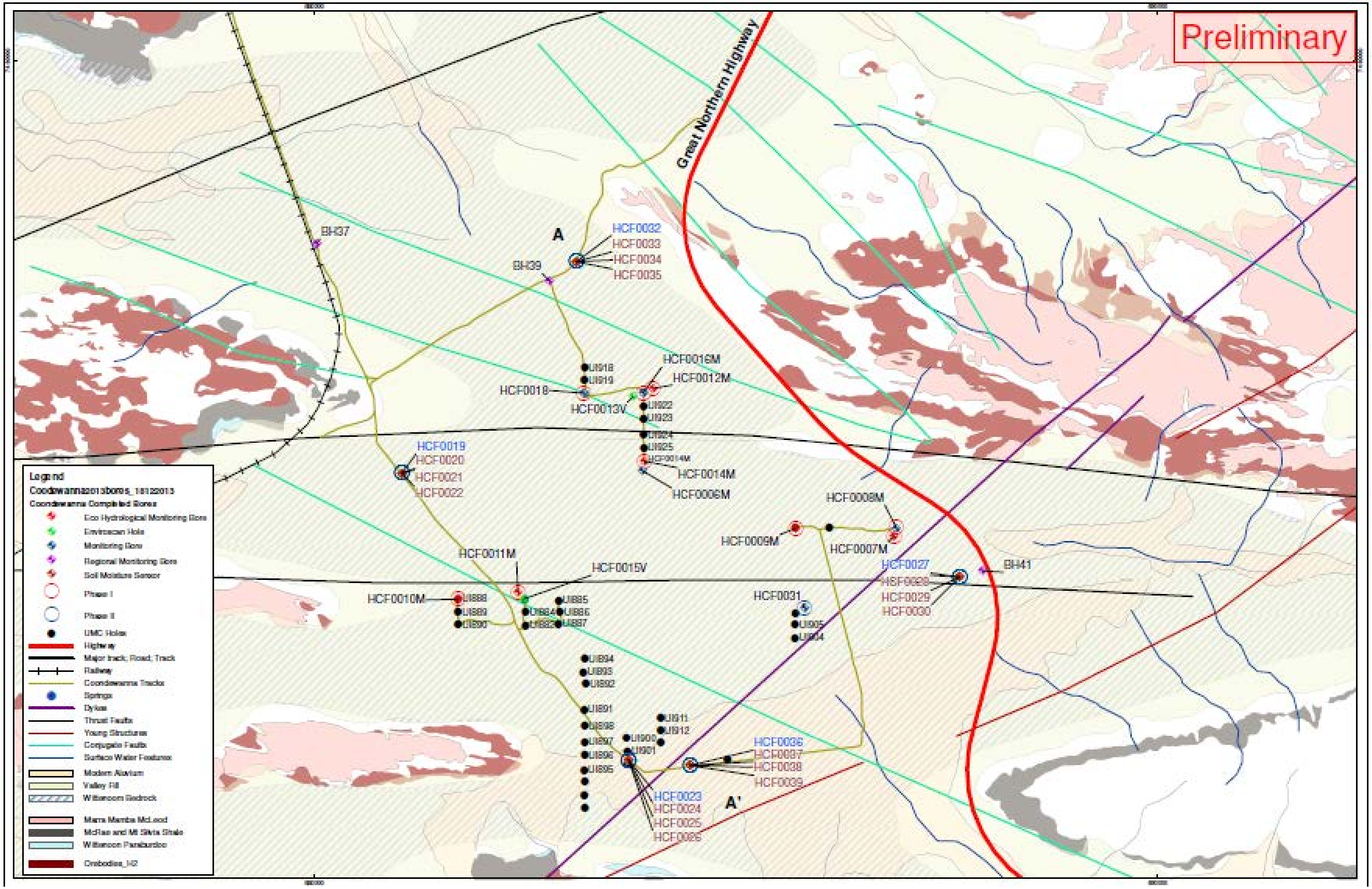


Figure 2 **Location of soil and groundwater data collection and monitoring points (reproduced from URS 2014)**

2.2.2 Key Findings from URS 2014 Work

2.2.2.1 Surface Water

Surface water assessment and analysis has not been a major focus of the URS studies. However, of the crest gauges that have been installed, the first station (SNPH0011) was installed on Homestead Creek in 2011 and six additional stations were installed in 2012. Station SNPH0011 on Homestead Creek now has three wet seasons of water level data with the recorded annual peak water levels as given in Table 4. At this stage, discharges are not available for these crest-gauging stations, as depth-discharge relationships have not been developed, however the data indicates that 2011/12 had a significantly higher runoff than the following two years. The groundwater hydrographs also reflect this with recharge only occurring in the 2011/2012 wet season.

Table 4 Crest Gauge Station SNPH0011 – Peak Water Levels

Wet Season	Date	Peak Water Level
2011–2012	Jan 2012	3.6 m
2012–2013	Nov 2012	1.1 m
2013–2014	Jan 2014	1.9 m

The six additional Coondewanna catchment crest gauges have just two years of wet season data (2012/13 and 2013/14), some of which is not continuous. One crest gauge (SNPH0019) is located on Homestead Creek around 5 km upstream from SNPH0011 and its main flow data (when available) mostly corresponds with flow events recorded on gauge SNPH0011, as expected. The other five crest gauges are located over the general Lake Robinson area and water level records for these gauges (when available) show no reliable indication of a flow or inundation event occurring. Possibly very shallow sheet-flow (or inundation) resulted from these main runoff events which were not detectable by the installed crest gauges. Correspondingly, groundwater hydrographs show no major recharge event over the two-year period for which data are available from these gauges (i.e. 2012 – 2014).

A comparison of the surface water data with groundwater levels confirms the importance of large volumes of surface water inundation on the Flats to cause groundwater recharge.

2.2.2.2 Hydrogeology

Results from recent drilling are consistent with the previous geological interpretation of Coondewanna Flats.

The geological sequence comprises a ubiquitous deposit of TD3 which is between 10 and 20 m thick. The TD3 unit is overlain by alluvium which is between 0 and 10 m thick. The overall detrital sequence is mainly sandy-clay with subordinate gravel and silt; the unit has a typical bulk-density in the range 1.5 – 2 g/cc.

The base of the detrital sequence is marked by calcrete at ~18 mbgl which appears continuous over a wide area. The top of the calcrete occurs at a consistent elevation although the thickness varies between 3 and 14 m. The calcrete is underlain by shale and dolomite of the Wittenoom Formation.

Groundwater levels range between 18 and 24 mbgl. Based on slug tests in many of the bores, estimates of permeability for each geological unit fall within the range that has previously been measured at Coondewanna and that is also expected for these geological units more broadly in the Central Pilbara (RPS 2014 present a comparison of estimated permeability for Coondewanna and the Central Pilbara area more generally).

The aquifer underlying Coondewanna is characterised by fresh water. Bicarbonate is the dominant anion while there are no dominant cations. Groundwater is not enriched with respect to stable isotopes.

Comparing isotope characteristics of groundwater with soil-water (cf 2.2.2.3 below) shows that soil water below a depth of ~6 m is not significantly different to groundwater. This suggests there are some rapid-pathways for infiltrating water into the soil profile to at least below the depths that maybe subject to direct evaporation from the soil surface. Thereafter, water quality evolves through dissolution and ion exchange affecting cations once the water is within the soil profile. Based on a concentration of chloride in the soil water at 10 – 18 mbgl (cf 2.2.2.3 below), the quality of infiltrating water is also affected by evapotranspiration from deeper root zones. Plant water uptake concentrates major ions but does not cause fractionation to affect stable isotope composition.

The recharge mechanism suggested is consistent with recharge processes described by Dogramaci and Dodson (2009) for the North Flank Valley.

Groundwater level monitoring data suggest significant recharge last occurred in 2011/2012 (and 2006/2007 prior to that). The largest water level rises occur in the south west of Coondewanna Flats (e.g. Bores HCF010 and HCF011) where water levels rise by ~4 m. To the north and east of the Flats the water level rise during recharge events is <1m (e.g. bores BH37, BH39 and HCF012). This suggests recharge is concentrated in the south and west of the Flats. The differential rise means the overall volume of recharge may be slightly less than previously estimated by RPS (2014).

2.2.2.3 Soil Water

Quantity

With respect to soil water quantity, moisture content in the unsaturated zone ranged between 1% and over 30% (Figure 3). Key trends were:

- The upper 2 m of profile was dry with moisture content ranging between 1% and 19%
- Below 12 m, soil moisture generally showed an increasing trend and ranged between 2% and 38%.
- Both the in-situ moisture probes and spot measurements in bores drilled during the wet and dry seasons indicate an increase in soil moisture following wet-season rainfall (Table 5). The increase is largest in the 0-5 m range which is consistent with a large soil-moisture deficit occurring in that zone which captures much of the infiltrating water.
- The increase in moisture both above and below 5 mbgl was moderate and did not approach the estimated levels of field capacity (i.e. the volume of moisture beyond which the soil will freely drain under gravity). This is consistent with no significant recharge to groundwater

being observed in 2014 (Table 5) and suggests the overall infiltrating volume was insufficient to fully replenish the soil moisture deficit.

Table 5 Change in Soil Moisture between 2014 Wet/Dry Season

Paired Holes		WL	DTW (mbtoc)	Cl	Soil Moisture % Moisture Content 0-5m	Moisture Content 5+m	Change (0-5m)	Change (5+m)
HCF0032	Dry	668.93	24.35	<300mg/L to 4m; 10mg/L to 24m	10.1	9	3.5	2.8
HCF0040	Wet	670.49	23.44	<10mg/L to 18m	13.6	11.8		
HCF0018	Dry	664.28	23.01	<10mg/L to 16m	10.6	12	2.7	-1
HCF0041	Wet	671.1	22.21	<10mg/L to 16m	13.3	11		
HCF0027	Dry	663.85	23.49	10-50mg/L to 16m; <10mg/L to 24m; max 50mg/L at 10m	11.2	7.9	-2.5	1.4
HCF0042	Wet	663.71	23.16	<10mg/L to 14m	8.7	9.3		
HCF0031	Dry	667.3	20	10-50mg/L to 8m; 50-200mg/L to 20m; max 200mg/L 12-16m				
HCF0043	Wet	672.94	20.54	<10mg/L to 20m	13.1	9.2		
HCF0023	Dry	663.72	18.85	<10mg/L 0-4m and 10-22m; max 300mg/L at 8m	4.2	12.2	0.9	-4.6
HCF0044	Wet	675.15	18.03	<10mg/L to 14m	5.1	7.6		
HCF0019	Dry	673.37	18.78	10-50mg/L to 18m; max 50mg/L at 8-12m	1	3.8	15.5	13.2
HCF0045	Wet	668.69	18.08	<10mg/L to 18m	16.5	17		
				Average Change in Soil Moisture			4%	2.36%

URS (2014) relate the increasing moisture content below 12 mbgl to capillary rise from the water table at 18 – 24 mbgl; however this is highly unlikely. The sediments have a significant sand fraction and most of the time, groundwater levels are below the top of the calcrete; neither of these mediums would be expected to support a capillary rise of over 6 m. Indeed, numerical modelling of the soil-water profile at Coondewanna (RPS 2014) showed effectively no capillary rise, even when simulating the negative pressures induced by up to 10 years of drought.

Rather than capillary rise, studies elsewhere have shown the increase in moisture is likely to result from a combination of residual drainage from previous recharge events (Nimmo et al. 2002) and also a cycle of dual phase flow where small amounts water-vapour rise from the water table, progressively condense and seep downwards again in a reflux-pattern (Walvoord et al. 2002).

Quality

Key findings with respect to soil water quality include:

- During the dry-season, the soil profile shows a concentration of chloride and isotope-enrichment in the upper 5 m; this suggests both evaporation and transpiration from the upper 5 m of profile. Broad experience suggests that the roots of *A. aptaneura* and under-storey vegetation are likely to be confined to this zone.
- In April 2014, after the wet season, Chloride concentrations in this upper zone are reduced as a result of flushing and dilution with infiltrating water; this indicates soil water replenishment in the upper horizons during the 2014 wet season.
- The soil profile shows a deeper horizon with increased chloride concentrations (10 – 18 mbgl). However, isotopes are not enriched in this zone. These data indicate this deeper zone is affected by root water uptake attributable to the deep rooted species *E. victrix*.
- In April 2014, after the wet season, chloride concentrations were variably and only partially reduced in this deeper zone. This is consistent with limited amounts of deep infiltration as suggested by changes in the soil the moisture profiles (and thus limited groundwater

recharge during the 2014 wet season), groundwater hydrographs and the surface water assessment.

Soil Water Accessibility

URS (2014) report a wide range in soil-matric potential both spatially and temporally (between wet and dry seasons). These data were collated by Astron (2014) (Figure 4). Key points include:

- Mean values of soil matric potential range between 1,000 kPa and -15,000 kPa.
- There is a zone of very low matric potential in the upper 5 m; this coincides with the upper zone of increased chloride content and is consistent with extensive evapotranspiration from this depth by vegetation with a very low permanent wilting point (e.g. *A. aptaneura*). While this zone of low potential is present in all data sets, it is less prevalent following the replenishment of soil water during the wet-season.
- There is a less pronounced secondary zone of low-matric potential around 10 mbgl.
- Soil-matric-potential is generally higher (i.e. less negative) after the wet season. This illustrates replenishment of the soil-water reservoir.
- Field capacity (the point at which a soil freely drains) is reached at -33 kPa; this value is almost never achieved in the soil profiles for November 2013 and April 2014. This suggests little drainage would have occurred through the profile and is consistent with limited groundwater recharge over the period. Deeper infiltration that did occur is likely to have been due, at least in part, to flow in preferential pathways.
- Comparing the measured soil matric-potential with the measured leaf-water potentials of both *A. aptaneura* and *E. victrix* suggests:
    - During the wet season, the plant leaf-water-potentials and the soil-matric potentials are statistically the same such that no distinct correlation can be made between specific soil zones and leaf water potential. It is likely both tree species source water over their entire rooting range (i.e 0-5 m and 0 – 15m for *A. aptaneura* and *E. victrix* respectively.)
    - During the dry-season, *A. aptaneura* trees source water from less than 5 m. The depth of source water for *E. victrix* extends to the range 9-15 m. Moreover, while *E. victrix* will have a root zone that extends over the entire range, based on their typical permanent wilting point, it is unlikely they source water from the shallow horizons during the dry season when matric pressure is lower than -5,000 kPa.
    - Neither the soil nor leaf-water potentials approach atmospheric pressure (0 kPa). This suggests the saturated zone (i.e. groundwater) may not play a significant role in soil-plant water interaction. However, it is noted that negative leaf-water-potentials may not rule out the use of groundwater where water tables are deep and significant hydraulic resistance occurs within the root water uptake path (Gou and Miller, 2013).

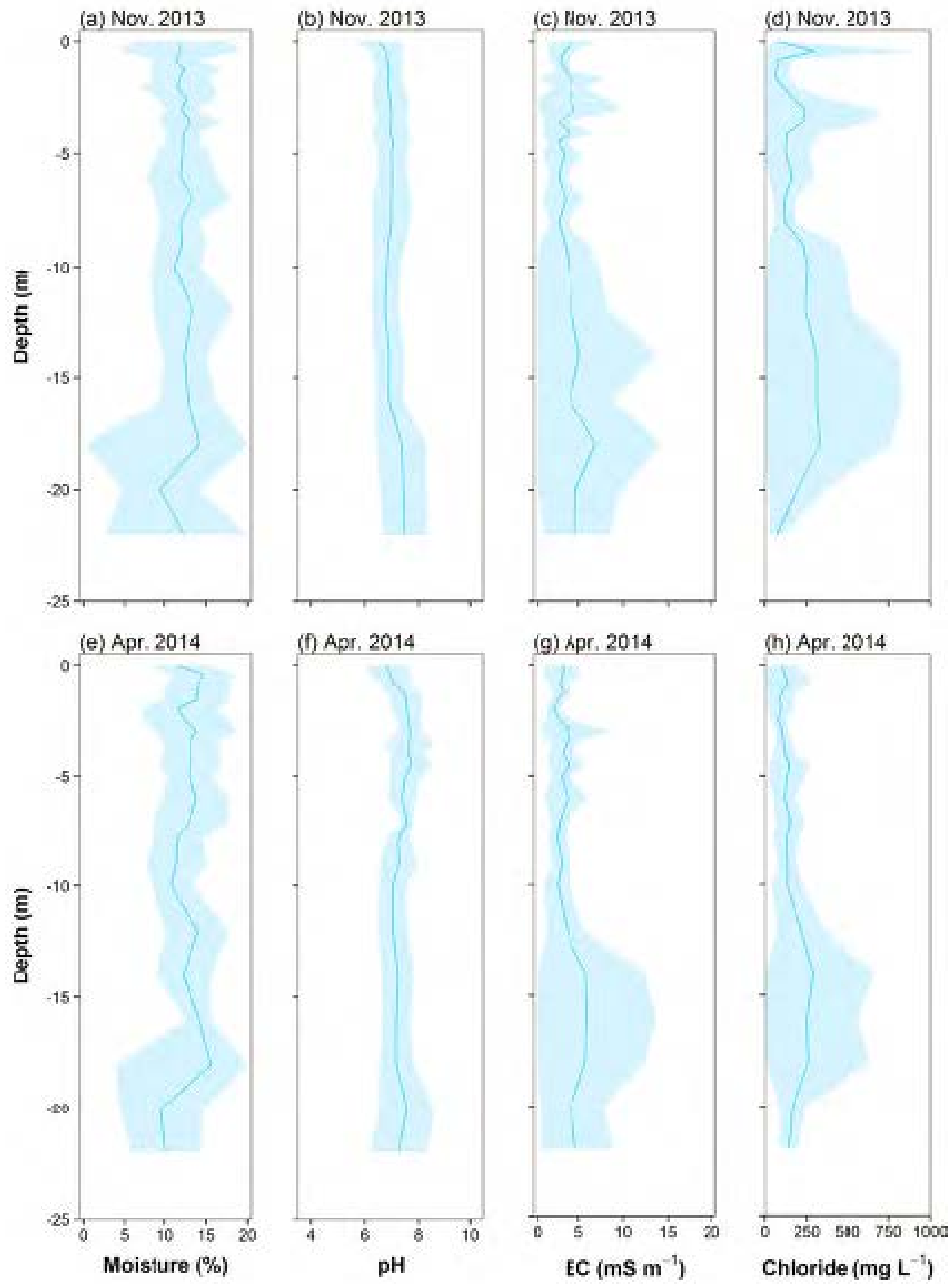


Figure 14: Mean soil volumetric water content (Moisture), pH, electrical conductivity (EC) and chloride concentration (Chloride) across the Coondewanna Flats from pads, measured in November 2013 (n = 7 sites) and April 2014 (n = 6 sites). Data are mean and standard deviation (light blue shading). Soil values are to the deepest depth sampled from at least three sites.

Figure 3 Soil water quantity and quality (reproduced from Astron (2014))

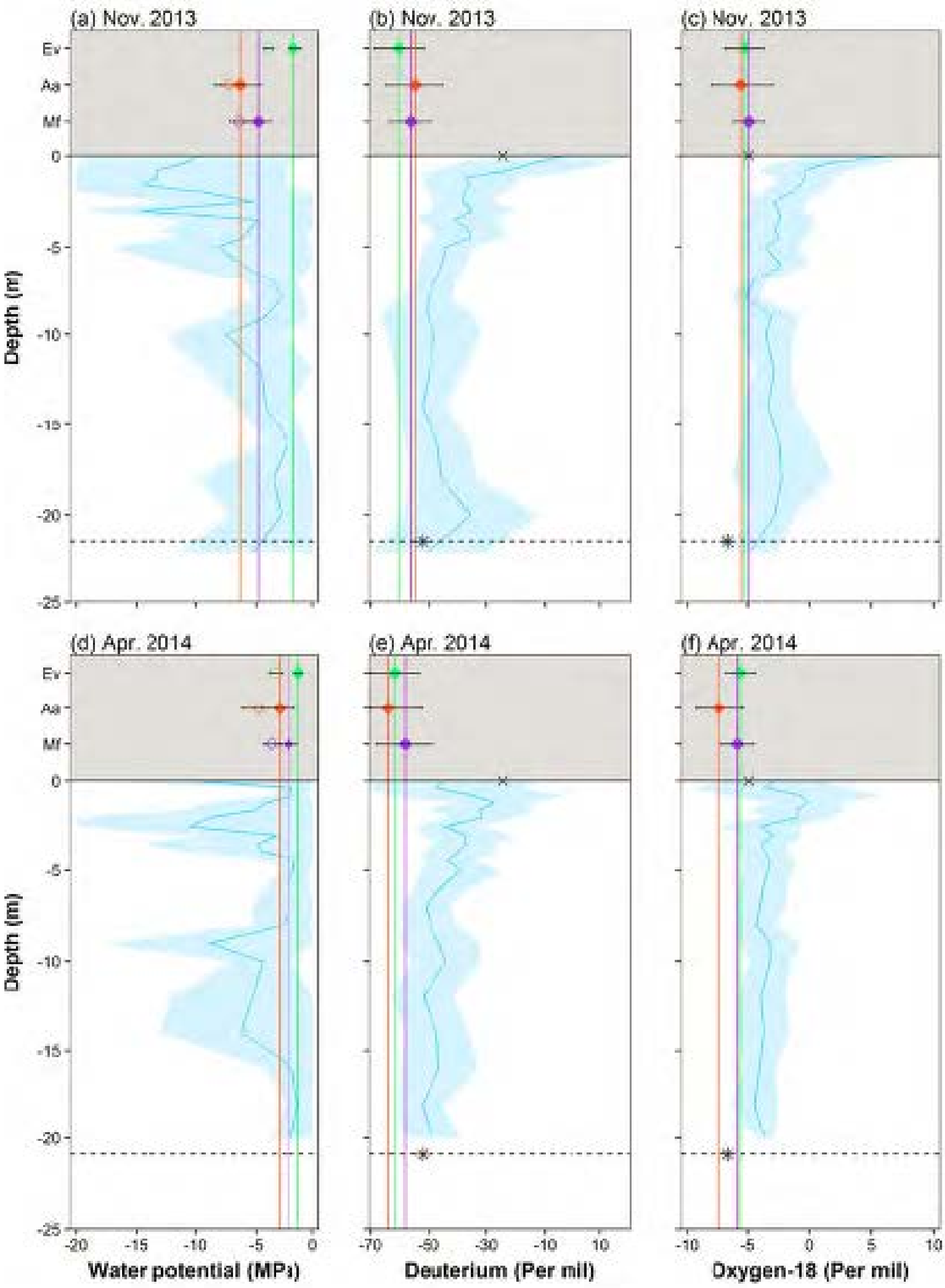


Figure 15: Mean values of water potential, Deuterium ($\delta^{2}H$ ‰ VSMOW) and Oxygen-18 ($\delta^{18}O$ ‰ VSMOW) for soil, *Eucalyptus victrix* (Ev), *Acacia aptaneura* (Aa), *Muehlenbeckia florulenta* (Mf), rain water (cross symbol) and groundwater (star symbol) across the Coondewanna Flats, measured in November 2013 (n = 7 sites) and April 2014 (n = 6 sites). Data are mean and standard deviation. Light blue shading is standard deviation for soil values. Plant (leaf) water potentials are shown for predawn (closed symbols) and midday (open symbols). Vertical lines show intersection of plant values with soil values (predawn only in water potential plots). Groundwater depth is shown by a horizontal dashed line. April 2014 isotope data for rain water and groundwater is shown for November 2013. Soil values are to the deepest depth sampled from at least three sites.

Figure 4 Soil matric potential and stable isotopes (reproduced from Astron (2014))

2.2.3 Astron Study of Ecological Water Requirements - 2014

The Astron (2014) report describes measurements of soil water and tree water use at the Coondewanna Flats in the period June 2013 to April 2014 (Table 6). This study focused on tree water use measurements for selected individuals of *E. victrix*, *A. aptaneura* and *M. florulenta* in proximity to regolith drilling locations established by URS including pads 11, 12, 13, 14, 15, 16, 17, 20 and 22 (Table 6). These 'focus' plants were in healthy condition at the time of selection and spanned a range of size classes for each species respectively. All were within at least 50 m of their associated pad, and the majority were within 20 m. Note that not all species were present at all pads.

Key findings made by Astron (2014) with respect to the determination of vegetation water use at Coondewanna Flats include:

- Cross sectional area of conducting sapwood (SA) was strongly related to stem diameter measured at breast height over bark [3] (DBH) for both *E. victrix* and *A. aptaneura*. Allometric equations relating DBH to SA were developed, which provide the basis for the calculation of sapwood area per unit land area at the site. This is a key metric for the estimation of stand water use.
- Stocking rates – the number of trees per hectare in 25 m radius circular plots established by Astron in April 2014 for each pad is shown in Table 7. The mean tree density for *E. victrix* was 27 trees/hectare and 70 trees/hectare for *A. aptaneura*. These data are somewhat indicative of the tree density across the Coondewanna Flats. Examination of aerial photography of the pad locations indicates that the plots established at pads 11 and 12 were not representative of the broader surrounds (vegetation density higher within the plots).

[3] 130 cm above ground level.

Table 6 Summary of Effective Data Capture Coondewanna Flats June 2013 – April 2014

Drilling Pad ID	Species and number of 'focus' trees	Descriptive plant traits	Projected foliar cover	Soil moisture sensor	Predawn and midday leaf water potentials	Sap flow	Stable isotopes (stem tissue)
11	*Eucalyptus victrix* (3) *Acacia aptaneura* (3) *Muehlenbeckia florulenta* (3)	✓	✓		✓	*Eucalyptus victrix* (1) *Acacia aptaneura* (1)	✓
12	*Eucalyptus victrix* (3) *Acacia aptaneura* (3) *Muehlenbeckia florulenta* (3)	✓	✓	✓	✓	*Eucalyptus victrix* (1) *Acacia aptaneura* (1)	✓
13	*Acacia aptaneura* (3)	✓	✓	✓	✓	*Acacia aptaneura* (1)	✓
14	*Eucalyptus victrix* (3) *Acacia aptaneura* (3)	✓	✓		✓	*Eucalyptus victrix* (1) *Acacia aptaneura* (1)	✓
15	*Eucalyptus victrix* (3) *Acacia aptaneura* (3) *Muehlenbeckia florulenta* (3)	✓	✓	× installed but ineffective data acquisition	✓	*Eucalyptus victrix* (1) *Acacia aptaneura* (1)	✓
16	*Eucalyptus victrix* (3) *Muehlenbeckia florulenta* (3)	✓	✓		✓	*Eucalyptus victrix* (1)	✓
17	*Eucalyptus victrix* (3) *Acacia aptaneura* (3) *Muehlenbeckia florulenta* (3)	✓	✓	× installed but ineffective data acquisition	✓	*Eucalyptus victrix* (1) *Acacia aptaneura* (1)	✓
20	*Eucalyptus victrix* (3) *Acacia aptaneura* (3) *Muehlenbeckia florulenta* (3)	✓	✓	✓	✓	*Eucalyptus victrix* (1) *Acacia aptaneura* (1)	✓
22	*Eucalyptus victrix* (3) *Muehlenbeckia florulenta* (3)	✓	✓		✓	*Eucalyptus victrix* (1)	✓

- Visual health assessment – the visual health of *E. victrix* was similar across the Coondewanna Flats and in general tree health improved from November 2013 to April 2014. This is consistent with an increase in canopy foliage density linked to increased water availability in April 2014. An annual loss/gain of leaf area of about 15% from a baseline is reported to be common for *E. victrix* in the Pilbara region (Batini 2009). In contrast there was no apparent trend in the trajectory of visual health of *A. aptaneura* between November 2013 to April 2014. This is consistent with expectations for this species, which tends to display minimal foliar response to seasonal conditions.
- Projected foliar cover - PCF for *E. victrix* increased between November 2013 and April 2014 at all measured locations with the exception of pad 12. There was no clear pattern of change in PFC for *A. aptaneura* over the same period. These findings align with the visual health assessment, indicating that the leaf area index of *E. victrix* trees increased in response to increased water availability in April 2014.
- Leaf water potentials - Predawn leaf water potential (ΨPD) of *E. victrix* did not vary spatially to a great extent across the Coondewanna Flats, with values ranging between -0.2 MPa and -2.1 MPa. The same was generally true for midday leaf water potential (ΨMD), which ranged

between -2.7 MPa and -4.6 MPa. Mean ΨMD was significantly lower in April 2014 compared to November 2013, although the difference was relatively small. These data are consistent with historical measurements reported by SKM (2012), and suggest that soil water extraction by the trees was more constrained in the dry season and associated with transpiration regulation mechanisms (such as stomatal closure and canopy level leaf area reduction).

- There was much greater variation in leaf water potential of *A. aptaneura*, both within and across pads and between seasons, with values ranging between -1.6 and -8.9 MPa for ΨPD and between -3.6 MPa and -8.6 MPa for ΨMD. Across all pads, mean ΨPD increased significantly from -6.3 MPa in November 2013 to -3.1 MPa in April 2014, while mean ΨMD increased significantly from -7.3 MPa in November 2013 to -4.8 MPa in April 2014. These results suggest that soil water extraction by the trees was confined to the drier surface layers of the soil profile. Some *A. aptaneura* trees experienced considerable moisture stress in the dry season.

  ΨPD values for *M. florulenta* were similar to *A. aptaneura* and ranged between -1.1 MPa and -6.5 MPa, while ΨMD values ranged between -2.8 MPa and -7.4 MPa. These results suggest that *M. florulenta* also mainly accessed water from the drier surface layers of the soil profile.

- The measured leaf water potentials were in general alignment with measured soil water potentials recorded in November 2013. The data suggest that the water use of *E. victrix* was substantially met by soil moisture from layers deeper than 2 m from the surface.
- Sapflow – As a general trend mean daily sap flux density (SFD) of *E. victrix* tracked closely with daily reference crop evapotranspiration (ETo) in June and July 2013, after which SFD decoupled from ETo and remained at a consistent rate throughout the remainder of the dry season from August to November 2013. However significant within tree variation was observed, with some trees maintaining a closer alignment with ETo throughout the measurement period. *E. victrix* trees exhibited a capability to match transpiration to water availability and evaporative demand, maintaining high daily rates when water was abundant but then reducing daily rates when faced with a water deficit or very high evaporative demand, or both.
- The trend of mean daily sap flux density (SFD) of *A. aptaneura* was broadly similar to that of *E. victrix*, however SFD decoupled from ETo several weeks earlier in comparison with *E. victrix* and SFD began to decrease slowly over time throughout the dry season rather than stay at a constant rate. These data suggest that *A. aptaneura* became progressively more drought stressed during the progression of the dry season.
- Transpiration flux - Astron (2014) reported total transpiration over the monitoring period (316 days) was 753 mm for *E. victrix* and 239 mm for *A. aptaneura* on a 100% cover basis. Monthly water use coefficients based on projected canopy area and sapwood area respectively were calculated, and used in the formulation of two methods for scaling up vegetation water use from individual trees to the stand level. These methods are further discussed in Section 3.5.

Detailed analysis of the Astron results suggests that the transpiration flux of *E. victrix* is likely to be an overestimate, with a value of approximately 450 mm a 100% cover basis more probable. These findings and methods are further discussed in Appendix 1.

Table 7 Summary of tree stocking rate measurements made by Astron at Coondewanna Flats in April 2014

Drilling Pad ID	Trees counted in plot (plot size 0.196 ha)				Equivalent trees per hectare			
	E. victrix alive	*E. victrix* dead	*A. aptaneura* alive	*A. aptaneura* dead	*E. victrix* alive	*E. victrix* dead	*A. aptaneura* alive	*A. aptaneura* dead
11	18	3	26	23	92	15	132	117
12	8	0	48	23	41	0	244	117
13	0	0	11	7	0	0	56	36
14	2	0	32	14	10	0	163	71
15	3	0	0	0	15	0	0	0
16	1	0	0	6	5	0	0	31
17	0	0	0	1	0	0	0	5
20	11	14	0	0	56	71	0	0
22	4	0	7	13	20	0	36	66
Mean					**27**	**10**	**70**	**49**
Coefficient of variation					**1.16**	**2.46**	**1.27**	**0.95**

2.3 Additional data collection and analysis

2.3.1 Aerial photography interpretation

Aerial photography interpretation was undertaken to provide an estimate of vegetation canopy cover across the Condewanna Flats. A set of random sample points was generated using the following procedure:

- A GIS system (Global Mapper™) was used to establish a 400 m square grid overlay encompassing the Condewanna Flats. The grid was initially aligned north-south/east-west conforming to the WGS 84 / UTM zone 50S projection.
- The grid was then shifted a randomly selected distance east (397 m) and north (37 m)[4] from an arbitrarily selected point west of Lake Robinson, and then rotated at a randomly selected angle (27^0) from the east west line in a clockwise direction.
- Plot locations were then defined by the grid point intersections of the rotated and anchored grid with the following vegetation mapping units provided by BHPB for the Coondewanna Flats):
    - Type 1 - Open Woodland to Low Open Woodland of *Eucalyptus victrix* over Low Open Shrubland of *Muehlenbeckia florulenta* and mixed species over Tussock Grassland to Open Tussock Grassland of *Eriachne benthamii* on clay soil flats. This includes the Lake Robinson area.
    - Type 2 - Low Open Woodland to Low Woodland of *Acacia aptaneura* (Maslin and J.E. Reid ms) and *Eucalyptus victrix* over Scattered Shrubs of *Muehlenbeckia florulenta* over Very Open to Open Tussock Grassland of *Eriachne benthamii*, *Eulalia aurea* and *Aristida contorta.* This includes the extensive flats south of Lake Robinson.

[4] Note random distance between 0 and 400 m.

Using this procedure, 42 potential plot locations within the Coondewanna Flats were identified (Figure 5). Circular plots were defined by buffering each point with a 40 m radius (i.e. plot area = 0.503 hectares). Twenty of these were selected for canopy cover estimation from aerial photography, including all plots in vegetation type 2 west of plot 23. A digital orthophoto (image acquisition date April 2014) was provided by BHPB for the assessment.

Canopy cover was estimated by overlaying the plot with a circular grid comprising 10 annuli of equal width (4 m) and 8 equal sectors (arc angle 45^0) (Figure 6). The percentage canopy cover was estimated for each grid cell and the overall plot canopy cover calculated from an area weighted summation of all grid cells. *E. victrix* and *A. aptaneura* trees could generally be distinguished by colour, enabling the relative contribution of each species to total plot canopy cover to be estimated. Obvious ground disturbance areas such as tracks and drill pads were excluded from plot area calculations where encountered (for example in plot 37; Figure 6).

The canopy cover estimates were further adjusted as follows:

- A shadow adjustment multiplier of 0.9 was applied, based on the interpreted extent of shadowing caused by trees on the digital orthophoto.
- 50% of canopy cover in outer annulus was subtracted from the plot level estimate, on the basis that a proportion of the canopy cover in the outer annulus was contributed by tree stems outside the plot.

The adjusted canopy cover estimates were then used to estimate stand water use using method 1 of Astron (2014)). The mean adjusted canopy cover was 28% (range 12% to 49%). The results are comparable with canopy cover statistics in woodland communities at the Mount Bruce Flats in Karijini National Park reported by Batini (2008). At this location the mean crown cover of *E. victrix* was 20% but with high variability (range 0 to 80%), and the mean crown cover of nearby *A. aptaneura* communities was 27%.

Consistent with the limitations of this estimation method described in Appendix 1, an alternative water use estimate was also calculated assuming a transpiration flux for *E. victrix* of 446 mm/year on a 100% cover basis. Using method 1 of Astron (2014) the mean stand transpiration flux was estimated to be 112 mm/year (range 37 to 304 mm/year; Figure 7), approximately equally proportioned between each tree species. Using the alternative estimation method for *E. victrix*, the mean stand transpiration flux was estimated to be 86 mm/year (range 36 to 186 mm/year; Figure 8).

2.3.2 Stand basal area measurements

A one-day site visit to Coondewanna Flats was undertaken by Dan Huxtable (Equinox Environmental) on 12 November 2014, as a ground truthing exercise in support of aerial photography interpretation and to enable the collection of stand basal area measurements. Rachel Taplin (BHPB Hydrogeologist) assisted with the measurements.

The DBH of all stems greater than 10 mm in diameter was measured in plots 26 and 37 using a diameter tape. These plots were selected to represent upper and lower levels of canopy cover, as constrained by site access and time limitations at the time of sampling. The tree status (alive or dead) and a GPS location for each measured tree was also recorded using a field computer (Trimble Juno T41).

The equivalent stem diameter for each measured sandalwood tree was calculated using the following formula:

$$\mathrm{D}equiv. = 2 \times \sqrt{\sum_{k=1}^{n} \left(\frac{\mathrm{D}k}{2}\right)^2}$$

where:

D*equiv.* (cm) = equivalent stem diameter at 150 mm AGL; and

D*k* (cm) = diameter of the *k*th stem at 150 mm AGL.

The *A. aptaneur*a tree size class distribution recorded in each plot is provided in Appendix 2.

The equivalent cross sectional area of conducting sapwood (SA) for each tree was calculated using the allometric equations developed by Astron (2014) for *E. victrix* and *A. aptaneura* respectively for all living stems using D*equiv.* as the input variable.

The resulting tree densities and stand basal area estimates for each plot are summarised in Table 8. The total basal area of trees in plot 26 was 3.4 m^2/ha, and the total basal area of trees in plot 37 was 7.4 m^2/ha. The corresponding SA estimates for plots 26 and 37 were 0.85 and 1.5 m^2/ha respectively. These are relatively low values in comparison with other Pilbara woodland vegetation types situated in environments receiving landscape inflows of water. Batini (2008) reported *E. victrix* stem densities of 0 to 200 stems/ha (mean = 90 trees/ha) in woodland communities at the Mount Bruce Flats in Karijini National Park[5]. The stand basal area of these woodland communities ranged from 4 to 18 m^2/ha (mean = 9 m^2/ha). Batini (2008) also reported the following statistics for nearby *A. aptaneura* communities: mean stem density 450 stems/ha[6] and mean stand basal area and 21 m^2/ha. Dense forests of *E. victrix* (close to 100% canopy cover) with tree densities of 180 to 200 trees/ha are known from Millstream National Park (Pfautsch et al 2011).

[5] Measured as the number of live stems > 10cm in diameter.

Table 8 Tree density and stand basal area in plots 26 and 27 measured on 12 November 2014

Plot	Living trees per hectare		Dead trees per hectare		Living *E. victrix*		Living *A. aptaneura*		TOTAL	
	E. victrix	*A. aptaneura*	*E. victrix*	*A. aptaneura*	Plot basal area (m^2/ha)	Plot SA (m^2/ha)	Plot basal area (m^2/ha)	Plot SA (m^2/ha)	Plot basal area (m^2/ha)	Plot SA (m^2/ha)
26	2	171	0	56	0.04	0.02	3.36	0.83	3.4	0.85
37	8	389	0	21	1.8	0.3	5.6	1.2	7.4	1.5

The tree stem data was used to calculate the annual tree water use in plots 26 and 37 using method 2 of Astron (2014). Details of the methodology are provided in Appendix 1. The mean stand transpiration flux was estimated to be 58 mm/year in plot 26 and 108 mm/year in plot 37. These results are comparable with plot estimates derived using the adjusted method 1 approach described in Appendix 1 and presented in Table 9 (plot 26 = 63 mm; plot 37 = 100 mm).

Table 9 Canopy cover and tree water use estimates for Coondewanna Flats

Plot	Canopy Cover	Adjusted Canopy Cover	Proportion of cover attributed to *E. victrix*	*A. aptaneura*	*E. victrix*	*A. aptaneura* water use (mm/year)	*E. victrix* water use (mm/year)	TOTAL (mm/year)
15	31%	23%	2%	23%	0%	59	4	63
21	28%	20%	20%	16%	4%	41	33	74
22	43%	31%	90%	3%	28%	8	227	235
23	41%	30%	2%	29%	1%	75	5	80
26	33%	24%	4%	23%	1%	59	8	66
27	16%	12%	50%	6%	6%	15	47	62
28	41%	30%	2%	29%	1%	75	5	80
29	40%	30%	50%	15%	15%	39	124	164
30	35%	26%	5%	24%	1%	63	10	73
31	32%	24%	2%	24%	0%	62	4	66
33	20%	14%	2%	14%	0%	35	2	37
34	36%	26%	50%	13%	13%	34	108	142
35	44%	32%	50%	16%	16%	41	130	171
36	36%	26%	33%	18%	9%	45	71	116
37	48%	35%	13%	31%	4%	80	36	116
38	40%	29%	5%	27%	1%	71	12	83
39	65%	49%	65%	17%	32%	44	260	304
40	37%	27%	20%	22%	5%	56	44	100
41	53%	39%	2%	38%	1%	99	6	105
42	48%	34%	2%	34%	1%	87	6	93
Mean	**38%**	**28%**	**23%**	**21%**	**7%**	**54**	**57**	**112**
Stdev	**11%**	**8%**	**27%**	**9%**	**9%**	**23**	**76**	**65**

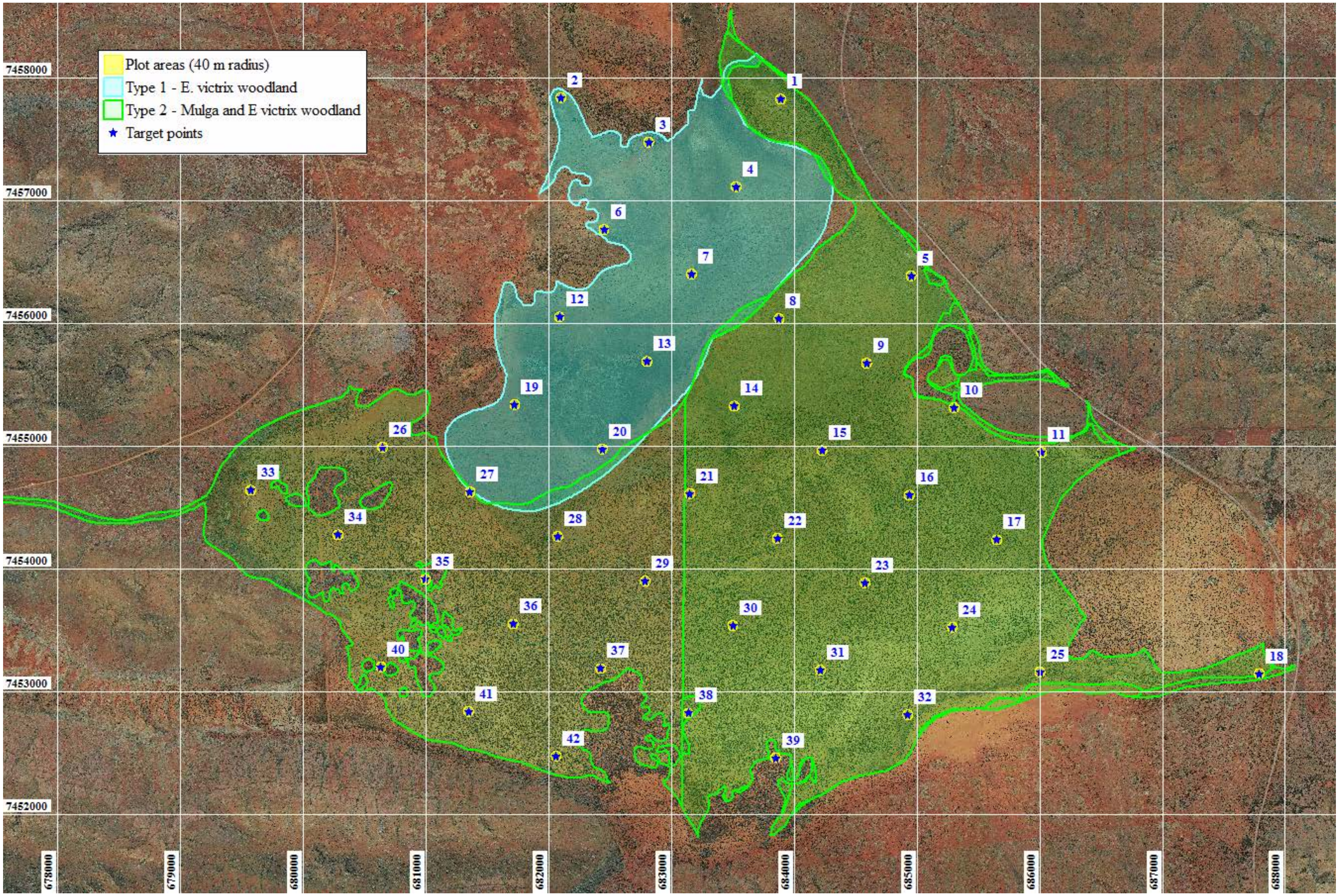


Figure 5 Random plot locations for canopy cover estimation

Figure 6 Canopy cover estimation grid for plot 37

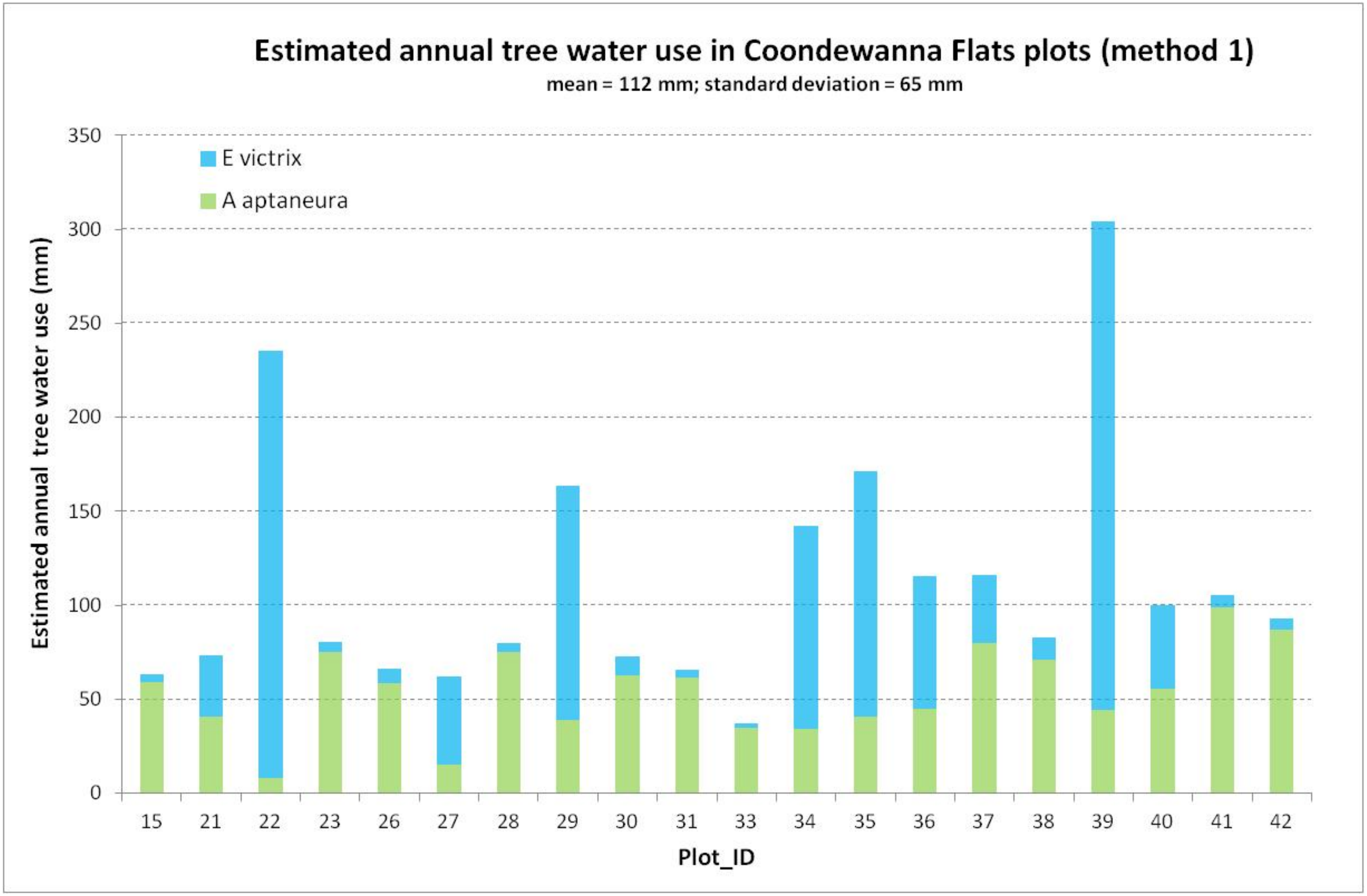


Figure 7 **Estimated annual tree water use in plots at Coondewanna Flats using method 1**

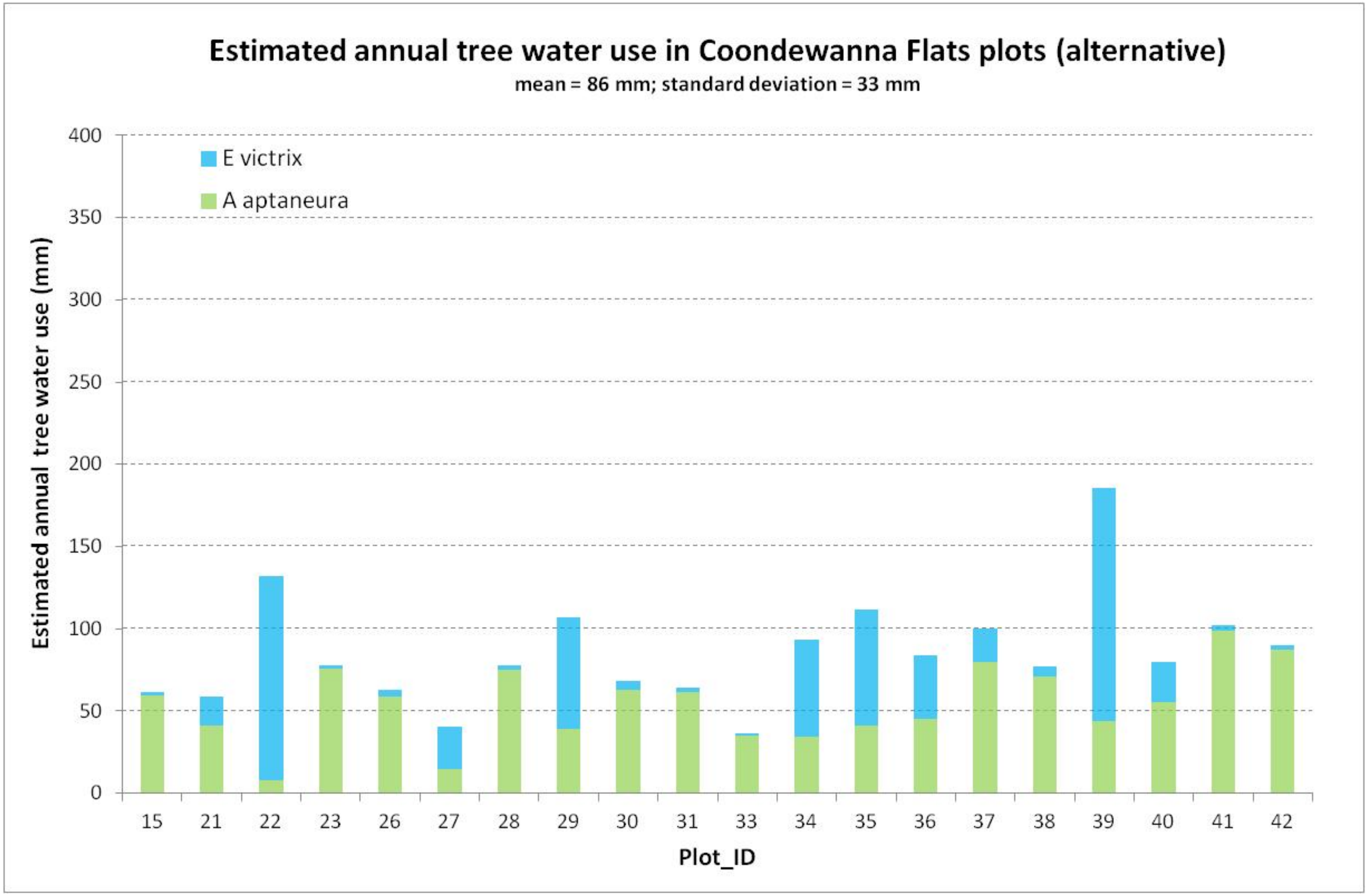


Figure 8 **Estimated annual tree water use in plots at Coondewanna Flats using the alternative method 1**

2.3.3 Coondewanna Flats Topographic Survey - High resolution LIDAR

BHPB acquired a high resolution LIDAR dataset for Coondewanna Flats in October 2014. The survey is shown in Figure 9. The following comments are made:

- Examination of the LIDAR dataset using GIS has shown that the Lake Robinson area is a local basin only (elevation >687 mAHD) with extensive areas in the southern and southwestern portion of the Flats having slightly lower elevation (686.5 to 687 mAHD).
- Surface water will be focused in this low elevation area. Figure 10 is a photograph from the 2011/2012 wet season which clearly shows focused inundation of the south and west of the Flats (and not "Lake Robinson'). The soil profile in this area will receive greater volumes of infiltration than elsewhere on the Flats.
- This low elevation zone includes the largest stands of *E. victrix*.
- The low elevation zone coincides with the area where groundwater levels respond the most to recharge events.

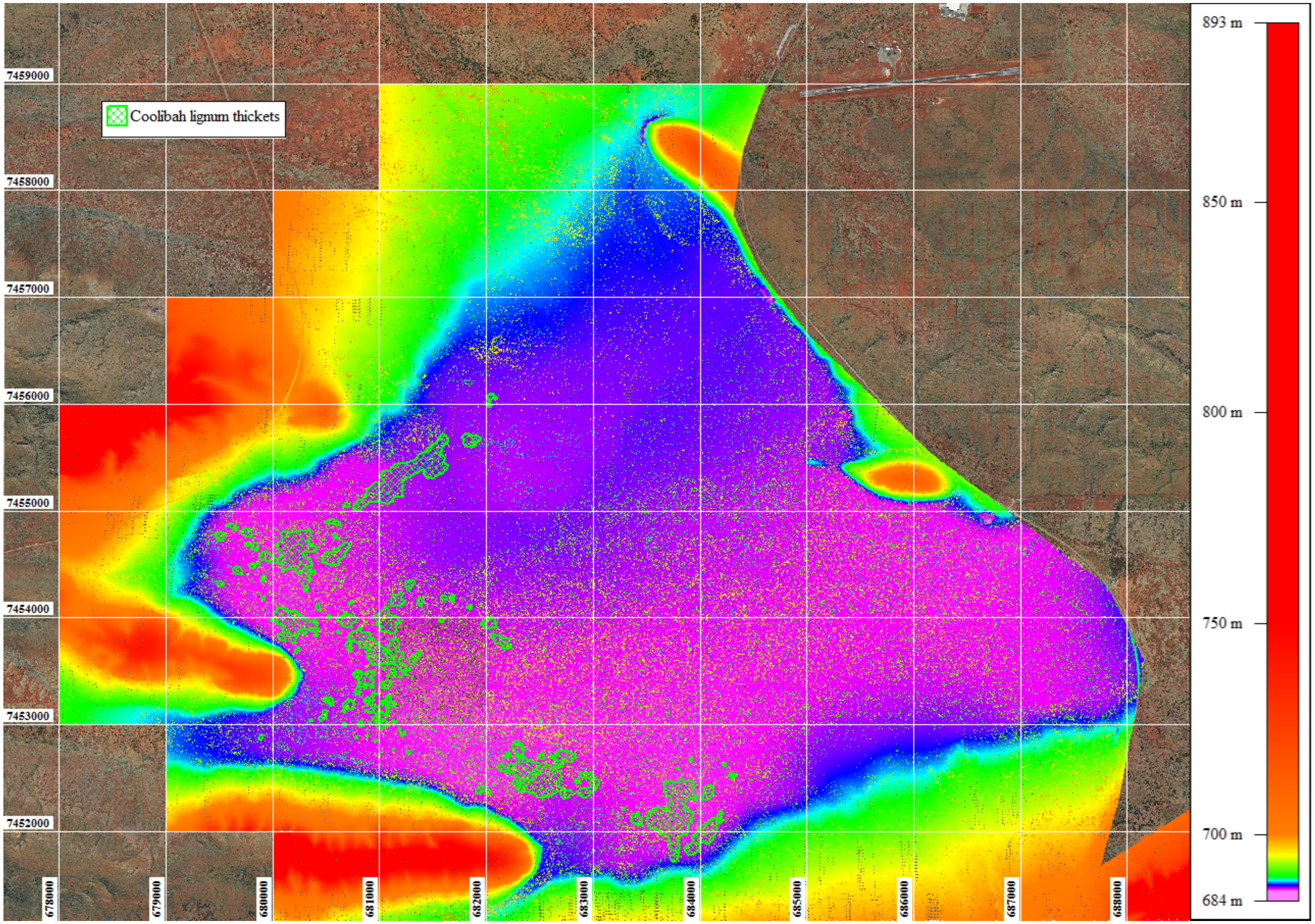


Figure 9 **LIDAR survey of Coondewanna Flats (Green hatched areas show the main stands of *E. victrix*.)**

Figure 10 Flooding at Coondewanna (March 2012) after 2011/2012 Wet Season from south east of the Flats looking approximately north west.

3 Ecohydrological Conceptualisation

3.1 Climate Weather and Hydrology

3.1.1 Rainfall

Analysis of the hydrology of Coondewanna Flats was undertaken as part of the current study; the report is provided in Appendix 3. A summary follows.

An assessment of the long-term annual rainfall totals for the Coondewanna catchment has been undertaken using the SILO annual rainfall data for the period 1900 to 2014, and using the July to June water year. These annual data are shown plotted in Appendix 3 - Figure 3, together with a plot of the five-year moving average annual rainfall and the average annual rainfall (328mm) for the period starting in July 1900. An examination of the annual data plot shows that since 1994, a higher proportion of years have recorded rainfall totals significantly in excess of the long-term average. This long-term apparent change in annual rainfall can be seen in the plot of the five-year moving average annual rainfall where average annual rainfall totals appear to have increased since the 1960s.

Over the past 50 years (July 1964 to June 2014), the average annual SILO rainfall at the Coondewanna catchment centroid is 372mm compared to the longer-term average of 328mm (1900 to 2014). Corresponding average annual SILO rainfall at the Flat Rocks catchment centroid over the past 50 years is 401mm, hence on average around 7% wetter.

The recent higher rainfall period would likely result in higher catchment runoff, soil moisture replenishment and aquifer recharge volumes, as compared to the long-term average.

It is likely the vegetation community has adapted to this wetter environment over the last 50 years and tree-density and size may not reflect the longer-term average.

3.1.2 Runoff

DoW streamflow gauging stations have not been located in the Coondewanna catchment with the nearest gauges being Flat Rocks (Marillana Creek – gauge S708001) and Tarina (Weeli Wolli Creek – gauge S708014). The DoW Flat Rocks streamflow gauging station is located to measure runoff from the upper portion of Marillana Creek (next main catchment north from Coondewanna) and has a catchment area of 1,370km^2. This station has been open since September 1967 and has approximately 47 years of mostly unbroken streamflow record, as shown in Appendix 3 - Figure 4. The upper Marillana catchment contains large flat storage areas, in particular the Munjina Claypan, which attenuates catchment runoff. The hydrological characteristics of Coondewanna catchment, with its numerous large relatively flat slow draining areas, are considered to be more akin to those within the upper Marillana catchment (recorded at Flat Rocks gauge) than those within the Weeli Wolli Creek system (recorded at Tarina gauge). As such, the Coondewanna catchment (860 km^2) runoff volumes are assumed to be a direct area proportion to those recorded for the upper Marillana Creek at Flat Rocks (1,370km^2).

The average annual runoff at Coondewanna is estimated to ~6,000 ML/d. However, this average figure is distorted by high magnitude/low frequency events; the median runoff of 2,000ML is a more representative figure.

Key findings in relation to the runoff regime to Coondewanna Flats are summarized below and in Table 10:

- The threshold for recharge to occur has been determined by correlating the magnitude of runoff events with observed groundwater hydrograph responses. Any runoff in excess of the threshold will contribute to groundwater recharge; any runoff below the threshold will be consumed by the soil-moisture-deficit. It is estimate the runoff threshold to result in groundwater recharge is 3,400ML/month.
- Runoff would discharge to Lake Robinson in most years, though in three out of four years runoff would typically be insufficient to initiate aquifer recharge (i.e it does not exceed the threshold), but would replenish soil moisture in the unsaturated profile. In one of these years (once in four years), runoff would be very low at less than 20% of the median annual runoff.
- Larger events resulting in aquifer recharge are likely to occur on average once every four years, triggered by a monthly rainfall in excess of approximately 180mm. These are the events that would result in groundwater recharge.
- The estimated average volume by which runoff will exceed the threshold provides an estimate of average rates of groundwater recharge. This assumes all of the exceedance volume contributes to recharge which is believed to be reasonable given the evidence outlined previously of rapid-infiltration into the deeper soil horizons and the lack of evaporation-effects evident in the chemistry of deeper soil water. On the basis of surface water inputs, it is estimated that annual average groundwater recharge is 3,500ML (9,500kL/d). This number is consistent with recharge estimates developed from a chloride balance and discussed in Chapter 4. Floods of this volume have an ARI of 4 years.
- It is estimated that soil-water will be replenished every year at a median rate of 2,000ML although ranging between 400ML (1,100kL/d) 1 in every four years to over 2,500ML (7,000kL/d) 1 in every 4 years.

Table 10 Coondewanna Runoff/Recharge Characteristics

Parameter	Annual Volume (ML)	Remarks
Median Runoff	2,060	No groundwater recharge - soil water replenishment only
Average Runoff	5,990	Sufficient to cause recharge (>2,500ML)
Groundwater recharge	3,500	
Soil and Evaporation Loss	2,500	

3.2 Hydrostratigraphy

Coondewanna Flats is bounded by hills of Marra Mamba and Brockman. Preferential weathering of the Wittenoom Formation between these outcrops resulted in a low-lying area which has subsequently been infilled with Tertiary deposits of alluvium and colluvium. The geological sequence comprises an upper Tertiary sequence (TD3) of variable sand, silt and gravel overlying a middle Tertiary sequence (TD2) of variable calcrete and silty gravel overlying shale and dolomite of the Paraburdoo Member. The calcrete lies close to the water table and the extent to which it is saturated varies with recharge state (up to a 5 m change in groundwater levels has been observed following inundation of the Flats). The hydrostratigraphy is summarized in Table 11 below.

Based on drill logs, the calcrete is described as karstic or vuggy and weathered in places, and hard in others. There is likely to be a considerable range in permeability for the calcrete.

Table 11 Hydrostratigraphy at Coondewanna Flats.

Age	Group	Formation	Approx Thickness (m)	Description	Hydro geology	Hydrogeological Description (for Coondewanna)
Quaternary	-	Alluvium	0-10	Heterogeneous mix of cobbles - clay	Soil Water	Receives infiltration during inundation on Flats; supports riparian vegetation.
Tertiary	Tertiary Detritals	TD3/TD2	10-20	Heterogeneous mix of sandy-clay with sub ordinate gravle and silt	Soil Water	Receives infiltration during inundation on Flats; supports riparian vegetation.
		Calcrete	3-18m	Calcrete	Aquifer	Aquifer
Archaean - Proterozoic	Hamersley	Wittenoom	400	Dolomite, BIF and Shale	Aquifer - Aquitard	Permeable where dolomite is karstic (Paraburdoo Member)
		Weeli Wolli	450	BIF, jaspilite, dolerite and shale	Aquitard	Generally an aquitard with low transmissivity and storage; may form localised aquifer in fracture zones.
		Brockman Iron	600	BIF, dolerite and shale	Aquitard	Generally an aquitard with low transmissivity and storage; may form localised aquifer in fracture zones or where mineralised.

3.3 Hydraulic Parameters

3.3.1 Permeability

Permeability tests have been undertaken in 16 bores and have provided information on the entire aquifer sequence. The results are provided below in Table 12.

Table 12 Estimates of Permeability for Coondewanna Flats

Geology	Permeability (m/d)				Specific Yield (%)
	Min	Max	Average	Median	Range
TD3	0.01	14.5	6.3	5.8	
TD2	0.1	2.8	1.1	1.0	8 - 14
Calcrete	1.8	27.9	12.2	12.1	
Dolomite	0.1	63.0	20.6	20.7	

The detritals have a median permeability of 1 – 5.8 m/d. However, the results span a wide range and illustrate the heterogeneous nature of the detritals.

The estimated permeability for the dolomite also spans a wide range. The higher estimates result from tests that have been undertaken in karstic - Paraburdoo Member while the lowest estimates result from tests that have been undertaken in Bee Gorge or West Angela Members.

3.3.2 Soil and Ground Water Storage

Groundwater Storage

With respect to water storage in the detritals, no long term pumping tests have been carried out to allow derivation of specific yield. During the current study, the specific yield for the detritals has been estimated from USDA equations (Saxton-Rawls Equations, 2004) which allow estimates of the saturated and unsaturated hydraulic properties of the detritals (Table 13).

Table 13 Calculated Moisture Content Characteristics for the Alluvium

		Moisture Content %			Water Availability %		
Code	Description	Saturated (0kPa)	Field Cap (-33kPa)	Tree Limit (-4000kPa)	Specific Yield %	Plant Available Soil Water	Bulk Density (g/cc)
1	Detritals	40	25	9	14	14	1.7
2	Gravel with Clay	43	34	15	9	12	1.9
3	Clay with Gravel	48	39	21	8	15	1.6
4	Clay with Calcrete	48	39	21	8	15	1.6
5	Clay	46	42	26	4	16	1.4
6	Silcrete/Calcrete	35	29	0	6	8	2.4
7	Silt with Clay	44	36	15	9	20	1.5
8	Clay with Sand	45	37	21	8	16	1.5
9	Clayey Sand	42	35	11	8	24	1.5
Mean - code 1 Detritals (upper 1m		40	25	9	14	14	1.7
Mean - codes 2-9 (TD3/TD2)		44	37	17	8	15	1.7
Mean - code 9 - URS typical soil		42	35	11	8	24	1.5

The data suggest specific yield could vary between 6% and 14% related to particle size distribution of the sample; the lower end of the range being associated with finer grained sediments which form the bulk of the detritals. Summarily:

- The average specific yield for Detritals with a larger gravel fraction (code 1) is 14%. This is believed to be representative of alluvium variably present in the upper horizons.
- The average specific yield for alluvium comprising sand, silt and clay is 8%. This is believed to be representative of the detritals of TD3(the bulk of the sequence).
- The clay unit (code 5) has a specific yield of only 4%. This is believed to be representative of the goethitic clay associated with TD2.
- Coarse particle composition, high specific yield and relatively low moisture content at field capacity (25%) mean the alluvium will drain more readily. Table 13 shows the plant-available-water is 14%.
- Fine grained sediments, higher moisture requirements for specific capacity to be reached (~35%) mean the detritals will require more moisture replenishment before deep infiltration starts and will drain more slowly. Table 13 shows the plant-available-water is estimated to be

15%-20%. Moreover, greater matric potential will mean this water will be released over a longer period of time.

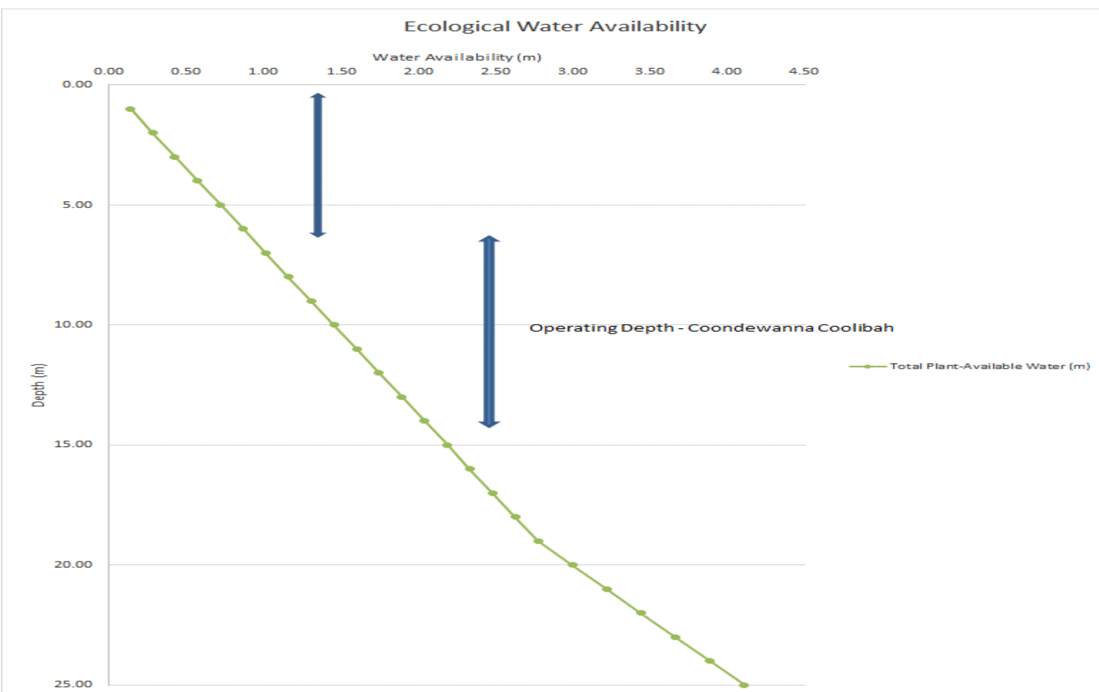
Soil Water Storage

Soil moisture profiles have been collected from the ecohydrological bores drilled on the Flats. Based on data from the Phase 1 work only, and assuming all samples were at 'field capacity' (i.e. the moisture content when the matric pressure is -33 kPa and the point at which the soil will start to freely drain), it was estimated that on average there was 0.16 m of plant-available water per m depth of soil profile (SKM 2012).

Data from Phases 1 to 3 have been reviewed during the current study, including sample descriptions provided in all drill logs, all moisture content profiles, particle size analysis and bulk density calculation. Based on this, key parameters have been developed for the several soil types that reflect the heterogeneous nature of the alluvium; these parameters have been used in Saxton-Rawls equations (Saxton-Rawls 2004) to define soil-moisture properties (c.f. Table 13) and Figure 11.

The estimated plant-available water (i.e. the moisture that can be released from the soil between 'field-capacity' - -33 kPa and 'permanent wilting point' - -4,500 kPa) ranges between 0.12 m/m and 0.24 m/m with an average of 0.15 m/m. A 'permanent wilting point' of -4,500 kPa is adopted to represent the lower range of observed Coolibah suction potential. Note that Mulga has been reported to maintain leaf water potentials less than -8,000 kPa under dry soil conditions (Page et al. 2011) and there the above definition of PAW is an underestimate for this species. However, the marginal increase in plant-available water at suction pressures less than -4,500 kPa is relatively small and therefore this value is considered to be an appropriate threshold for the purposes of this study.

Figure 11 Plant available water in the tertiary sediments of the Coondewanna Flats



The results are consistent with the previous SKM assessment and would indicate sufficient soil-water to support the vegetation community over a prolonged period of drought. Based on a simple volumetric balance, provisional estimates would be for ~9 years (with current stocking rates and tree-water use as outlined below). It was previously estimated that the unsaturated zone contained sufficient water to support the vegetation for 7 years (RPS 2014); this estimate was based on slightly higher estimates of evapotranspiration.

3.4 Water Levels and Recharge

3.4.1 Groundwater Levels

Although Coondewanna Flats is an internally draining surface water feature, groundwater levels show it is in connection with the regional groundwater system (eg RPS 2014). Groundwater inflow occurs from valleys to the north and west. Groundwater gradients along these valleys are very low and inflow will be small regardless of the permeability of any aquifers underlying the valleys.

Groundwater outflow is eastward into the South and North Flank valleys. Groundwater levels across the flats are in the range 665mAHD with groundwater levels in the upper South Flank valleys falling to 635mAHD in relatively close proximity to Coondewanna Flats; the steep gradient between Coondewanna Flats and the valley being related to the NE/SW trending dyke.

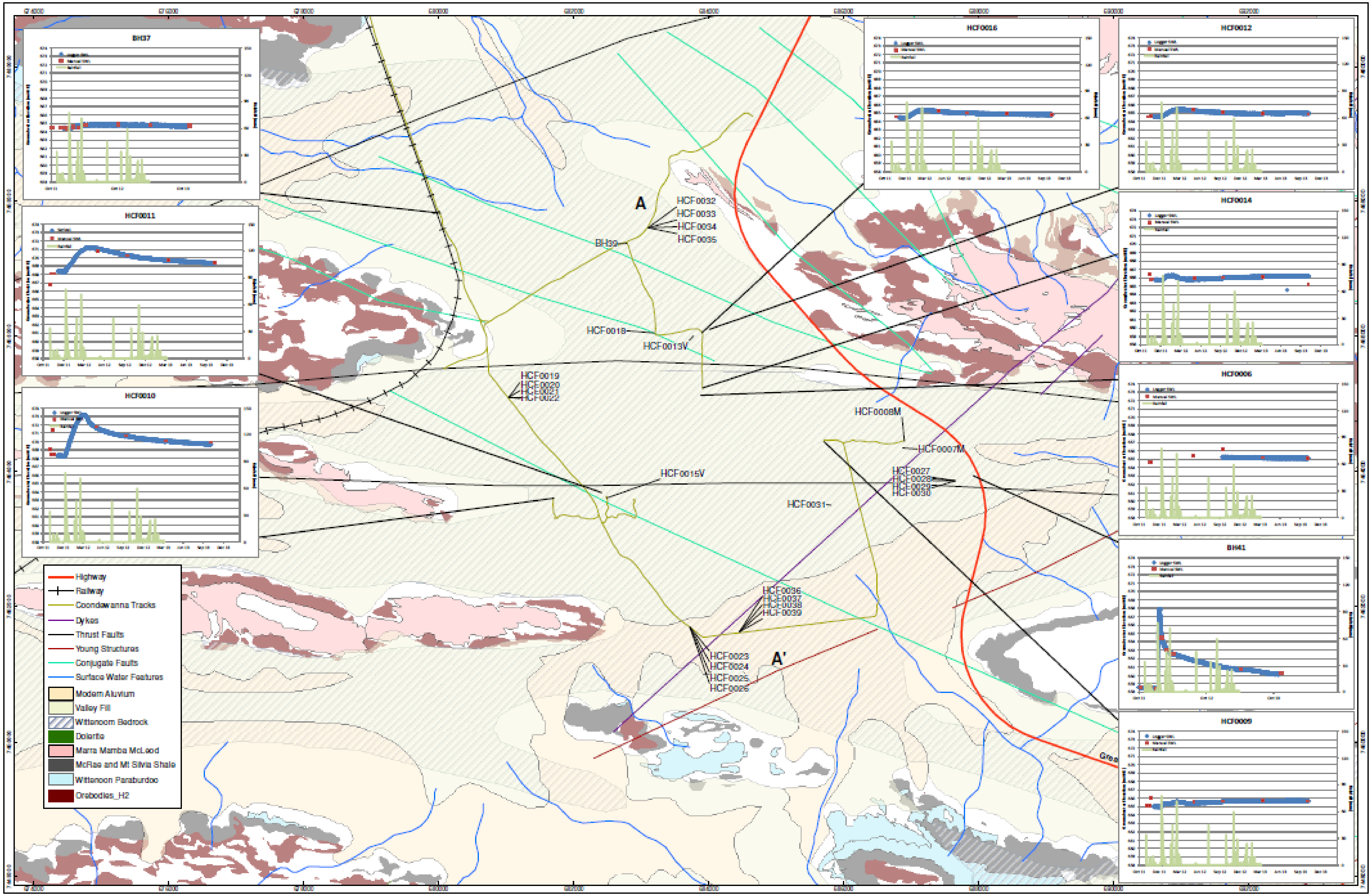
Depth to ground water is approximately 20mbgl. South of the dyke, depth to groundwater increases to approximately 50mbgl.

Available groundwater level monitoring data for Coondewanna Flats are shown in Figure 12. Two significant rises in the water table (recharge events) can be seen since 2006. The following are interpreted from these hydrographs:

- Water table rises vary between approximately 1m and 5m bringing groundwater levels to within approximately 15m to 21m of the surface.
- The rise in groundwater levels is relatively rapid suggesting a relatively rapid recharge process. This is consistent with isotope analysis (URS 2014) that suggests groundwater is not subject to much evaporation prior to recharge.
- Given the rapid rise in response to rainfall and the low groundwater gradients which will drive little inflow into Coondewanna Flats, recharge mainly occurs locally from infiltrating surface water rather than groundwater throughflow from upstream in the catchment.
- The rise in groundwater levels in the south and west of the Flats (e.g. bores HCF0010M, and HCF0015M for the 2011/2012 wet season) is more rapid and of larger magnitude than bores in the central and northern parts (eg. Bores HCF012M and HCF016M). This is believed to relate to the location of the bores where flow and/or inundation is concentrated (cf Section 2.3.3). HSF0002M/BH41 in the south east of the Flats shows a similar response; this response is anomalous but there may be water locally retained by the Great Northern Highway road embankment.

- During the 2011/2012 event, groundwater levels were highest in bores HCF0010M and HCF0011M suggesting a recharge mound related to infiltration of water from flooding showing in Figure 10.
- The decline in groundwater levels in HCF0010M (while groundwater levels in other, distant bores continue to rise) suggests the short term dissipation of the recharge mound under HCF010M with the dissipating groundwater continuing to recharge other areas across the Flats. The hydrographs in Figure 12 illustrate the mound dissipating with groundwater flow to the north (towards bore HCF0002M (BH37)) and east (towards bores HCF008M/007M). Thus, while groundwater gradients are low across the Flats in general, there is likely to be considerable variation and local flow at a local scale and following rainfall-recharge events.

Figure 12 Groundwater Hydrographs Coondewanna Flats (reproduced from URS 2014)



3.4.2 Soil Water

In the unsaturated zone, the moisture content at field capacity is estimated to be on average 37% (cf 3.3 above). This is approximately the maximum measured moisture content in the available data (38%) from the period November 2013 to April 2014; most measurements are considerably less than this. The moisture content would only exceed field capacity while 'free-drainage' was occurring (i.e groundwater recharge). Hydrograph data suggest there has not been a recharge event since 2011/2012 and so it would be expected that most of the soil profile would be at less than field capacity. No soil moisture readings are available from the 2011/2012 recharge event. However, it is assumed that much of the soil profile must have reached and exceeded field capacity (for deep infiltration and recharge to occur).

Notwithstanding the lack of groundwater recharge, the available soil moisture data confirm soil moisture replenishment during the 2013/2014 wet season. Moisture content increased by between 2% and 4%. When compared with dry-season moisture content of around 10%, the increase equates to between a 20% and 40% overall increase in soil moisture.

Most of the available soil moisture monitoring occurred in the low-lying area in the south and west of Coondewanna Flats, which is prone to inundation and likely receives preferential runoff (Figure 2). As a comparison, the increase in soil moisture at Pad 20A (northern part of the low lying area) was 15% compared with 3% at Pad 15A (central-flats away from the low lying area).

The three functional soil moisture loggers were located at Pads 20A, 12A and 13A (Figure 2) – all located within the low-lying zone. All showed an increase in soil moisture of over 10% (i.e around a 50% increase based on a dry-season starting moisture content of between 10% and 20% measured at those pads). While there is only the spot measurement from Pad 15A (with a 3% increase) to compare against, it does appear the topographically lowest zone along the western and southern side of the Flats receives preferential soil water replenishment resulting from the focusing of surface water runoff and hence infiltration. (The re-commissioning of continuous loggers at Pads 15A and 17A (both outside the low lying zone) will help confirm the importance of focused surface water runoff to soil-water replenishment.

The low lying area of greatest soil-moisture increases corresponds with largest stands of *E.victrix* (Figure 9) and suggests and association between tree-distribution and soil-water availability.

3.5 Vegetation and Water Use

E. victrix and *A. aptaneura* open woodlands are the dominant species in the vegetation communities of the Coondewanna Flats. Small patches of dense *E. victrix* over lignum occur in the southern and south western portion of the Flats. The Lake Robinson area includes scattered *E. victrix* over an understory of lignum and perennial grasses.

Based on the up-scaling of long term sapflow measurements undertaken by Astron (2014), annual tree water use of the mixed *E. victrix* and *A. aptaneura* woodland communities across the Flats is estimated to be approximately 100 mm.

Under dry conditions (no flooding) the balance of annual rainfall is considered to be lost to interception, evaporation from the soil surface and water use by understory plants. Soil evaporation is likely to be a significant component of ET (in the order of 200 mm/year) consistent with water balance studies in similar environments with open vegetation (e.g. Gwenzi et al. 2013; Wang et al. 2014).

The root systems of *A. aptaneura* and understorey species such as lignum are predominantly confined to the top 5 m of the profile. These species experience increasing levels of drought stress during prolonged dry conditions.

E. victrix trees have considerably deeper root systems that extend to approximately 15 m. By accessing deep soil water reserves, this species can maintain higher rates of water use and avoid severe drought stress. However, leaf water potential measurements indicate that *E. victrix* does experience some degree of seasonal drought stress as surface soil layers dry out. This is consistent with a dimorphic root system and plasticity of water use, as observed at other Pilbara locations where this species occurs (Pfautsch et al. 2014; Grigg 2009).

Under prolonged dry conditions soil water will be gradually depleted by the vegetation communities. During flood events soil water in the deep unsaturated profile is replenished, potentially resulting in losses to the groundwater system (i.e. recharge) where flooding is extensive and prolonged.

4 Water Balance

4.1 Main Elements of Groundwater Balance

The water balance for Coondewanna Flats has been estimated, taking into account surface water flow, groundwater recharge and natural groundwater discharge. The groundwater balance has been developed using a chloride mass balance (outlined below) and also an assessment of recharge and discharge and a soil-moisture balance as outlined above (cf Chapter 3). The water balance is summarized in Table .

The following assumptions underpin the water balance estimate:

- The catchment is in long term steady state balance on the basis that:
    - There are no areas of continuously rising or falling water levels over the long term;
    - There was no long term salinisation of the catchment
- If tree-water use is a significant component of groundwater discharge, then it should be accommodated in the groundwater balance for the catchment.
- Notwithstanding seasonal and longer-term wet and dry periods, total groundwater recharge must, on average, equal total groundwater discharge and the main inflows and outflows for the groundwater system are:
    - Groundwater throughflow (inflow) across the western boundary of Flats from the Tandanya and Mudlark areas; on the basis of the very low hydraulic gradients that have been interpreted from available data (eg RPS 2014), groundwater inflow will be small.
    - Recharge to the alluvial aquifer from infiltration during flood events.
    - Groundwater throughflow (outflow) across the eastern boundary of the Flats into the North and South Flank Valleys.
    - Potentially, groundwater discharge as evapotranspiration from riparian vegetation on the Flats.

Groundwater outflow from the Flats represents groundwater inflow to the Weeli Wolli Creek catchment and there are other controls on the water balance of the Weeli Wolli Catchment:

- Surface water outflow and spring flow are gauged at the Weeli Wolli gauging station.
- Drilling and monitoring at Weeli Wolli Spring allows an estimate of groundwater outflow to be made based on both measured hydraulic parameters and a chloride balance.
- Estimates of evapotranspiration-discharge in the area of Weeli Wolli Spring were made during the Hope Downs EIA (Hope Downs 2000).
- A groundwater balance was developed for the whole of the Weeli Wolli catchment, taking into account the above factors, as part of work completed for BHPB’s SEA (RPS 2014).

The estimated groundwater outflow from the Flats must also be consistent with the overall water balance for the Weeli Wolli catchment.

4.2 Chloride Balance

A chloride balance has been used to assess groundwater outflow from Coondewanna Flats and also to confirm that the overall water balance for Coondewanna Flats is consistent with that for Weeli Wolli Spring. Details of the chloride balance calculations are presented in Appendix 4; summary comments follow.

Chloride is generally considered a conservative element in the natural environment (Hem 1985). In the Coondewanna Flats catchment, groundwater is generally fresh and there are no obvious areas of active salinisation. As such, under steady-state conditions, it is assumed that the chloride delivered to the catchment (as a solute in rainfall) will equal chloride leaving the catchment (as a solute in water outflow).

A chloride balance has been calculated for the Coondewanna Flats catchment and for the entire Weeli Wolli Spring catchment. The former has been used to estimate groundwater recharge on Coondewanna Flats. As the groundwater outflow from Coondewanna ultimately discharges through Weeli Wolli Spring for which reasonable estimates of total discharge are available (e.g. RPS 2014), the latter has been used to ensure the Coondewanna water balance is consistent with the broader regional water balance. The key components of the chloride balance are summarised below:

- Chloride inflow to the system as solutes in rainfall over the appropriate catchment area at an annual average rate of 328 mm/yr. The concentration of chloride in rainwater is estimated at 0.5 mg/L based on published measurements from Rio Tinto's Yandi Mine site (Hedley et al 2009, Dogramaci and Dodson, 2009).
- Coondewanna Flats are internally draining and there is no removal of Chloride as solutes in surface water flood flow.
- Chloride outflow as solutes in groundwater throughflow into the North and South Flank Valleys. Groundwater chemistry data are available from pumping bores on the eastern-margin of Coondewanna Flats, and the western ends of the North and South Flanks Valleys. Chloride concentrations in the groundwater are approximately 43 mg/L (based on URS 2013 and average values extracted from the ioWater database).

Assuming that chloride is in balance, then throughflow can be estimated as that required to remove the volume of chloride to maintain balance (given the other components of chloride input and output outlined above). The partitioning of groundwater flow from Coondewanna Flats into the North and South Flank Valleys is currently uncertain. However, as the Chloride concentration reported in groundwater is the same for both valleys, this method can be used to give an estimate of total discharge from Coondewanna Flats without the need to determine the distribution of flow between the two valleys.

The development of a chloride balance specifically for Coondewanna Flats has allowed refinement of the previous estimate of groundwater outflow made during the SEA (RPS 2014). The results of the chloride balance suggest groundwater outflow from Coondewanna Flats is ~9000 kL/d (compared with an original estimate of 11,000 kL/d). This reduced recharge estimate is also consistent with differential rates of recharge and water level rise associated with the preferential focusing of runoff onto the south and west parts of the Flats. By contrast, during the original SEA assessment, large water levels associated with recharge were assumed to apply over a wider geographical area. During surface water analysis undertaken during the current study (cf Appendix 3, RPS 2015), it was estimated that maximum seepage to groundwater was between 9,000 kL/d and 9,500 kL/d; this estimate is also consistent with reduced recharge estimate derived from the Chloride balance.

4.3 Water Balance

Table presents a summary of the groundwater balance for the Flats. A range of water balance scenarios are presented to reflect uncertainty in the key parameters. The "overall compilation" represents the best combination of parameters, based on available data, where none fall outside of their measured or plausible operating range; this is the adopted water balance.

It is estimated that groundwater outflow from the Flats is ~10,000 kL/d. It is also apparent that the water balance is most consistent with other constraints under a scenario of zero discharge from groundwater due to evapotranspiration .

If there is no evapotranspiration from groundwater, then the water use requirements of the vegetation must be met by soil-water. Table 14 illustrates cumulative water availability through the soil-profile and also provides an estimate of the number of years that soil-water would theoretically support the ecosystem (based on the total vegetation-stand-level water consumption estimated during this study – refer to Section 3.3).

Table 14 Soil Water Balance and Vegetation Use

Depth (m)	Cumulative Ground water (m)	Cumulative Soil Water (m)	Total Plant-Available Water (m)	Yrs PAW meets transpiration reqs		Remarks
				Victirx (@ 0.112m/yr)	Mulga (@ 0.108m/yr)	
1		0.14	0.14		1	Mulga Root Depth
2		0.28	0.28		3	
3		0.43	0.43		4	
4		0.57	0.57		5	
5		0.72	0.72		7	
6		0.87	0.87		8	
7		1.01	1.01	1	9	Coolibah Root Depth
8		1.16	1.16	3		
9		1.31	1.31	4		
10		1.45	1.45	5		
11		1.60	1.60	7		
12		1.75	1.75	8		
13		1.89	1.89	9		
14		2.04	2.04	10		
15		2.19	2.19	12		
16		2.33	2.33	13		
17		2.48	2.48	14		
18		2.63	2.63	16		
19		2.77	2.77	17		
20	0.08	2.92	3.00	18		
21	0.15	3.07	3.22	20		
22	0.23	3.21	3.44	21		
23	0.30	3.36	3.66	22		
24	0.38	3.51	3.89	24		
25	0.46	3.65	4.11	25		

Salient points from this are:

- Based on average conditions of soil-water replenishment 3 in 4 years and a major recharge event 1 in 4 years, there is abundant water in the soil zone to support the Coondewanna Flats vegetation communities.
- In the case of an extreme drought, based on known tree-physiology and the detailed studies and data collected from Coondewanna since 2012, the main zones of soil water uptake (reflecting tree root distributions) are 0-5 mbgl and 0 – 15 mbgl for Mulga and Coolibah respectively. For each species, there would be sufficient soil water in the root zone to support stand level water use for ~9 – 12 years. The degree of convergence in the estimated time-period for the shallow and deeper rooted vegetation community tends to suggest that the vegetation is in a state of long term ecohydrological equilibrium.

4.4 Analysis of Water Balance

The key parameters in the water balance are subject to varying degrees of uncertainty. Indeed, many parameters likely have an 'operating range' through which they fluctuate, depending on environmental conditions. In particular, the volume of groundwater recharge to the alluvial aquifer and evapotranspiration from the aquifer are uncertain and a relatively wide range has previously been discussed.

Table illustrates the results of varying these key parameters through a plausible range:

- The "low-volume" and “medium-volume” balances represent the main groundwater fluxes, if recharge is at the lower end of the estimated range. In this case, groundwater outflow approximates the outflow derived from the chloride balance. These scenarios do not require any evapotranspiration from the groundwater table, which is consistent with measured LWP and the transpiration flux estimates based on sapflow measurements.
- The "high-volume" balances illustrates the main groundwater fluxes, if recharge is at the highest end of the estimated range. In this case, groundwater outflow exceeds the estimate derived from the chloride balance. Moreover, evapotranspiration actually exceeds total plant water-use based on the sapflow data collected since 2012; the LWP data does not indicate any groundwater use (let alone continuous excessive groundwater use); These factors militate against this water balance scenario.
- The "compilation" balances represent different combinations of averages of the main parameters. In both cases, all the main fluxes are close to the estimated ranges and these balances are believed to represent typical conditions. In particular:
    - The resulting estimate of groundwater recharge represents 1.3% of total rainfall on the Coondewanna catchment and 0.66% of total rainfall on the overall Weeli Wolli catchment.
    - The estimate of recharge to the whole of the Weeli Wolli (0.66%) catchment is consistent with other recent estimates for the central-Pilbara that have been in the range 0.4% to 0.8% (Dogramaci and Dodson, 2009; RPS, 2014 inter alia);
    - The estimate of recharge to the Coondewanna catchment (1.3%) is consistent with an area of enhanced recharge associated with surface water focusing; by comparison (and notwithstanding some hydrogeological differences), it has been estimated that recharge to the Fortescue River catchment is ~1.7% of rainfall associated with enhanced recharge from Ophthalmia Dam (RPS 2014).
    - The ‘compilation balances’ do not require evapotranspiration by riparian vegetation from the groundwater table which is consistent with the relatively large depth to water, the large soil-moisture availability, the seasonal patterns in the LWP data, and transpiration flux estimates based on sapflow measurements.

AQ2

Table 15 Water Balance

Coondewanna Catchment Balance (kL/d)

	Water Balance Scenarios								
Groundwater Recharge	**High Vol Recharge Constrained**	**High Vol Discharge Constrained**	**Medium Vol Recharge Constrained**	**Medium Vol Discharge Constrained**	**Medium Vol ET Constrained**	**Low Vol recharge const**	**Low Vol discharge const**	**Overall Compilation**	
GW Inflow from Mudlark / Tandanya	1070	250	387	250	250	250	250	250	250
Recharge on Coondewanna Flats	9930	11000	8980	9785	9785	8980	8730	9735	9785
In direct recharge - remainder of catchment / soil moisture	0	0	0	0	0	0	0	0	0
Total Groundwater Recharge	**11000**	**11250**	**9367**	**10035**	**10035**	**9230**	**8980**	**9985**	**10035**
Groundwater Discharge									
Evapotranspiration - Coondewanna Vegetation	2270	1070	58	863	0	0	0	0	58
Total Groundwater Outflow	8730	10180	9308	9172	10035	9230	8980	9985	9977
Total Groundwater Discharge	**11000**	**11250**	**9367**	**10035**	**10035**	**9230**	**8980**	**9985**	**10035**

Weeli Wolli Catchment Balance (kL/d)

Groundwater Recharge									
GW Inflow from Coondewanna	8730	10180	9308	9172	10035	9230	8980	9985	9977
Recharge in the Weeli Wolli area	2500	2500	2500	2500	2500	2500	2500	2500	2500
Diffuse Recharge	1189	1189	1189	1189	1189	1189	1189	1189	1189
Total Groundwater Recharge	**12419**	**13869**	**12998**	**12861**	**13724**	**12919**	**12669**	**13675**	**13666**
ET - Weeli Wolli & Ben's Oasis	1560	3010	2138	2002	2865	2060	1810	2815	2807
Spring Baseflow	7,200	7,200	7,200	7,200	7,200	7,200	7,200	7200	7200
Groundwater throughflow	3660	3660	3660	3660	3660	3660	3660	3660	3660
Total Groundwater Discharge	**12419**	**13869**	**12998**	**12861**	**13724**	**12919**	**12669**	**13675**	**13666**

Analysis									
Recharge as % Rainfall									
In Coondewanna Catchment	1.42%	1.46%	1.21%	1.30%	1.30%	1.19%	1.16%	1.29%	1.30%
In Overall Catchment	0.71%	0.72%	0.63%	0.66%	0.66%	0.62%	0.61%	0.66%	0.66%
GW ET Rate (m/yr)									
In Coondewanna Catchment	0.121	0.057	0.003	0.046	0.000	0.000	0.000	0.000	0.003
In Weeli Wolli Catchment	0.076	0.146	0.104	0.097	0.139	0.100	0.088	0.137	0.137

5 Conceptual Ecohydrological Model

5.1 Structure of the Ecohydrological model

The Conceptual Ecohydrological model for Coondewanna Flats can be described as series of discrete elements that can be distinctly defined within the Coondewanna Flats system. These elements are critically linked to each other and the broader environment, through a series of key processes. Elements comprise:

- Vegetation Communities dominated by Coolibah and Mulga (comprising the Coondewanna Flats PECs)
- Soil Water Reservoir - water resources contained in the unsaturated zone
- Groundwater Reservoir - groundwater resources contained in the saturated alluvial aquifer.

Linking processes comprise:

- Hydrological processes that result in flood flows that inundate the Flats (preferentially in the topographically low area to the south and west).
- Infiltration of water into the alluvium during flood events; infiltrating water replenishes both soil water and (less frequently) groundwater resources.
- Tree water uptake by roots in the unsaturated zone.
- Evapotranspiration from the trees, under-storey vegetation and bare soil to the atmosphere.
- Outflow of groundwater from Coondewanna Flats to the east into the North and South Flank Valleys.

5.2 Conceptual Model

The ecohydrological model of Coondewanna Flats is summarised in Figures 13 and 14. Figure 3 specifically highlights the key elements, linking processes, operating parameters and their functional range.

Summarily, the conceptual ecohydrological model of Coondewanna Flats comprises:

- Surface water runoff from the surrounding catchments is attenuated in the internally draining low-relief landscape of the flats, principally accumulating in south and west of the Flats (south west of ‘Lake Robinson’) but extending into Lake Robinson and even more widely across the flats in very large and infrequent flood events.
- Upstream catchment-area is the major control on catchment runoff and inundation on the Flats (and consequently on soil and groundwater recharge). Each 5% reduction in upstream catchment area will reduce groundwater recharge by 6-7% although the effect on soil water is likely to be less marked.
- Underlying the Flats is an unconfined aquifer comprising Tertiary Detritals (sand and clay). An extensive calcrete occurs at a depth of ~18 mbgl. This is underlain by low to high permeability basement of the Wittenoom Formation.

- The Detritals are very heterogeneous. Median saturated permeability is between 1 and 5 m/d and specific yield is around 9%.
- Groundwater level gradients across the flats have a general west-east direction. Gradients are low and little groundwater flows into the area from the west. Consequently recharge derived from ponding of surface water runoff is the major source of soil-water and groundwater replenishment in Coondewanna Flats.
- A southwest-northeast trending dyke acts as a partial (low flow) groundwater flow barrier at the eastern end of Coondewanna Flats; as indicated by a steep groundwater gradient.
- Groundwater is some 20 mbgl whilst downstream (south and east of the dyke) groundwater levels are around 50 mbgl. Most of the Tertiary Detrital sequence is unsaturated.
- Evaporation exceeds rainfall by an order of magnitude and maintains a large soil-moisture deficit which must be overcome before groundwater recharge occurs.
- Surface water flows typically reach Coondewanna Flats three out of every four years and replenish soil moisture in the unsaturated profile, even when groundwater recharge does not occur.
- The unsaturated zone is characterised by moisture content ranging between 1% and 38% (Field capacity is estimated to be around 37% and so moisture content would only exceed this level immediately after a recharge event, when water was actively infiltrating through the profile).
- Matric pressures in the unsaturated zone range between -200 kPa and -10,000 kPa; varying with both depth and season.
- The distribution of matric pressure and soil-water-chemistry suggests plant-water abstraction from 0-5 mbgl by vegetation that has very low permanent wilting point (eg A.aptaneura) and up to 15 mbgl by vegetation with water potentials around -4,500 kPa (E.victrix)
- Recharge occurs predominantly as infiltration from surface water in the area south and west of Lake Robinson. Recharge events have a return period of approximately four years and although recharge is highly variable over time, annual average recharge rates are approximately 10,000 kL/d over the broader Coondewanna Flats area. The latter represents approximately 75% of total recharge to the down-gradient Weeli Wolli (groundwater) Catchment.
- The main discharges from the hydrological system are groundwater outflow to the east and evapotranspiration from the soil-water reservoir:
  - Groundwater discharge occurs as outflow to the South and North Flank Valleys, thus connecting the Coondewanna and Weeli Wolli Catchments from a groundwater perspective. The distribution of groundwater flow between the North and South Flank valleys is uncertain. Notwithstanding. Coondewanna Flats is the major source of groundwater throughflow that ultimately reaches Weeli Wolli Spring.
  - Average ET discharge from soil-water is estimated to be ~0.11 m/yr over the riparian area.
- Total plant-available-water from the unsaturated zone is 0.15 m/m depth of profile. It is estimated that the soil-water reservoir could sustain the vegetation community for a drought period of ~9 years.

- Vegetation of the Lake Robinson area includes Western Coolibah (*Eucalyptus victrix*) woodlands over open shrub land of Lignum (*Muehlenbeckia florulenta*) and tussock grassland growing on orange brown loamy clay.
- Vegetation of the slightly more elevated flats surrounding the Lake Robinson area includes open forest of Mulga (*Acacia aptaneura* and closely related taxa) with occasional *E. victrix* over sparse Lignum and tussock grasses growing on red brown clay loam.
- The Western Coolibah trees on Coondewanna Flats rely on stored soil moisture to meet water requirements. They obtain water from both the upper-soil horizon immediately following recharge and more generally from the zone between 6 and 15 mbgl. Pre-dawn leaf water potentials of -4,600 kPa have been measured during the dry season.
- Mulga and under-storey vegetation obtain water from the upper 5 m of soil profile. They are able to abstract water at very low matric potentials; -8,500kPa has been measured to data at Coondewanna and -10,000 kPa has been measured elsewhere.
- The vegetation communities at Coondewanna do not appear to rely on groundwater:
    - There is abundant water in the soil profile to support the community for extended periods of time;
    - The depth to groundwater is beyond the range commonly associated with groundwater dependence;
    - Soil matric-potential and soil water chemistry indicate plant water abstraction from 0-5mbgl and 6-15 mbgl
    - Measured pre-dawn leaf water potentials for all species are all negative. Moreover, changes in leaf water potential have reflected changes in soil-moisture and matric pressure.
- The surface water dynamics of Coondewanna Flats are likely to influence Western Coolibah bud-set, flowering, seed production and seedling recruitment.

Key elements of Ecohydrological model

Input Processes			
Key Feature / Process	**Magnitude**	**Frequency**	**Constraint**
Surface water inflow and infiltration			
Runoff	1.72% (average) / 0.59% (median) annual rainfall	3 in 4 years	
Infiltration to soil moisture	>70mm inundation depth, increase soil moisture content	3 in 4 years	
Deep infiltration and Recharge	>200mm inundation depth, increase soil moisture content and water level rise (1-4m)	1 in 4 years	
Groundwater Inflow			
Groundwater inflow from upper-catchment areas	small - v. low hydraulic gradient		small - based on updated water balance and comparable hydraulic gradients

Static Elements		
Key Feature / Process	**Range**	**Constraints**
Riparian Vegetation Community		
Mulga/Lignum shallow unsaturated zone	<5mbgl	<5 mbgl based on isotopes and LWP (-8.9mPa); consistent with >5mbgl soil zone
Coolibah - deeper root zone	5 - 15 mbgl	5-15 mbgl based on isotopes, Cl and continuously -ve LWP (-0.3 - -2.1mPa); consistent with deep soil zone
Deep roots into groundwater zone	no GW dependence; based on isotopes and -ve LWP	
Soil Water Reservoir		
Moisture content sufficient to support vegetation	0.15m/m ~9 yrs. of water demand	
Matric pressure at levels accessible by vegetation	0-5mbgl >-10MPa; 5-15mbgl >-4.5MPa	
Replenished seasonally	3/4 yrs.	
Replenished seasonally	Increased moisture content	
Replenished seasonally	Increased matric pressure (more unsaturated water available)	
Groundwater Reservoir		
Water Levels deep	WL ~20mbgl	
Recharge ~1/4 yrs.	WL rise 1 -4 m	
Recharge threshold	180mm rainfall; soil profile >38% moisture content	

Outputs			
Key Feature / Process	**Magnitude**	**Frequency**	**Constraint**
Surface Water Outflow			
Internal draining basin - no outflow	no outflow	n/a	
Evapotranspiration			
Evapotranspiration from soil water	112mm/yr	continuous	
Evapotranspiration from groundwater	0	n/a	
Groundwater Outflow			
Outflow from Coondewanna (preferential recharge zone)	~10,000kL/d to east	continuous	
Flow Constraints	flow barrier caused by dyke across SE	n/a	
Flow to NFV/SFV	uncertain (60%/40% previously adopted)	continuous	
Capillary Rise into Soil Zone	0	n/a	

Figure 13 Ecohydrological Conceptual Model – key elements, linkages and parameter ranges

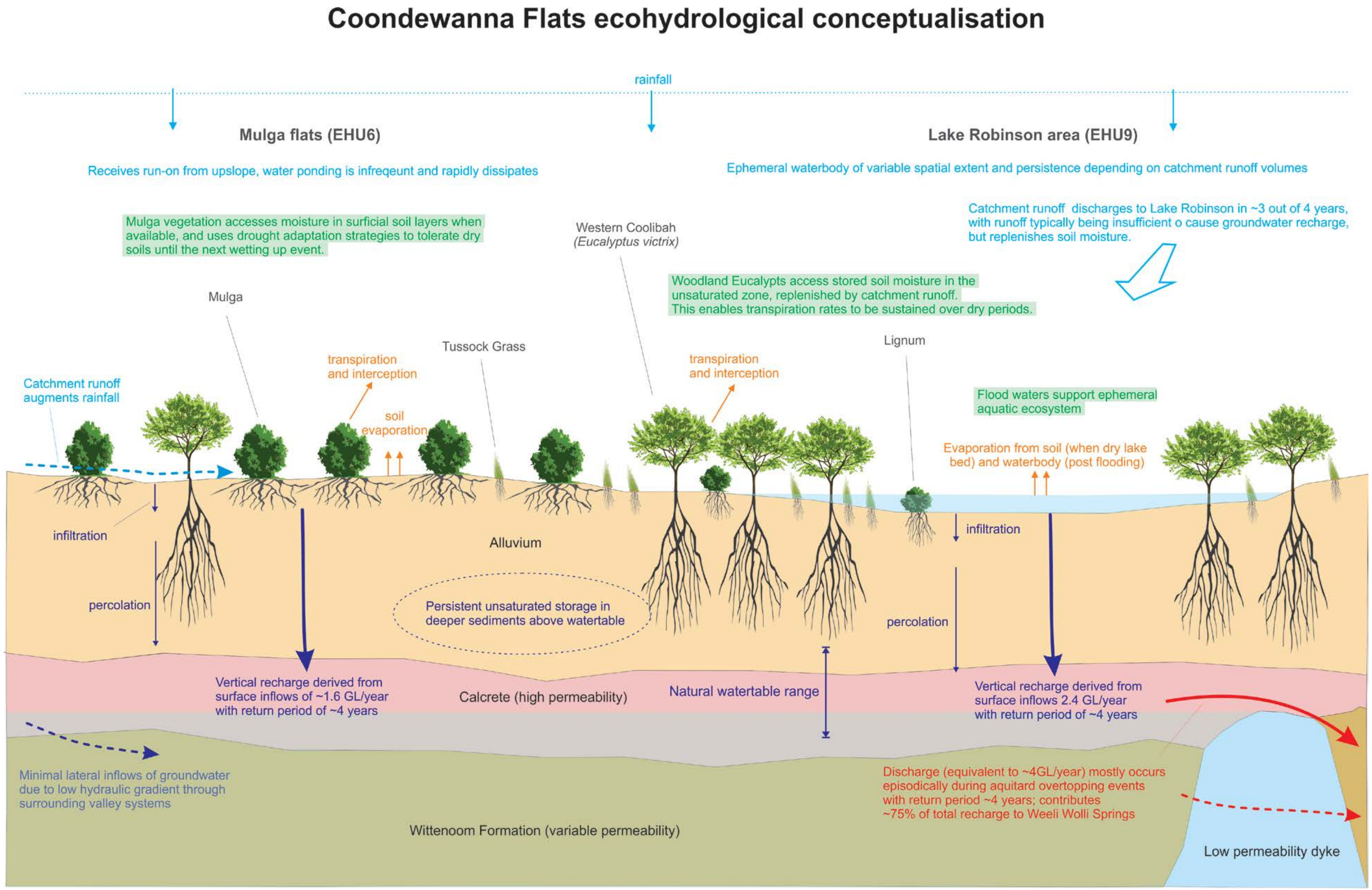


Figure 14 **Ecohydrological Conceptual Model – diagrammatic representation (adapted from RPS (2014))**

5.3 Regional Integration

The ecohydrological conceptualization will be more robust if it is consistent with and has analogues in other areas of the Pilbara region. For example:

- Where analogous environments have been studied, then the overall hydroecological function should be similar
- Key elements of the model such as rates of recharge and tree water use should be consistent with findings from other comparable locations in the Pilbara;
- Water fluxes between the Coondewanna ecohydrological system and it's adjacent environment should be should be consistent.

Table 16 provides a regional context for some key aspects of the ecohydrological system. It can be seen that all aspects fall within ranges that have been measured regionally and/or have regional analogues.

Table 16 Regional Comparison of Key Aspects of Coondewanna Ecohydrological Model

Aspect	Comparator	Remarks
Overall ecological conceptualisation: No groundwater dependency with Coolibah over deep water table and subject to periodic inundation.	Mt Bruce Flats	Extensive work by Rio Tinto concluded the Coolibah were dependent on soil water with root zone around 12 mbgl
Groundwater recharge - 1.3%; enhanced recharge zone; 0.66% for whole catchment	Estimates of recharge at Ethel Gorge (RPS) and Yandi (AQ2); estimates of recharge North Flank Valley and Karijini National Park (Rio Tinto)	Recharge in range 0.4% - 0.7% for natural systems; recharge at Ethel Gorge 1.7% related to enhanced recharge from Opthalmia Dam
Tree Water Use ~20 to 300 L/tree/day for *E. victrix* and ~10 to 40 L/tree/day for *A. aptaneura*. For each species tree water use is positively correlated with tree size (DBH).	Measured *E. victrix* water use rates at Millstream (Pfautsch et al. 2011) and Weeli Wolli Creek (Pfautsch et al. 2011).	Upscaling of individual tree water use estimates based on tree density at Coondewanna Flats corresponds with an annual transpiration flux of ~100 mm/yr
Groundwater outflow from Coondewanna Flats (~10,000kL/d)	Surface water infiltration on Coondewanna Flats assesed from hydrological studies; inflow to support Weeli Wolli groundwater balance	Infiltration from surface water estimated to be 9,500kL/d; inflow consistent with Weeli Wolli water balance

With respect to the groundwater outflow from the Coondewanna area into the Weeli Wolli catchment, the overall flux of ~10,000kL/d is consistent with the water balance and current ecohydrological model for Weeli Wolli Spring. However, other than discharge at Weeli Wolli Spring, there are no other controls on groundwater flux between Coondewanna and Weeli Wolli Spring. Thus, the actual distribution of flow between the North and South Flank Valleys is uncertain at present. Recent work at MAC (AQ2 2014, RPS 2014) adopted 60% / 40% split between the North and South Flank Valley's respectively on the basis of differential hydraulic gradients. However this was only a 'working assumption' and no data are available from the South Flank Valley to confirm this.

From the current study, it is now apparent that the topographic low and focusing of surface to the south of Coondewanna Flats results in more recharge in the southern and western parts of the Flats. Geographically, the zone part of the Flats is closer and contiguous with the South Flank Valley and it may well be that more groundwater flow occurs into this area. Further work is recommended in this regard to better quantify not only the overall quantum of flux between Coondewanna Flats and Welli Wolli Spring, but also the actual flow paths and distribution.

5.4 Change Risk Assessment

It can be seen from the ecohydrolgical model and water balance that Coondewanna Flats is a surface water driven-system. Surface water runoff supplies essentially all of the water to the Flats; groundwater inflow is minimal. Surface water infiltration:

- Replenishes the soil moisture store which is the source of water for vegetation on the Flats; and
- Less frequently, it recharges groundwater and is an important source of recharge and groundwater flow in the broader Weeli Wolli catchment.

Thus, the greatest risk to the ecohydrological system relates to changes in the surface water regime and in particular magnitude and frequency of runoff. The largest risk in this regard relates to loss of catchment in the Tandanya and Mudlark mining areas due to creek diversion or catchment interception by waste dumps and so forth, when future mines are developed.

Reductions in runoff associated with catchment loss will progressively reduce volumes of surface water reporting to the Flats. This means there will be fewer occasions when the runoff volume will be sufficient to replenishment the soil moisture deficit and cause groundwater recharge; groundwater recharge will reduce and groundwater levels will fall. It has been estimated during the current study that each 5% reduction in catchment area will lead to a 6-7% reduction in annual average recharge volume. Groundwater level.

However, it does not appear that the vegetation communities at Coondewanna Flats rely on groundwater and so there should be limited local impact. Coondewanna is an important recharge source for the broader Weeli Wolli catchment. In the long-term, reduced recharge may have an impact at Weeli Wolli Spring. This can be determined during the current study. Additional work with the Weeli Wolli groundwater model is recommended to consider reduced-recharge scenarios and their impact on the Spring.

While runoff volumes will be reduced, runoff frequency will not be reduced to the same extent. It is estimated that catchment loss would have to exceed 30% for runoff frequency to be materially altered. Even when the volume of surface water reaching Coondewanna Flats is reduced, each event will still result in soil-water replenishment (even if the event is of insufficient magnitude to cause groundwater recharge). The soil water reservoir is more robust to changes in catchment area of less than 30% (20% is conservatively recommended in this study as a monitoring threshold).

6 Uncertainty Assessment and Recommendations

6.1 Recommendations

Recommendations are summarized in Table . With respect to addressing areas of uncertainty that will either add confidence to or allow refinement of the ecohydrological model, the following recommendations are made:

- Hydrological monitoring:
    - In the rainfall network around the Flats
    - Calibration and remote monitoring of the crest-gauges installed on the Flats
- Continued monitoring of groundwater levels. Monitoring data should be reviewed on an annual basis to the understanding of the 'operating range' of water levels and also to compare trends in vegetation physiology with groundwater levels and confirm there is no link over the long term.
- Continued monitoring of soil moisture content using the installed probes to confirm the magnitude and frequency of soil moisture replenishment (refer also the recommendation below regarding soil-matric potential).
- Continued monitoring of tree-health indicators to compare with trends in climate and changes to the soil and groundwater regime. This monitoring should move from an intensive study/campaign basis to more regular operational monitoring:
    - Regular test sites should be adopted (the investigation previously used that coincide with locations of detailed hydrological monitoring are recommended).
    - Tree water use can assessed by the proxies of Sapflow and / or Leaf Water Potential
    - Tree health can be assessed by canopy cover assessment or remotely using NVDI
    - Tree water use can also be inferred from regular stem basal area measurements (at the end of the dry season and wet season respectively). Fast growth rates correspond with higher water use, in connection with an increase in sapwood area. In combination with sapflow measurements, stem basal area measurements provide the basis for calculating stand level water use.
- In addition to on-going monitoring, the following specific studies are also recommended:
- If core is still available from any of the investigation holes drilled on Coondewanna Flats, this should be subject laboratory analysis to determine the relationships between moisture content and soil matric pressure. These relationships will allow a semi-quantitative assessment to be made of soil matric potential based on measured soil moisture probes. Matric potential is notoriously difficult to measure at low pressures and this information may offer a proxy.
- Drilling and testing should be undertaken in the South Flank Valley to determine aquifer properties of the regional aquifer and provide water levels to determine the gradient between Coondewanna Flats and the South Flank Valley. This level information already exists for the North Flank Valley. In combination, this will allow better definition of the distribution of groundwater outflow between the two valleys.

- The Weeli Wolli groundwater model should be updated once more information is available on the aquifer properties of the South Flank Valley. The model should then be used to assess the long term implications of reduced recharge at Coondewanna on Weeli Wolli Spring.
- To compliment the assessment of changes in recharge at Coondewanna on Weeli Wolli Spring, it is recommended that the ecohydrological model developed during the SEA is reviewed and enhanced including the description of key processes and elements in the model and the development of semi-quantitative operating ranges as described during this study for Coondewanna Flats.
- A more broad recommendation is for the assessment of Chloride concentrations in rainfall across BHPB sites. Chloride is a useful tool in assessing regional water balances. However, adopted concentration of chloride in rainfall originates from a relatively short series of measurements at Rio Tinto's Yandi (and published in a journal paper).

Table 17 Summary of Recommendations

Recommendation	Outcome / Purpose	Method / Resources	Schedule / Type
Hydrological measurements	Rainfall and runoff	Installed gauges and loggers	on-going
Regular monitoring of groundwater levels.	More data on aquifer range in water levels and recharge frequency - extend data period into average and dry conditions	Existing Monitoring Bores	minimum monthly / on-going
Monitor tree Health Indicators	Increase baseline conditions and pro-active monitoring	Sapflow or LWP, LAI or other qualitative measure, basal area growth rates	seasonal / on-going
Monitor unsaturated zone moisture content	Confirm water balance assessment and water storage capacity (and hence dimensions) of unsaturated engineered aquifer	Use exiting soil-moisture probes and loggers	minimum monthly / on-going
Assessment of integration with regional system	Impact of reduced groundwater recharge on Weeli Wolli; distribution go flow NFV/SFV	Drilling and assessment in SFV	study
Refinement of Weeli Wolli Eco-Hydrological model	Impact of reduced groundwater recharge on Weeli Wolli	Detailed data compilation and study and Weeli Wolli Groundwater Model	study
Rainfall Chloride	Improve water balances using Cl	Laboratory analysis on rainfall samples	periodic

7 References

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APPENDIX 1

Critical review of stand water use estimation methods developed by Astron (2014)

The vegetation transpiration flux is a key component of the Coondewanna Flats water balance. Critical review of the methods proposed by Astron (2014) for scaling up vegetation water use from individual trees to the stand level was recognised as a key task for improving the ecohydrological conceptualisation of the Coondewanna Flats.

Astron provided the raw data for descriptive plant traits (i.e. DBH, crown dimensions and height) in Appendix C of their report. These data was used to review the relationships between diameter at breast height (DBH), projected canopy area (PCA) and tree water use estimates based on methods 1 and 2 respectively. The results are summarised in Table A, with the basis of the calculations further described in Table C.

A comparison of tree water use estimation using methods 1 and 2 for each tree of each species (i.e. *E. victrix* and *A. aptaneura*) is shown in Figure A. In the case of *A. aptaneura* there is generally good agreement between the two methods. However, in the case of *E. victrix* it is apparent that method 1 (based on PCA) gives a substantially higher estimate that method 2.

Plots of DBH against PCA for *E. victrix* revealed a poor correlation especially for larger trees Figure B). This is in contrast with data presented by Astron (2014) in Figure 9 of their report, which omitted two trees from the dataset used to determine the relationship between DBH and PCA on the basis that these trees were “outliers”. Note that the omitted trees had significantly larger diameters than the remainder of the trees in the dataset, and by implication greater sapwood area and transpiration flux despite having only modest PCA values.

The Astron (2014) report did not provide raw data on monthly transpiration flux for each measured tree, or indicate which trees were included or excluded from calculations of monthly water use coefficients based on projected canopy area and sapwood area as presented in Figure 24 of their report. However, calculations of unit canopy transpiration flux based on tree water use from method 2 divided by the tree projected canopy area suggest that the transpiration estimate for *E. victrix* of 753 mm (100% cover basis over the 316 day monitoring period) proposed by Astron (2014) may be an overestimate (Table B). Across all trees, the weighted mean unit canopy transpiration flux derived using this alternative method gave an annualised value of 464 mm (Table A). Note that similar calculations for *A. aptaneura* gave an estimate of 268 mm (Table A); which is in close agreement with the Astron estimate of 219 mm over the 316 day monitoring period that equates to an annualised value of approximately 258 mm (refer to Table C).

Table A **Unit canopy transpiration flux based on tree water use from method 2 divided by projected canopy area**

Species	Tree water use (sum of all trees) based on method 1 (L/year)	Tree canopy cover (sum of all measured trees) (m^2)	Unit canopy transpiration flux ($L/m^2/year$)
E. victrix	512,736	1,150	446
A. aptaneura	178,079	664	268

The revised transpiration flux estimate for *E. victrix* of 464 mm on a 100% cover basis more closely aligns with other stand level tree water estimates for *E. victrix* in the Pilbara than the Astron (2014) estimate. Pfautsch et al. (2011) reported annual water use of 405 mm/year in a dense woodland of *E. victrix* (tree densities of 180 to 200 trees/ha) growing with unrestricted access to shallow groundwater near Millstream. The largest tree at this site (DBH 58 cm) transpired up to 8,000 L/month (equivalent to about 270 L/day). Examination of the relationship between DBH and the method 1 and method 2 tree water use estimates further support the conclusion that the Astron (2014) method 1 estimates are unrealistic (Figure C); with water use estimates for many trees lying above a prediction curve developed by Pfautsch et al. (2011) for the Millstream site. Additional measurements of *E. victrix* water use in the Weeli Wolli Creek system reported by Pfautsch et al. (2014) correspond with daily transpiration in the order of 10 to 240 L/tree/day for trees spanning a DBH range of approximately 20 to 75 cm. The water use of trees with perennial access to abundant moisture was more than double that of trees growing in drier settings. These results are also more consistent with the method 2 estimations shown in Figure C.

Astron (2014) identified that a major limitation of method 1 is that it does not account for water uptake by any roots that may extend beyond the projected canopy area or additional water uptake within the projected canopy area by neighbouring plants with overlapping roots. However, *E. victrix* is known to have a laterally spreading root system that may extend well beyond its projected canopy area (RTIO 2011, Grigg 2009[6]). A photographic example is provided in Figure D, which shows the lateral root system of this species recorded by Equinox Environmental in another study in the Central Pilbara Region. The assumption that the root system does not significantly extend beyond the projected canopy area does not reasonably apply to *E. victrix*, and this phenomenon may also have contributed to the anomaly between the Astron (2014) methods 1 and 2 described in the preceding discussion.

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[6] Grigg AM 2009, 'An ecophysiological approach to determine problems associated with mine-site rehabilitation: a case study in the Great Sandy Desert, north-western Australia', PhD Thesis, School of Plant Biology, University of Western Australia, Perth

Table B Water use estimates for individual trees measured by Astron at Coondewanna Flats based on method 1 and method 2 respectively

Tree ID	DBH (cm)	Projected canopy area (m^2)	Method 1		Sapwood area (cm^2) Calculated using allometric equation of Astron (2014)	Method 2	
			Tree water use (L/year)	L/day (averaged over 12 months)		Tree water use (L/year)	L/day (averaged over 12 months)
E. victrix							
11.E1	37.6	54	44172	121	226.7	20179	55
11.E2	32.5	46.5	38037	104	186.9	16636	46
11.E3	22.0	24.9	20368	56	114.2	10165	28
12.E1	91.0	78.8	64458	177	805.7	71716	196
12.E3	27.8	23.5	19223	53	152.9	13610	37
12.E5	38.6	56.2	45972	126	234.4	20864	57
14.E1	47.6	40.5	33129	91	312.2	27789	76
14.E2	57.4	140.1	114602	314	405.8	36120	99
14.E3	19.1	9.2	7526	21	96.3	8572	23
15.E1	30.5	37.3	30511	84	172.2	15328	42
15.E2	22.5	14.3	11697	32	117.5	10459	29
15.E3	18.2	9.9	8098	22	90.8	8082	22
16.E1	30.5	14.6	11943	33	172.5	15354	42
16.E2	23.4	36.1	29530	81	123.1	10957	30
16.E3	15.0	11.2	9162	25	72.4	6444	18
17.E1	37.5	80.3	65685	180	225.3	20054	55
17.E2	25.9	32.5	26585	73	139.9	12453	34
17.E3	44.0	134.8	110266	302	279.9	24914	68
20.E1	51.6	109.7	89735	246	349.0	31065	85
20.E2	21.0	12.6	10307	28	107.9	9604	26
20.E3	88.1	67.6	55297	151	765.9	68173	187
22.E1	35.0	33.2	27158	74	205.7	18309	50
22.E2	29.9	30.7	25113	69	167.6	14918	41

Tree ID	DBH (cm)	Projected canopy area (m^2)	Method 1		Sapwood area (cm^2) Calculated using allometric equation of Astron (2014)	Method 2	
			Tree water use (L/year)	L/day (averaged over 12 months)		Tree water use (L/year)	L/day (averaged over 12 months)
22.E3	38.7	51.5	42127	115	235.6	20971	57
A. aptaneura							
11.A1	37.5	79.9	20614	56	225.6	15327	42.0
11.A2	19.5	19.1	4928	14	98.6	6699	18.4
11.A3	22.8	36.9	9520	26	119.7	8132	22.3
12.A1	19.4	30.1	7766	21	98.0	6298	17.3
12.A2	20.2	29.9	7714	21	102.9	6991	19.2
12.A3	18.5	17.7	4567	13	92.7	6298	17.3
13.A2	19.7	30.7	7921	22	100.1	6801	18.6
13.A3	17.7	13.6	3509	10	87.9	5972	16.4
13.A4	13.0	17.6	4541	12	61.4	4171	11.4
14.A2	19.9	15.7	4051	11	101.3	6882	18.9
14.A3	21.1	34.7	8953	25	108.6	7378	20.2
14.A4	20.1	27	6966	19	102.1	6936	19.0
15.A1	36.8	55.2	14242	39	219.6	14919	40.9
15.A2	24.3	39.1	10088	28	129.4	8791	24.1
15.A3	14.5	20	5160	14	69.7	4735	13.0
17.A1	22.2	25.4	6553	18	115.5	7847	21.5
17.A2	31.7	35.5	9159	25	181.0	12297	33.7
17.A3	31.9	56	14448	40	182.5	12399	34.0
20.A1	24.2	19.6	5057	14	128.5	8730	23.9
20.A2	28.0	30.6	7895	22	154.0	10462	28.7
20.A3	27.0	29.6	7637	21	147.4	10014	27.4

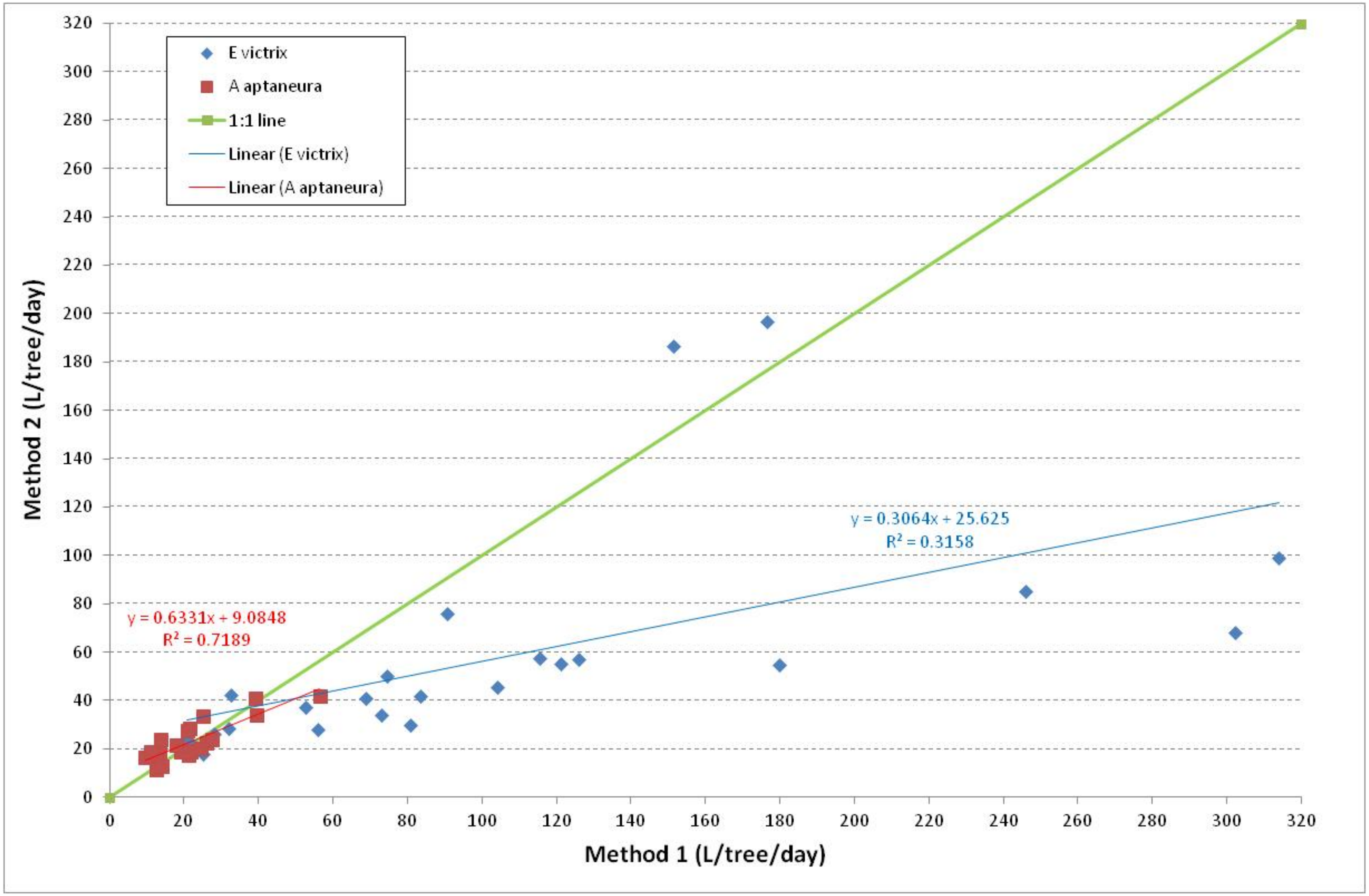

Figure A **Individual tree water estimates – comparison of methods 1 and 2 proposed by Astron (2014)**

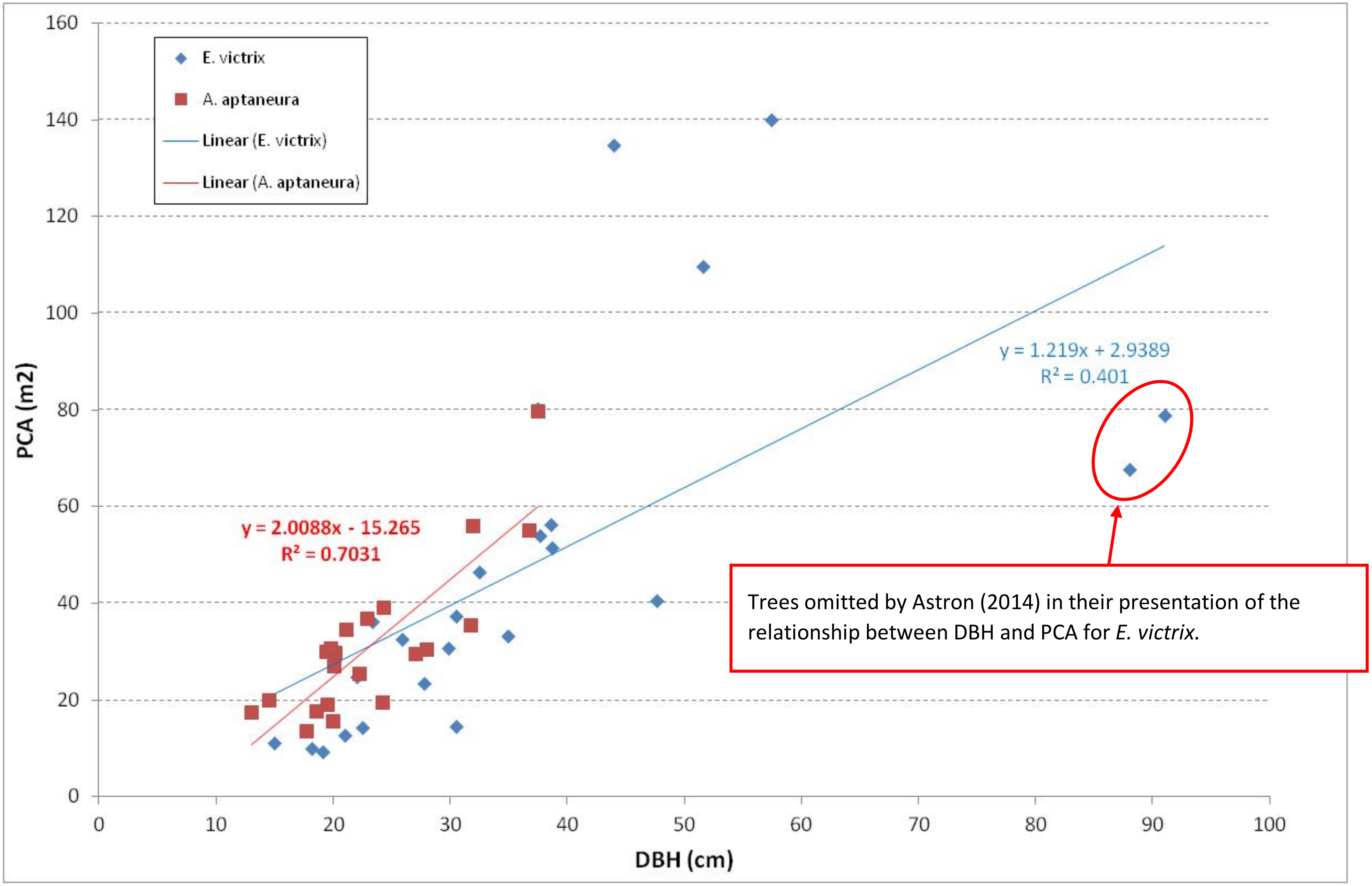

Figure B **Relationship between DBH and PCA for trees at Coondewanna Flats measured by Astron (2014)**

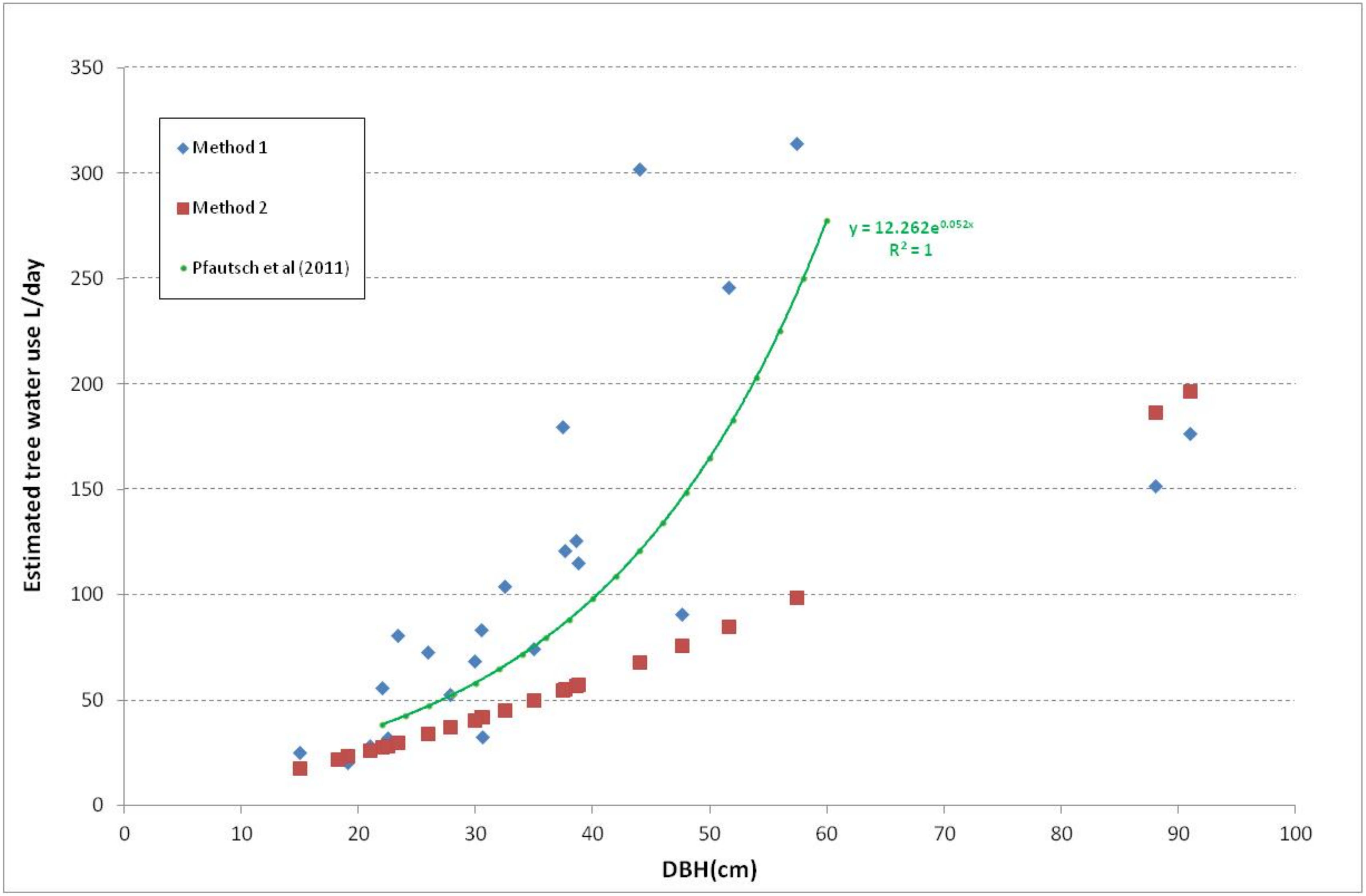

Figure C **Relationship between DPH and tree water use estimates (methods 1 and 2) as per Table B.**

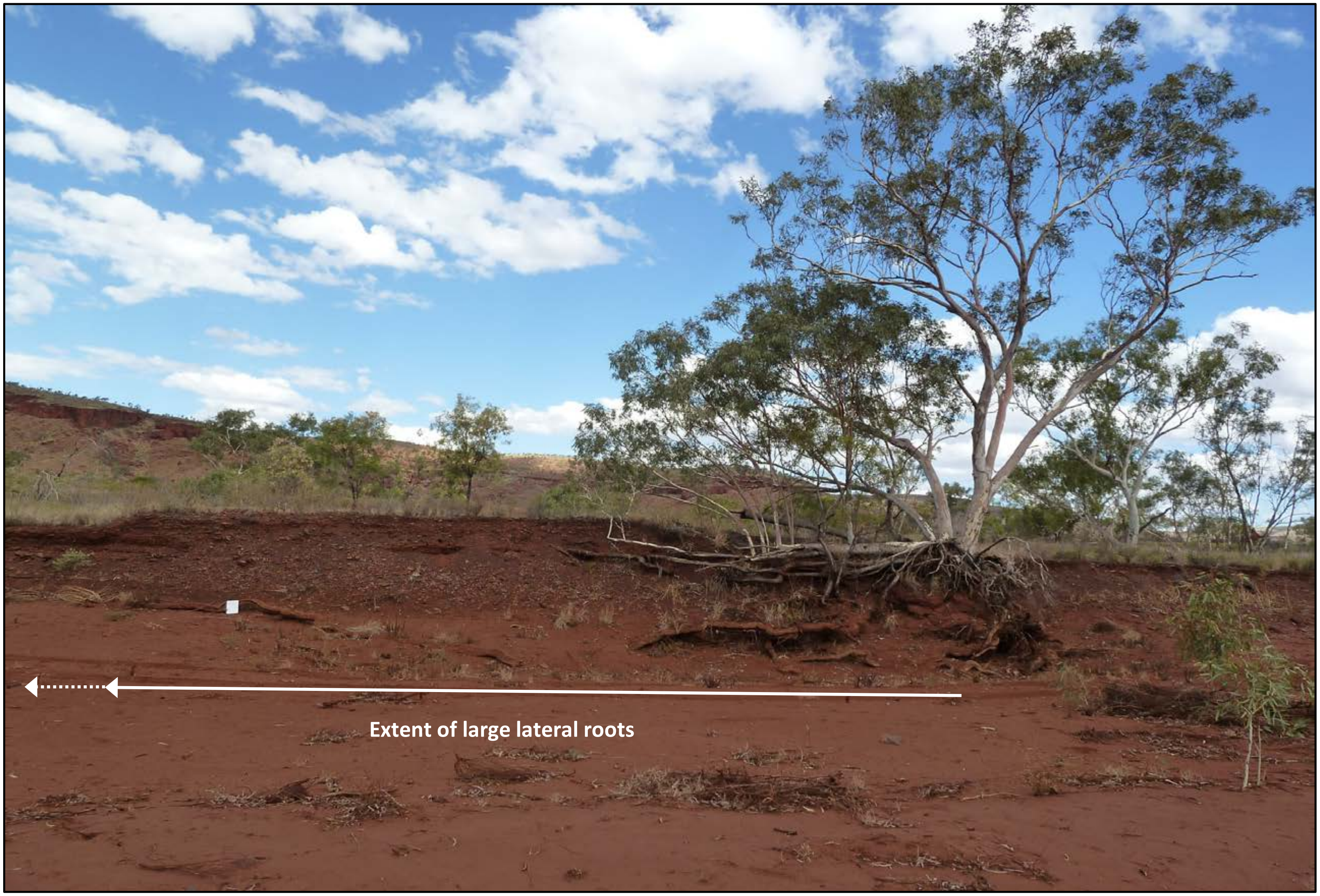

Figure D **Lateral roots of E. victrix exposed in an eroded section of the Weelumurra Creek system, Central Pilbara Region**

Table C: Scaling up vegetation water use from individual trees to the stand level using Astron (2014) methods 1 and 2

Method 1: values for K1 obtained from Astron (2014) Figure 24; values for ET_0 estimated from Astron (2014) Figure 23

E. victrix **- annual transpiration estimate**

	June	**July**	**August**	**September**	**October**	**November**	**December**	**January**	**February**	**March**	**April**	**May**[7]	**Total**
K1 (E/ETo)	0.71	0.70	0.51	0.39	0.31	0.27	0.33	0.41	0.49	0.51	0.56	0.64	**0.49**
ET_0 (mm)	40	90	130	160	190	220	210	210	200	200	120	90	**1860**
Cover	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	**100%**
Transpiration (mm) = K1 x ET_0 x 100%	28	63	66	62	59	59	69	86	98	102	67	57	**818 mm**

A. aptaneura **- annual transpiration estimate**

	June	**July**	**August**	**September**	**October**	**November**	**December**	**January**	**February**	**March**	**April**	**May**	**Total**
K1 (E/ETo)	0.20	0.22	0.16	0.13	0.09	0.08	0.10	0.15	0.18	0.16	0.15	0.18	**0.15**
ET_0 (mm)	40	90	130	160	190	220	210	210	200	200	120	90	**1860**
Cover	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	**100%**
Transpiration (mm) = K1 x ET_0 x 100%	8	20	21	21	17	18	21	32	36	32	18	16	**258 mm**

[7] K1 and ETo for May extrapolated from the Astron (2014) dataset that spanned that period June 2013 to April 2014

Method 2: values for K2 obtained from Astron (2014) Figure 25; values for ET_0 estimated from Astron (2014) Figure 23

***E. victrix* – example of annual transpiration estimate for a single tree with DBH = 50 cm (sapwood area = 334 m^2/tree)**

	June	July	August	September	October	November	December	January	February	March	April	May[8]	Total
K2 ($cm^3/cm^2/mm$)	0.71	0.70	0.51	0.39	0.31	0.27	0.33	0.41	0.49	0.51	0.56	0.64	**0.49**
ET_0 (mm)	40	90	130	160	190	220	210	210	200	200	120	90	**1860**
L used per tree = K2 x ET_0 x 334 ÷ 1000	996	2,157	2,344	2,297	2,258	2,372	2,636	3,078	3,505	3,619	2,424	2,030	**29,716**
										Mean daily water use =			**82.5 L/day**

***A. aptaneura* – example of annual transpiration estimate for a single tree with DBH = 25 cm (sapwood area = 93 m^2/tree)**

	June	July	August	September	October	November	December	January	February	March	April	May	Total
K2 ($cm^3/cm^2/mm$)	0.20	0.22	0.16	0.13	0.09	0.08	0.10	0.15	0.18	0.16	0.15	0.18	**0.15**
ET_0 (mm)	40	90	130	160	190	220	210	210	200	200	120	90	**1860**
L used per tree = K2 x ET_0 x 93 ÷ 1000	200	477	523	498	400	412	516	775	888	786	436	388	**6,300**
										Mean daily water use =			**17.5 L/day**

[8] K1 and ETo for May extrapolated from the Astron (2014) dataset that spanned that period June 2013 to April 2014

APPENDIX 2

Tree size class distribution at Coondewanna Flats in plots 26 and 37

Tree size class distributions for *A. aptaneura* in plots 26 and 37 are presented in Figures AA and BB. Plot 26 included a relatively uniform spread of tree sizes, whilst plot 37 included a large proportion of small trees associated with a recent recruitment event. There were 71 living trees with D*equiv.*≥ 10 cm in plot 26 (equivalent to 141 trees/ha), and 40 living trees with D*equiv.* ≥ 10 cm in plot 37 (equivalent to 84 trees/ha).

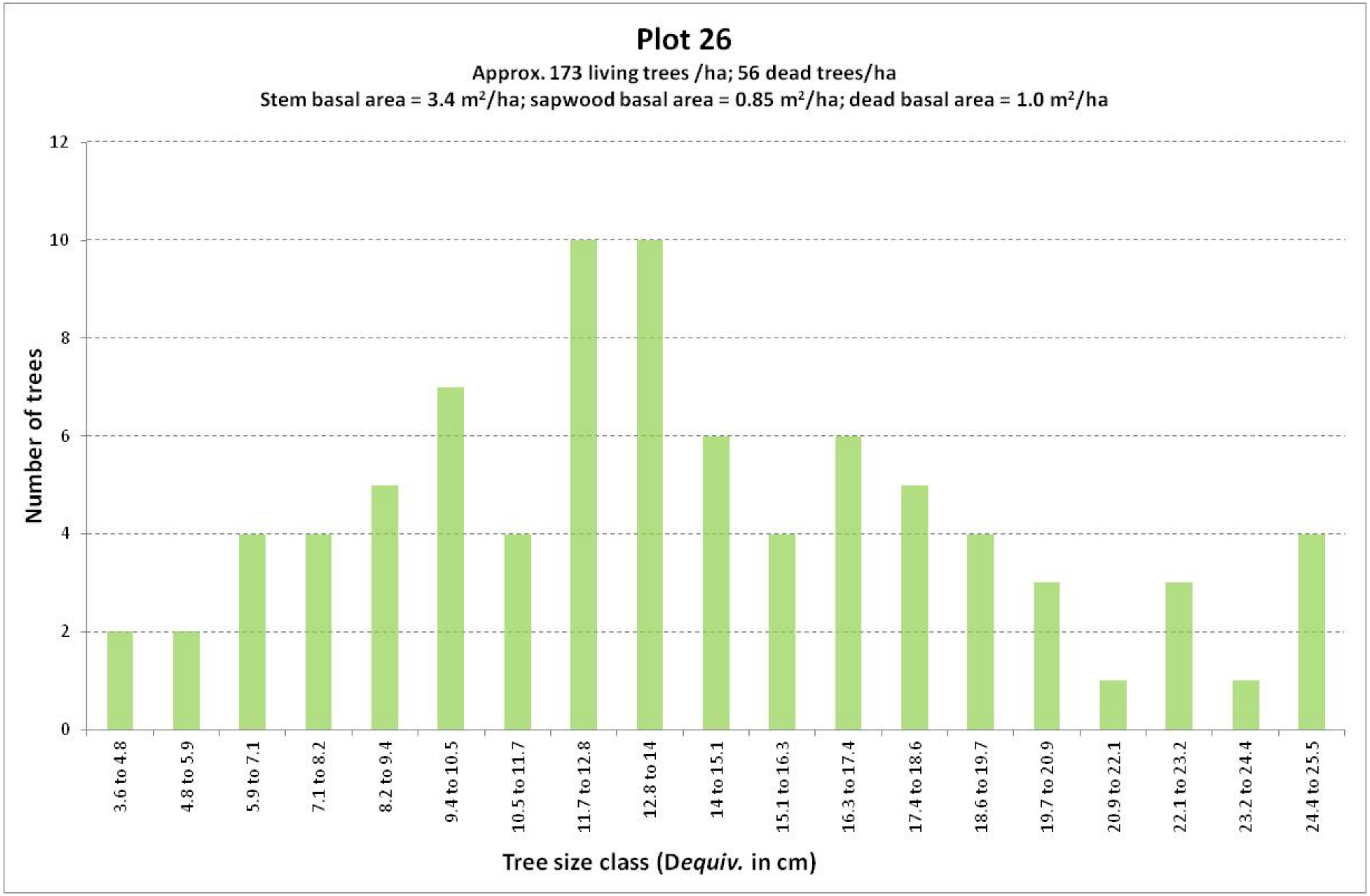

Figure AA **A. aptaneura tree size class distribution in plot 26**

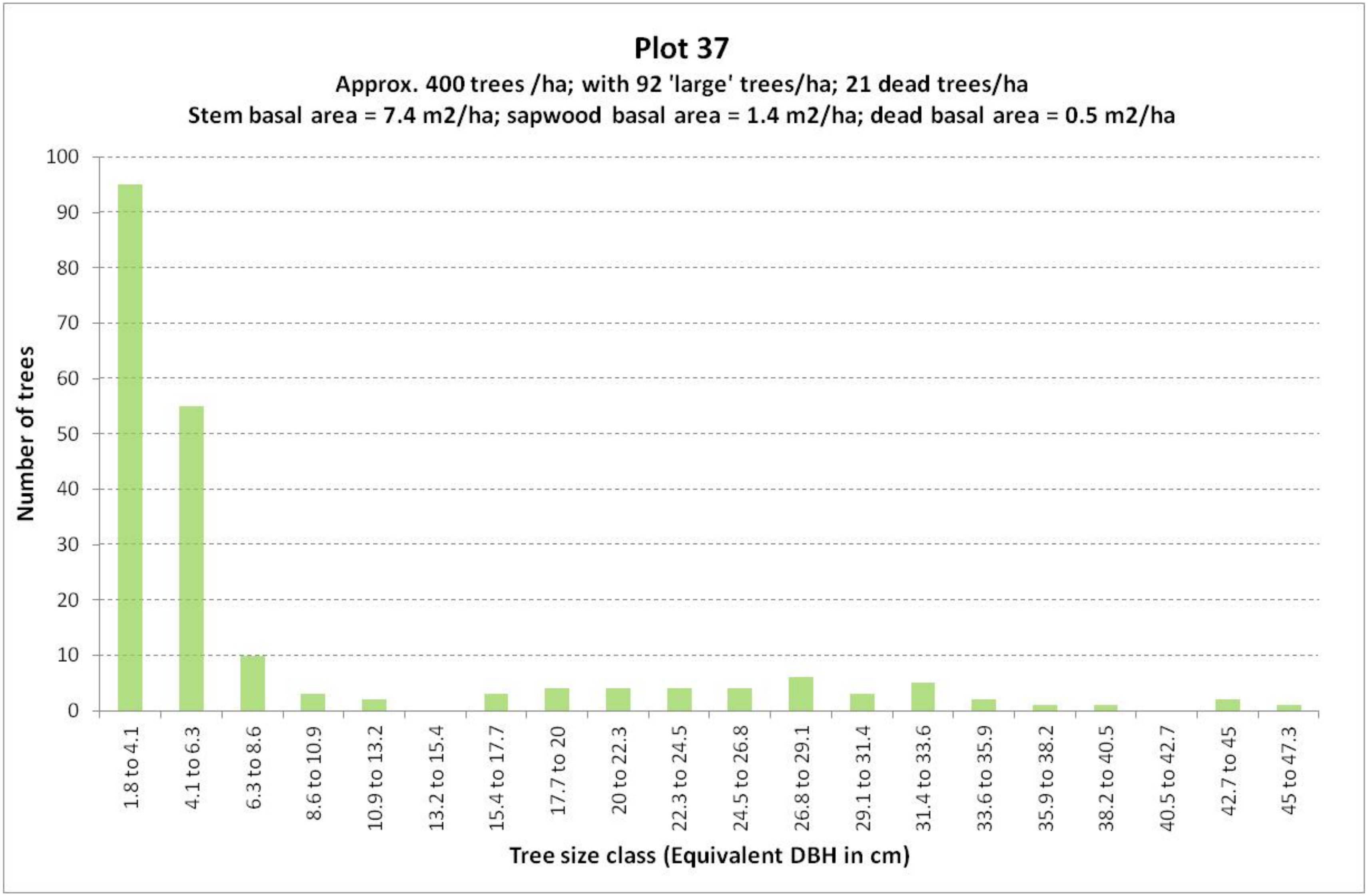

Figure BB A. aptaneura tree size class distribution in plot 37

APPENDIX 3

RPS Surface Water Report

38 Station Street, Subiaco Western Australia 6008, PO Box 465, Subiaco Western Australia 6904
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MEMORANDUM

COMPANY:	AQ2		
ATTENTION:	Duncan Storey		
FROM:	Vince Piper		
DATE:	15 January 2015	JOB NO: 1733B	DOC NO: 005a
SUBJECT:	Coondewanna Catchment - Surface Water Recharge to Aquifer Assessment		

This memo assesses the impact of potentially reduced Coondewanna catchment areas on surface water runoff volume thresholds and occurrence frequency for initiation of recharge to groundwater in Lake Robinson. The scope of works comprises:

- Prepare a conceptual model of the key surface water runoff processes throughout the Coondewanna catchment, aided by a catchment landscape plan using Dept of Agriculture data.
- Review previous surface water runoff volume threshold assessment and update with 2013–2014 Flat Rocks streamflow gauging data and associated rainfall data.
- Assess streamflow-gauging data available from recently installed local gauging stations within the Coondewanna catchment and include any relevant runoff characteristics within the previous threshold assessment.
- Assess range sensitivity of adopted runoff thresholds to occurrence frequency, based on the Flat Rocks streamflow data and with SILO rainfall data (if viable).
- Correlate potential catchment area reduction to runoff occurrence frequency, as possible from the data available.

During the assessment, the scope was expanded to include estimates of the aquifer recharge volumes arising from the surface water runoff.

1. Catchments and Flowpaths

The Coondewanna catchment with an area of around860 km^2 drains to an internal depression named Lake Robinson (Figure 1). Lake Robinson is located in the south-eastern sector of the catchment and is the lowest area at approximately 687m AHD. However, this lake bed elevation is approximately 130m higher than Weeli Wolli Spring, which is located in the adjacent Weeli Wolli Creek catchment.

Due to Lake Robinson being the receiving drainage basin for the Coondewanna catchment, large runoff events inundate the lake bed. An aerial view of Lake Robinson after the January 2012 flood event is shown in Plate 1. Following runoff, surface water on the lake bed would slowly dissipate by seepage and evapotranspiration. Seepage would infiltrate the lake area, replenishing soil water in the unsaturated zone and potentially contributing to groundwater recharge.

Sub-catchments and main flowpaths within the Coondewanna catchment are shown on a topography plan in Figure 1. Several east to west aligned ridgelines are located within the catchment, which dictate the drainage flow directions. Three of Western Australia's highest mountains (Mount Meharry, Mount Robinson and The Governor) are also located in the catchment. The main flowpath discharging to Lake Robinson is Homestead Creek, which drains the northern half of the catchment. Where Homestead Creek passes adjacent to the Packsaddle Hill, approximately 8 km north from Lake Robinson, the creek has a well-defined single alluvial channel, and a BHPBIO water level gauging site (SNPH0011) has recently been established (2011). The creek bed at this location is described as comprising coarse gravels and sands, approximately 15 m wide with 1 to 2 m high banks (URS). Scattered eucalypt trees are located along the creek bed. During 2012, additional BHPBIO water level gauging sites were established within the Coondewanna catchment.

Although the runoff characteristics from ridgelines in the Coondewanna catchment would be typical of Pilbara catchments, detailed topographical mapping shows that the catchment contains numerous large relatively flat areas where runoff would tend to pool and slowly flow downstream. These areas represent the hard-pan landscape units and runoff over many of these flattish areas would discharge as sheetflow. These characteristics indicate that relative runoff volumes from these areas would be low compared with a more free-draining catchment area.

During a high rainfall event, runoff could potentially discharge to Lake Robinson from all sides, with proportionally higher runoff from ridgelines, which are in close proximity. However, it is estimated that as runoff from over 50% of the catchment would need to pass through flattish slowly draining areas prior to reaching Lake Robinson, relative runoff volumes to the lake would typically be low for small to medium rainfall events. Significant runoff to Lake Robinson would likely only occur after a large rainfall event.

Two RTIO railway corridors and the main North West Highway pass through the Coondewanna catchment, as shown in Figure 1. Earthworks associated with these transport corridors interrupt the natural flowpaths, and culverts or bridges (and floodways on roads) are typically located at identified drainage flowpaths to allow runoff to pass downstream. Similarly, access tracks may potentially interrupt the natural drainage flowpaths. Although culverts/bridges may have been located on identified drainage flowpaths, sheetflow zones are more difficult to manage. To cater for the sheetflow zones, it is understood that additional culverts have been installed along the railway corridors.

2. Runoff Processes

In common with most natural drainage systems in the Pilbara region, the Coondewanna catchment contains ephemeral drainage systems flowing in direct response to rainfall. Streamflow mainly occurs during the summer months of December through to March and is associated with the large and more intense rainfall events. Streamflow in the smaller flow channels is typically short in duration, and ceases soon after the rainfall passes. In the larger flow channels which drain the larger sub-catchment areas, runoff can persist for several weeks following major rainfall events such as those resulting from tropical cyclones.

In arid and semi-arid zones, such as the Pilbara, surface runoff is typically generated when the rate of rainfall exceeds the infiltration capacity of the ground causing overland flow. This is termed "infiltration excess" runoff. Surface runoff can also be generated from soils already saturated to the surface where additional rainfall becomes overland flow. This is termed "saturation excess" runoff. Another mechanism for surface runoff generation is by groundwater flowing to the surface (e.g. Weeli Wolli Spring). Similarly surface runoff could be lost from a catchment by interception, infiltration and evaporation.

All of these runoff (generation and loss) processes may be active at the same time within the one catchment depending on rainfall intensity/duration/areal extent, as well as the variable catchment conditions including surface topography, soil types, soil depths, antecedent soil moisture status, vegetation conditions and hydrogeology.

Four broad types of landscape units that influence surface runoff can be defined and all may be present in the larger catchments:

- Upland Source Landscape Units where runoff is generated
- Upland Transitional Landscape Units where runoff is both generated and concentrated into drainage channels
- Lowland Transitional Landscape Units where the drainage is poorly organised or comprises complex redistribution patterns
- Lowland Receiving Landscape Units where runoff is directed into major surface water features and dissipated.

Upland Landscape Units are characterised as rocky upland areas with shallow stony soils and steep slopes. In these low infiltration areas, runoff will be generated following a relatively low rainfall event and drainage is typically characterised by short-distance overland flow towards many small gullies.

Upland and Lowland Transitional Landscape Units may be characterised by several land systems including stony slopes lying below the steeper Upland Landscape Units; stony plains comprising gently sloping colluvial and alluvial plains extending across the valley; and ephemeral drainage channels through the stony slopes and plains. Drainage occurs as sheetflow and channel flow into larger drainage channels.

Receiving Landscape Units comprise a variety of land systems and may include claypans characteristic of internally draining playas; river channels and floodplains; and expansive areas of calcrete. Drainage is also as varied as the land-systems with overland sheetflow and inundation in the playas, and well-defined channels and flood plains along the river systems with runoff dissipated by infiltration, evapotranspiration and flow downstream.

These broad landscape units can generally be identified from the topographical mapping covering the Coondewanna catchment area (Figure 1). This mapping shows a high density of drainage gullies adjacent to the ridgelines, indicating higher runoff characteristics, discharging into a lower density of drainage channels away from the ridgelines, then draining downstream into larger more mature creek channels on the flatter slopes and terminating into Lake Robinson. The main flow channels of creek systems with reducing bed gradients typically show signs of becoming less defined with distance downstream and developing wider flood plains. These drainage characteristics lower the runoff velocities and spread runoff over a wider area, allowing more time and area for detention and infiltration, thus typically reducing the overall discharge volume progressing downstream. Homestead Creek and the other main creeks flowing towards Lake Robinson have these characteristics.

These broad landscape units can also be generally identified from the Land Type mapping covering the Coondewanna catchment area (Figure 2). This mapping shows Land Types 1 and 4 as being the Upland Source Landscape Units, Land Type 10 as being the Lowland Receiving Landscape Units and the between land types as being the Upland and Lowland Transitional Landscape Units.

3. Coondewanna Hydrological Data

3.1 Rainfall Data

A few existing and closed BOM and DoW rainfall monitoring station sites are located within and around the Coondewanna catchment area with the closest stations listed in Table 1. The earliest data records start in 1969–1970. BHPBIO has a full weather station at Area C and has recently (late 2012) installed four rainfall stations within the Coondewanna catchment for assessing rainfall variability.

Table 1: BOM and DoW Rainfall Monitoring Stations

Site No.	Site Name	Owner	Type	Date Commenced	Date Closed
505004	Munjina	DoW	Continuous	1969	-
505011	Flat Rock	DoW	Continuous	01/03/1970	-
505014	Packsaddle	DoW	Continuous	30/05/1970	03/09/1999
507012	Wonmunna	DoW	Continuous	28/11/1984	-
5089	Packsaddle Camp	BOM	Daily	1989	21/07/2002
505015	Juna Downs Station	DoW	Daily	1971	1973
505020	Juna Downs	DoW	Continuous	29/09/1973	18/11/1980

Generated rainfall data for the study area are also available from the SILO database where SILO is a meteorological dataset managed by the Science Delivery Division of the Department of Science, Information Technology, Innovation and the Arts (DSITIA). SILO is able to provide daily historical weather estimates from 1889 to present, for any location in Australia to the closest 0.05° latitude/longitude. Given the absence of long-term rainfall data for the catchment, SILO rainfall data generated for the catchment centroid have been utilised. It should be noted however that this data set is generated from long-term rainfall data available in the same general area, hence in areas were historical data are sparse, the SILO data would have less reliability.

An assessment of the long-term annual rainfall totals for the Coondewanna catchment has been undertaken using the SILO annual rainfall data for the period 1900 to 2014, and using the July to June water year. These annual data are shown plotted in Figure 3, together with a plot of the five-year moving average annual rainfall and the average annual rainfall (328mm) for the period starting in July 1900. An examination of the annual data plot shows that since 1994, a higher proportion of years have recorded rainfall totals significantly in excess of the long-term average. This long-term apparent change in annual rainfall can be seen in the plot of the five-year moving average annual rainfall where average annual rainfall totals appear to have increased since the 1960s.

Over the past 50 years (July 1964 to June 2014), the average annual SILO rainfall at the Coondewanna catchment centroid is 372mm compared to the longer-term average of 328mm (1900 to 2014). Corresponding average annual SILO rainfall at the Flat Rocks catchment centroid over the past 50 years is 401mm, hence on average around 7% wetter.

The recent higher rainfall period would likely result in higher catchment runoff, soil moisture replenishment and aquifer recharge volumes, as compared to the long-term average.

CSIRO in partnership with the Western Australian Government Departments of Water and Regional Development, BHP Billiton and the Water Corporation is carrying out a scientific assessment of water resources in the Pilbara. This assessment will provide an overview of the effect of future climates and proposed developments on the region's surface water and groundwater resources. In August 2013, the Pilbara Water Resource Assessment released its interim report on the past, present and future climate of the region. The latest climatic models indicate there is large uncertainty as to whether the recent wetting trend in most of the Pilbara will continue. Most projections indicate that future rainfall is likely to be close to the mid-long term average (1961–2012) and not increase – as has been experienced in the central and eastern Pilbara since the 1960s.

3.2 Runoff Data

DoW streamflow gauging stations have not been located in the Coondewanna catchment with the nearest gauges being Flat Rocks (Marillana Creek – gauge S708001) and Tarina (Weeli Wolli Creek – gauge S708014). The DoW Flat Rocks streamflow gauging station is located to measure runoff from the upper portion of Marillana Creek (next main catchment north from Coondewanna) and has a catchment area of 1,370km^2. This station has been open since September 1967 and has approximately 47 years of mostly unbroken streamflow record, as shown in Figure 4. The upper Marillana catchment contains large flat storage areas, in particular the Munjina Claypan, which attenuates catchment runoff. The hydrological characteristics of Coondewanna catchment, with its numerous large relatively flat slow draining areas, are considered to be more akin to those within the upper Marillana catchment (recorded at Flat Rocks gauge) than those within the Weeli Wolli Creek system (recorded at Tarina gauge). As such, the Coondewanna catchment (860 km^2) runoff volumes are assumed to be a direct area proportion to those recorded for the upper Marillana Creek at Flat Rocks (1,370km^2).

An assessment of the annual correlation between rainfall depths and runoff volumes for the Flat Rocks catchment has been undertaken. This assessment used the catchment SILO annual rainfall data (for the catchment centroid) and the Flat Rocks annual discharge volumes for the 45 year period of usable data (two years of data not complete 1979/80 and 1980/81) at the gauging station, using the July to June water year. The available annual data is shown in Table 3 and a summary of the assessment results is given in Table 2. The total catchment runoff over the 45-year period is estimated at 2.03% of the total rainfall (average 8.2 mm/year). Whereas the median catchment runoff at 0.59% of average annual rainfall (2.39 mm/year) could be considered a more typical runoff characteristic for the catchment (50% AEP – annual exceedance probability) and is significantly less than the long-term average runoff which is influenced by the more extreme flood volume events. Based on a probability assessment for the annual runoff volumes, the long-term annual average runoff volume (11,272 ML) represents approximately a 25% AEP (4 year ARI) event.

Table 2: Flat Rocks Catchment - Annual Rainfall and Runoff Summary (1967 – 2014)

	Annual SILO Rainfall	Annual Runoff Volume	Annual Runoff	Annual Runoff (% of Average Rainfall)
Average	405mm	11,272ML	8.23mm	2.03%
Median	375mm	3,274ML	2.39mm	0.59%

As commented above, the long-term average catchment runoff volume is influenced by the more extreme flood volume events, which is normal. However, the 1975/76 runoff year is very extreme, being three times greater than the next highest runoff year (1972/73), and estimated at less than a 0.5% AEP event (greater than 200 year ARI). Including this volume within the average annual runoff estimate distorts the calculated average, though it should not be ignored. Reassessing the annual average runoff estimate using just 50% of the 1975/76 runoff year volume gives an average annual runoff of 1.72% of the total rainfall (average 7.0mm/year). The median runoff estimate is unchanged at 0.59% of average annual rainfall (2.39mm/year). A summary of these reassessed estimates is given in Table 4 and these data are considered more representative.

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Table 3: Flat Rocks – Annual Rainfall and Runoff (July 1967–June 2014)

Year	SILO Rainfall (mm)	Runoff (ML)	Runoff (%)
1967–1968	460	4,960	0.79
1968–1969	222	1,246	0.41
1969–1970	198	47	0.02
1970–1971	526	23,635	3.28
1971–1972	139	77	0.04
1972–1973	611	51,469	6.15
1973–1974	412	5,327	0.94
1974–1975	352	258	0.05
1975–1976	629	155,415	18.05
1976–1977	165	102	0.04
1977–1978	278	5,383	1.41
1978–1979	379	3,274	0.63
1981–1982	402	8,574	1.56
1982–1983	246	1,745	0.52
1983–1984	367	25,746	5.12
1984–1985	450	6,899	1.12
1985–1986	207	8	0.00
1986–1987	302	1,980	0.48
1987–1988	477	17,971	2.75
1988–1989	356	3,920	0.80
1989–1990	190	3,171	1.22
1990–1991	225	25	0.01
1991–1992	339	1,102	0.24
1992–1993	379	3,252	0.63
1993–1994	259	1,016	0.29
1994–1995	664	23,957	2.63
1995–1996	275	303	0.08
1996–1997	726	20,176	2.03
1997–1998	221	80	0.03
1998–1999	892	6,435	0.53
1999–2000	1097	38,730	2.58
2000–2001	411	3,181	0.56
2001–2002	311	2655	0.62
2002–2003	540	34,767	4.70
2003–2004	426	2,227	0.38
2004–2005	133	411	0.23
2005–2006	809	13,445	1.21
2006–2007	375	650	0.13
2007–2008	305	5,251	1.26
2008–2009	374	4,660	0.91
2009–2010	123	64	0.04
2010–2011	526	3,486	0.48

Year	SILO Rainfall (mm)	Runoff (ML)	Runoff (%)
2011–2012	565	10,105	1.31
2012–2013	464	2,336	0.37
2013–2014	431	7,714	1.31
Average (45 years)	405	11,272	2.03
Median	375	3,274	-

Table 4: Flat Rocks Catchment - Annual Rainfall and Revised Runoff Summary (1967–2014)

	Annual SILO Rainfall	Annual Runoff Volume	Annual Runoff	Annual Runoff (% of Average Rainfall)
Average [(1)]	405mm	9,545ML	6.97mm	1.72%
Median	375mm	3,274ML	2.39mm	0.59%

[(1)] Average annual estimate uses 50% of the 1975–1976 runoff year volume

The annual data in Table 3 show the highly variable nature of the catchment runoff. In 11 of the 45 years of record (approx. one in four years), annual runoff is 650ML or less which represents less than 20% of the median annual runoff (and less than 7% of the revised average annual runoff), hence a very low runoff volume.

Although runoff is directly related to rainfall, the relationship is complex with runoff dependent upon numerous factors including rainfall intensities, rainfall duration, catchment wetness and catchment vegetation conditions. An assessment of the relationship between Flat Rocks catchment rainfall and runoff shows that there is a poor correlation between both monthly and annual rainfall and corresponding runoff volumes, though reasonable correlation for runoff frequency with the larger rainfall events.

To supplement the DoW streamflow monitoring system, BHPBIO has installed crest (water level) gauges around the Coondewanna catchment. The first station (SNPH0011) was installed on Homestead Creek in 2011 (Figure 1) and six additional stations were installed in 2012. Station SNPH0011 on Homestead Creek now has three wet seasons of water level data with the recorded annual peak water levels as given in Table 5. At this stage, discharges are not available for these crest-gauging stations, as depth-discharge relationships have not been developed, however the data indicates that 2011/12 had a significantly higher runoff than the following two years.

Table 5: Crest Gauge Station SNPH0011 – Peak Water Levels

Wet Season	Date	Peak Water Level
2011–2012	Jan 2012	3.6m
2012–2013	Nov 2012	1.1m
2013–2014	Jan 2014	1.9m

The six additional Coondewanna catchment crest gauges have just two years of wet season data (2012/13 and 2013/14), some of which is not continuous. One crest gauge (SNPH0019) is located on Homestead Creek around 5km upstream from SNPH0011 and its main flow data (when available) mostly corresponds with flow events recorded on gauge SNPH0011, as expected. The other five crest gauges are located over the general Lake Robinson area and water level records for these gauges (when available) show no reliable indication of a flow or inundation event occurring. Possibly very shallow sheetflow (or inundation) resulted from these main runoff events (Table 5), which were not detectable by the installed crest gauges.

4. Aquifer Recharge Thresholds

4.1 Aquifer Recharge Events

Surface water runoff to Lake Robinson pools over the lake area replenishing soil water in the unsaturated zone, potentially contributing to groundwater recharge, and also dissipates by evapotranspiration. Groundwater level monitoring in bores located in the Lake Robinson area (starting in 2004) indicates that aquifer recharge events occurred in 2006 and 2012. Extrapolation from groundwater level data for a bore located in the adjacent South Flank valley indicates that an earlier aquifer recharge event is likely to have occurred in 2003. Based on anecdotal information, significant inundation is reported to have occurred on Lake Robinson in 2006 and 2012, which corresponds with the two latter aquifer recharge events.

4.2 Recharge Frequency Based on Rainfall Assessment

Based on a previous study (Ecological Conceptualisation for the Central Pilbara Hub, Internal RPS 2014), the monthly rainfall data was concluded to likely provide the best indication as to when runoff would be sufficient to initiate aquifer recharge. To investigate the frequency of aquifer recharge events based on rainfall data, SILO monthly rainfall data for the Coondewanna catchment from July 2002 (to cover the recent aquifer recharge events), are shown in Figure 5. These data show that the highest monthly rainfalls were in 2002/03, 2005/06 and 2011/12, which coincide with the main aquifer recharge events.

Based on these SILO monthly rainfall data, a threshold monthly rainfall total of 180mm has been adopted as the indicative rainfall required to initiate aquifer recharge at Lake Robinson. This rainfall total was selected to capture the 2002/03, 2005/06 and 2011/12 peak rainfall months, and to avoid the 2003/04 and 2010/11 peak rainfall months. Using this 180mm monthly rainfall total threshold, the monthly SILO rainfall data for the past 100 years (July 1914–June 2014) has been assessed. This monthly data is shown in Figure 6.

For the initial 50 years of SILO rainfall data (1914/15 to 1963/64), nine of the 50 years had a 180mm or greater monthly rainfall total. For the more recent 50 years of data (1964/65 to 2013/14), 12 years had a 180mm or greater monthly rainfall total. This increase in the number of larger monthly rainfall totals corresponds with the apparent long-term increase in annual rainfall for Coondewanna catchment, shown in Figure 3. Using this assumption, over the past 50 years, an aquifer recharge event would likely occur on average approximately every four years. In the prior 50-year period, an aquifer recharge event would likely have occurred on average approximately every five years. Note that these recharge frequencies are sensitive to the threshold rainfall total adopted. If a threshold of 200 mm were adopted, the event numbers would become five in the prior 50 years and nine in recent 50 years, indicating an aquifer recharge event occurrence likely on average approximately every 10 years and six years respectively.

4.3 Recharge Frequency Based on Streamflow Assessment

As previously discussed, long term streamflow data are not available for the Coondewanna catchment and streamflow data recorded for the adjacent upper Marillana Creek catchment at the Flat Rocks gauging station have been adopted as representative. Runoff volumes in the Coondewanna catchment (860 km^2) are assumed to be a direct area proportion to those recorded at Flat Rocks (1,370km^2). To investigate the frequency of aquifer recharge events under Lake Robinson based on streamflow data, the monthly streamflow data at the Flat Rocks gauging station have been assessed.

The monthly Flat Rocks runoff volumes for the 2002 to 2014 period, covering the recent aquifer recharge events (2002/03, 2005/06, and 2011/12), are shown plotted in Figure 7. These data show the 2002/03, 2005/06, 2011/12 and 2013/14 wet seasons as containing the larger monthly runoff events, corresponding to the known 2002/03, 2005/06 and 2011/12 aquifer recharge events, however 2013/14 is not a known Coondewanna aquifer recharge event.

The Flat Rocks catchment centroid monthly rainfall data for the 2002 to 2014 period are given in Figure 8. Comparing these Flat Rocks rainfall data with the corresponding Coondewanna rainfall data (Figure 5) shows a generally similar rainfall trend with the main divergence being in January 2014 where a relatively large rainfall volume was recorded over the Flat Rocks catchment (232mm), compared with a smaller volume over the Coondewanna catchment (51mm). This larger Flat Rocks rainfall corresponds with the relative large Flat Rocks runoff volume recorded in January 2014. Based on these rainfall data, it is concluded that the Coondewanna catchment did not receive a runoff event sufficient to initiate aquifer recharge in January 2014.

Although it is apparent that the Flat Rocks catchment runoff sequence does not totally reflect the runoff sequence in the Coondewanna catchment, it is assumed that the runoff statistics for the catchments are similar (i.e. in proportion to their areas).

In the Flat Rocks catchment, the 2005/06, 2011/12 and 2013/14 wet seasons (when aquifer below Lake Robinson was recharged) all have a peak monthly runoff around 8,000ML (7,200 to 8,200ML). In comparison, the 2007/08, 2008/09 and 2010/11 wet seasons, when aquifer recharge did not occur, all have a peak monthly runoff around 3,000ML (3,000 to 3,300ML). Based on these data, the threshold monthly runoff volume (to initiate aquifer recharge below Lake Robinson) would be between the lowest recharge month (7,200ML) and the highest non-recharge month (3,300ML). The mid-point between these two events is 5,300ML and this value has been nominally adopted as the threshold runoff volume (at Flat Rocks) required to initiate aquifer recharge below Lake Robinson.

The Flat Rocks monthly runoff volumes since records started in August 1967 are shown in Figure 9. This record has missing streamflow data during the 1979/80 and 1980/81 wet seasons. Based on these data and adopting a threshold monthly runoff volume of 5,300ML to initiate aquifer recharge (under Lake Robinson), then 13 of the 45 years had a runoff event sufficient to cause aquifer recharge. Hence using these assumptions, an aquifer recharge event would have likely occurred on average approximately every four years (over the available 45 years of data). This frequency of recharge generally agrees with the estimate derived using the most recent 50 years of SILO monthly rainfall data (1964/65 to 2013/14) with a 180mm rainfall threshold.

Over the 45 years of Flat Rocks runoff data, the lowest monthly runoff volume “above” the adopted monthly runoff threshold for aquifer recharge (5,300ML) is 7,192ML (February 2006), and the highest monthly runoff volume “below” the adopted monthly runoff threshold is 4,217ML (February 1978). Based on these data, provided the monthly runoff threshold is located between 4,217ML and 7,192ML, the frequency of aquifer recharge events (under Lake Robinson) should not vary, though the recharge volume would likely vary. These values are 20% below and 35% above the adopted threshold volume. Hence, (using these assumptions) should the catchment area contributing to Lake Robinson be reduced by less than 35%, the frequency of aquifer recharge events would not be altered, but the volume would be. In conclusion, the frequency of aquifer recharge events appears not to be sensitive to moderate reductions to catchment area (say < 20% to be conservative) discharging to Lake Robinson.

5. Lake Robinson Runoff and Aquifer Recharge Volume Estimates

5.1 Runoff Volume Estimate

Assuming that the Coondewanna catchment ($860km^2$) runoff volumes are a direct area proportion to those recorded for the upper Marillana Creek at Flat Rocks ($1,370km^2$), then the predicted corresponding annual runoff volumes for the Coondewanna catchment are shown in Table 6. These data are based on factoring the Flat Rocks runoff volumes (1967/68 to 2013/14) by the area ratio (0.628) and using 50% of the extreme 1975/76 runoff year volume (refer Table 4).

Table 6: Coondewanna Catchment - Estimated Runoff Volumes (1967–2014)

	Annual Runoff Volume	Annual Runoff
Average	5,990ML	6.97mm
Median	2,060ML	2.39mm

As discussed for the Flat Rocks catchment, the predicted Coondewanna catchment median annual runoff of 2,060ML (2.39mm/year) could be considered a more typical runoff characteristic for the catchment (50% AEP – annual exceedance probability) and is significantly less than the long term average runoff which is influenced by the more extreme flood volume events. Based on a probability assessment for the Flat Rocks annual runoff volumes, the Coondewanna long-term annual average runoff volume (5,990ML) represents approximately a 25% AEP (4 year ARI) event. If the full 1975/76 runoff volume was included in this assessment, then the average annual runoff would increase to 7,080ML (8.23mm) which still represents around a 25% AEP event. The median annual runoff would remain at 2,060ML.

On an annual basis, the Coondewanna catchment runoff would be highly variable with some years (July to June) having effectively zero runoff, others possibly around 20,000ML (pro-rata of Flat Rocks 2002/03 runoff) and a very extreme event could approach 100,000ML (pro-rata of Flat Rocks 1975/76 runoff – Cyclone Joan).

Based on LIDAR data, Lake Robinson has an approximate area of 30km² below the 688m AHD contour; for an assumed typical annual runoff of 2,060ML (50% AEP), this represents an average inundation depth of around 70mm over the lake bed. Given this relatively low volume, it is likely that most of this water would infiltrate into the base of the drainage flowpaths and lake bed with just isolated pockets of ponding. Infiltration from these typical annual events, while insufficient to recharge groundwater, would replenish soil moisture; particularly the upper 5m; the rooting depth of the mulga, herbaceous understorey and the shallow root zone of mature western coolabah trees.

In comparison, the estimated average annual runoff for Coondewanna of 5,990ML represents an average inundation depth of around 200mm over the lake bed and a rather wet year of 20,000ML runoff (e.g. 2002/03) would give an average inundation depth of approximately 700mm. For an extreme runoff event of 100,000ML (e.g. 1975/76 – Cyclone Joan), runoff would give an average inundation depth of around 3m over a 30km^2 lake area; hence water would pond beyond the confines of the lake into the adjacent lower lying drainage flowpaths. Anecdotal information reports that following Cyclone Joan (December 1975), the resulting inundation on Lake Robinson persisted for many months.

In summary to conceptualise the surface water recharge over Lake Robinson:

- Runoff would discharge to Lake Robinson in most years, though in three out of four years runoff would typically be insufficient to initiate aquifer recharge, but would replenish soil moisture in the unsaturated profile. In one of these years (once in four years), runoff would be very low at less than 20% of the median annual runoff.
- Larger events resulting in aquifer recharge are likely to occur on average once every four years, triggered by a monthly rainfall in excess of approximately 180mm.

5.2 Aquifer Recharge Volume Estimate

Using the Flat Rocks catchment monthly runoff data and adopting the monthly runoff threshold for aquifer recharge of 5,300ML, then the monthly runoff volumes above this threshold can be estimated. The volumes above this threshold (pro-rata 3,300ML for Coondewanna) are potentially available for aquifer recharge. On Lake Robinson, runoff volumes below this threshold are assumed to recharge soil moisture and dissipate by evaporation.

For the Coondewanna catchment, pro-rata monthly runoff volumes above the threshold (adjusted for successive wet months) have been estimated and averaged over the 45 years of data availability giving an average annual volume of 3,480ML potentially available for aquifer recharge (Note these data use 50% of the extreme 1975/76 runoff year volume). If the runoff threshold was nominally increased by 20% (pro-rata 4,000ML for Coondewanna), the estimated maximum average annual runoff volume potentially available for aquifer recharge reduces to 3,270ML. These estimated volumes are given in Table 7 together with the estimated maximum volumes potentially available for aquifer recharge with catchment area reductions of 5%, 10%, 15% and 20%.

Table 7: Lake Robinson – Estimated Maximum Aquifer Recharge from Runoff

	Maximum Aquifer Recharge Adopting 3,300 ML/mth Runoff Threshold		Maximum Aquifer Recharge Adopting 4,000 ML/mth Runoff Threshold	
	Average Annual Volume (ML/yr)	Average Daily Volume (ML/d)	Average Annual Volume (ML/yr)	Average Daily Volume (ML/d)
Full Catchment Area	3,480	9.5	3,270	9.0
Catchment Loss 5%	3,260	8.9	3,040	8.3
Catchment Loss 10%	3,030	8.3	2,820	7.7
Catchment Loss 15%	2,810	7.7	2,590	7.1
Catchment Loss 20%	2,590	7.1	2,380	6.5

Based on the estimated maximum aquifer recharge volume assessment data given in Table 7, increasing the adopted monthly runoff threshold by 20% reduces the available recharge volumes by around 6–8%, hence potential recharge volumes are not overly sensitive to the threshold adopted. Reducing the catchment area discharging to Lake Robinson by 5% increments reduces the available recharge volumes by 6–7% increments; hence potential recharge volume reductions are sensitive to catchment area reductions by around a factor of 1.3 (e.g. a 10% catchment area reduction gives around a 13% recharge volume reduction).

For existing conditions at Lake Robinson (using 50% of the 1975/76 runoff volume), the estimated surface water balance is given in Table 8. If the full 1975/76 runoff volume was included in this assessment, then the estimated average annual runoff volume and potential annual runoff volume available for aquifer recharge would both increase by around 1,100ML.

Table 8: Lake Robinson – Estimated Average Annual Surface Water Balance

Component	Average Annual Volume (ML)
Surface Water Runoff	6,000
Maximum Aquifer Recharge	3,500
Minimum Loss to Soil Moisture and Evaporation	2,500

We trust this assessment meets your current requirements. Please do not hesitate to contact us should you require further information.

Yours sincerely,
RPS Water Management

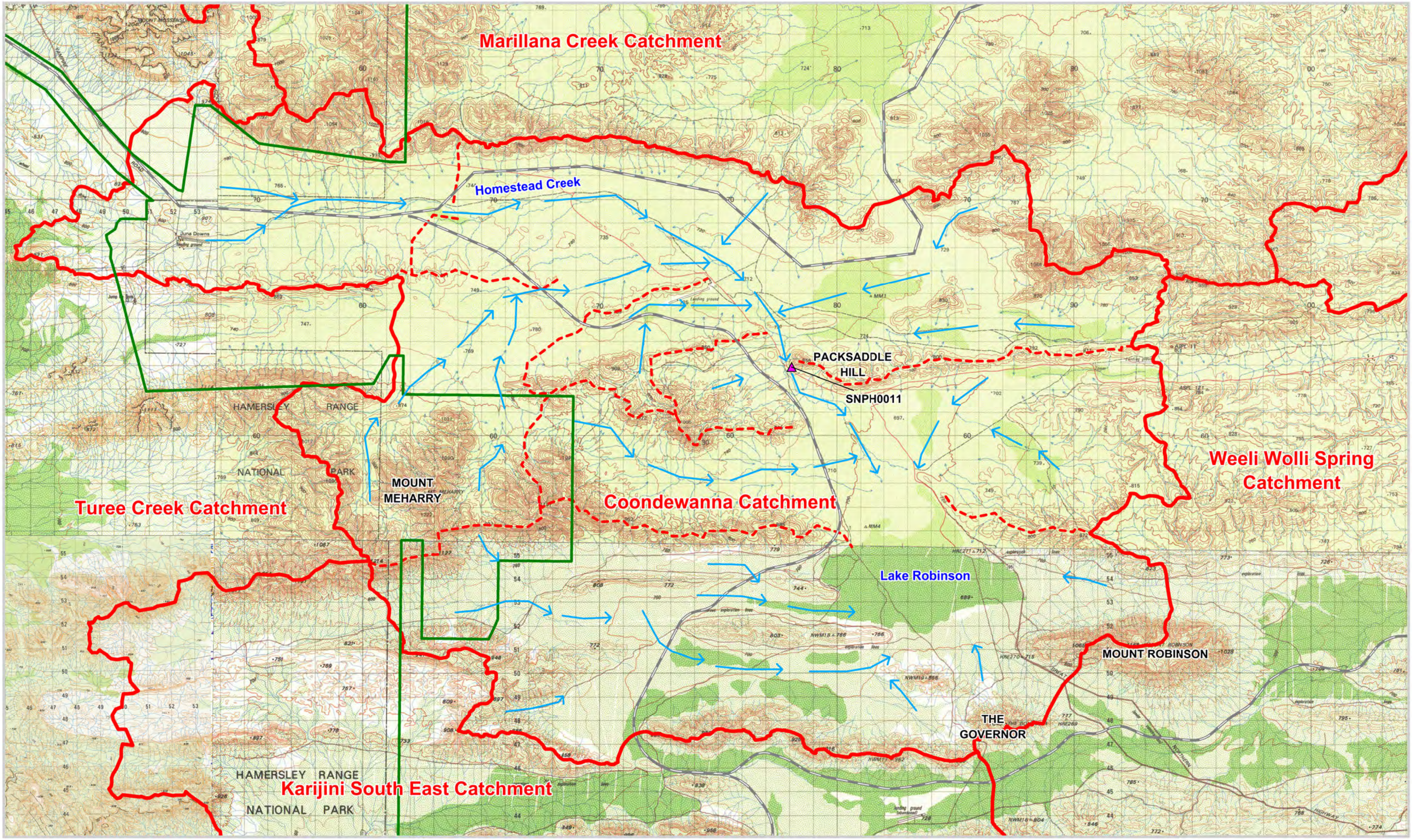
Vince

Vince Piper
Senior Principal Water Resources Engineer

Mark

Mark Nicholls
Senior Water Resources Engineer

FIGURES



N

0 2 4 6

Kilometres

Scale: 1:150,000 @A3

GDA 1994 Zone 50

AUTHOR:	VP	REPORT NO:	005
DRAWN:	MR	REVISION:	a
DATE:	07/01/2015	JOB NO:	1733B

LEGEND

- Main Catchment Boundary
- Sub-Catchment Boundary
- Existing Flow Paths
- National Park Boundary
- Railway
- Streamflow Gauging Station

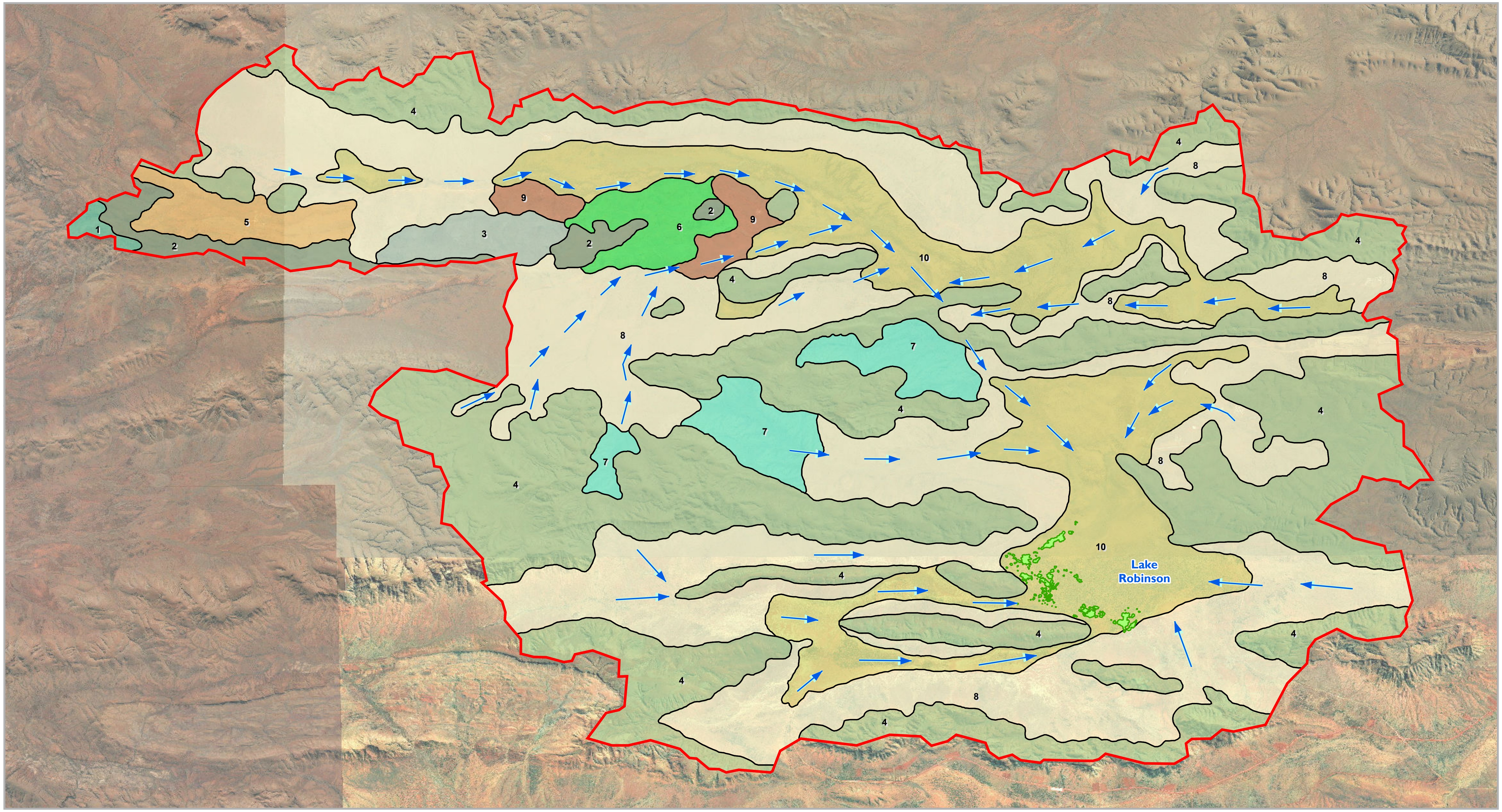
DATA SOURCES:
1:100,000 Topography Maps

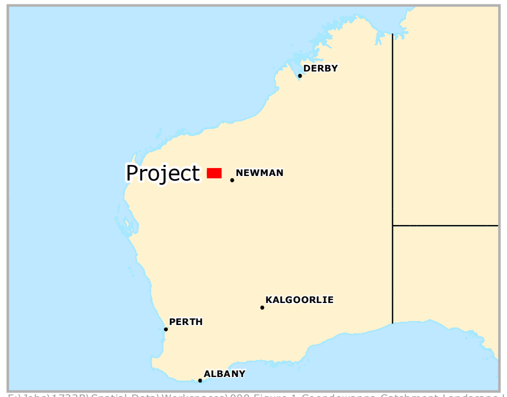
RPS

FIGURE 1

COONDEWANNA CATCHMENT SUBCATCHMENTS AND FLOWPATHS

Location: F:\Jobs\1733B\Spatial_Data\MapInfo\Workspaces\005a Figure 1 - Coondewanna Catchment.wor





N

0 0.5 1 2 3 4
Kilometres

SCALE 1:150,000 @ A3

GDA 1994 MGA Zone 50

Disclaimer: While all reasonable care has been taken to ensure the information contained on this map is up to date and accurate, no guarantee is given that the information portrayed is free from error or omission. Please verify the accuracy of all information prior to use.

AUTHOR	VP	REPORT NO	005
DRAWN	MR	REVISION	a
DATE	07/01/2014	JOB NO.	1733B

F:\Jobs\1733B\Spatial Data\Workspaces\000 Figure 1 Coondewanna Catchment Landscape Units MR 150107.mxd

LEGEND

Catchment Boundary   Existing Flowpath   Coolibah lignum thickets

Land Systems - Land Type and Description

1 Hills and ranges with acacia shrublands - Basalt hills and restricted stony plains supporting grassy mulga shrublands.
2 Hills and ranges with spinifex grasslands - Basalt hills, plateaux, lower slopes and minor stony plains supporting hard spinifex (and occasionally soft spinifex) grasslands.
3 Hills and ranges with spinifex grasslands - Hills, ridges, plateaux remnants and breakaways of meta sedimentary and sedimentary rocks supporting hard spinifex grasslands.
4 Hills and ranges with spinifex grasslands - Rugged jaspilite plateaux, ridges and mountains supporting hard spinifex grasslands.
5 Stony plains with acacia shrublands - Basalt derived stony gilgai plains and stony plains supporting snakewood and mulga shrublands with spinifex, chenopods and tussock grasses.
6 Stony plains with acacia shrublands - Stony plains on basalt supporting sparse acacia and cassia shrublands and patchy tussock grasslands.
7 Stony plains with spinifex grasslands - Dissected slopes and raised plains supporting hard spinifex grasslands.
8 Stony plains with spinifex grasslands - Stony lower slopes and plains below hill systems supporting hard and soft spinifex grasslands or mulga shrublands.
9 Wash plains on hardpan with mulga shrublands - Gently undulating gravelly hardpan plains and dissected slopes supporting groved mulga shrublands and hard spinifex.
10 Wash plains on hardpan with mulga shrublands - Hardpan plains and internal drainage tracts supporting mulga shrublands and woodlands (and occasionally eucalypt woodlands).

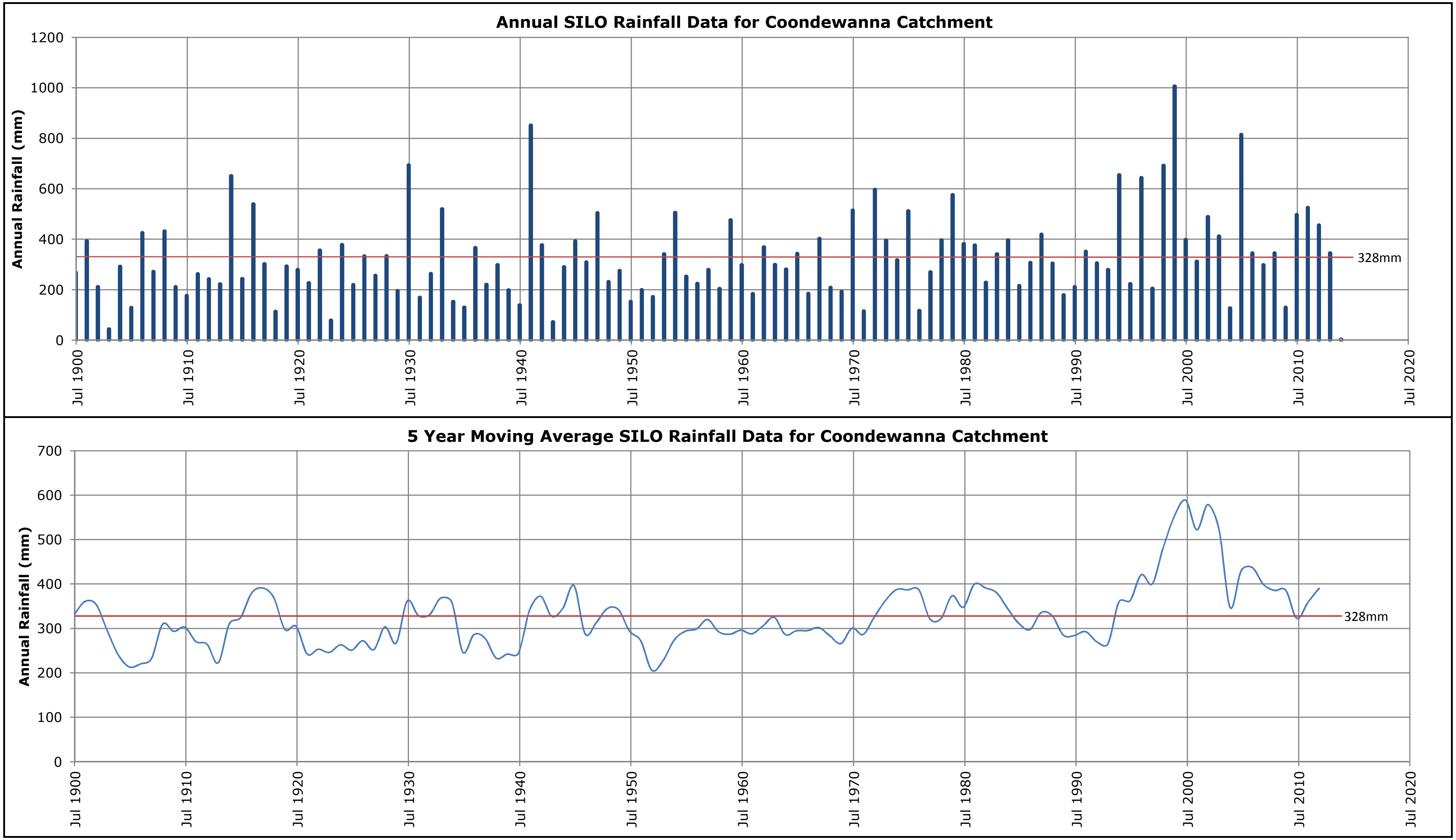
DATA SOURCES

Orthophoto - Landgate Mosaic, 2014. Land Types - Department of Agriculture, 2009

RPS

Figure 2

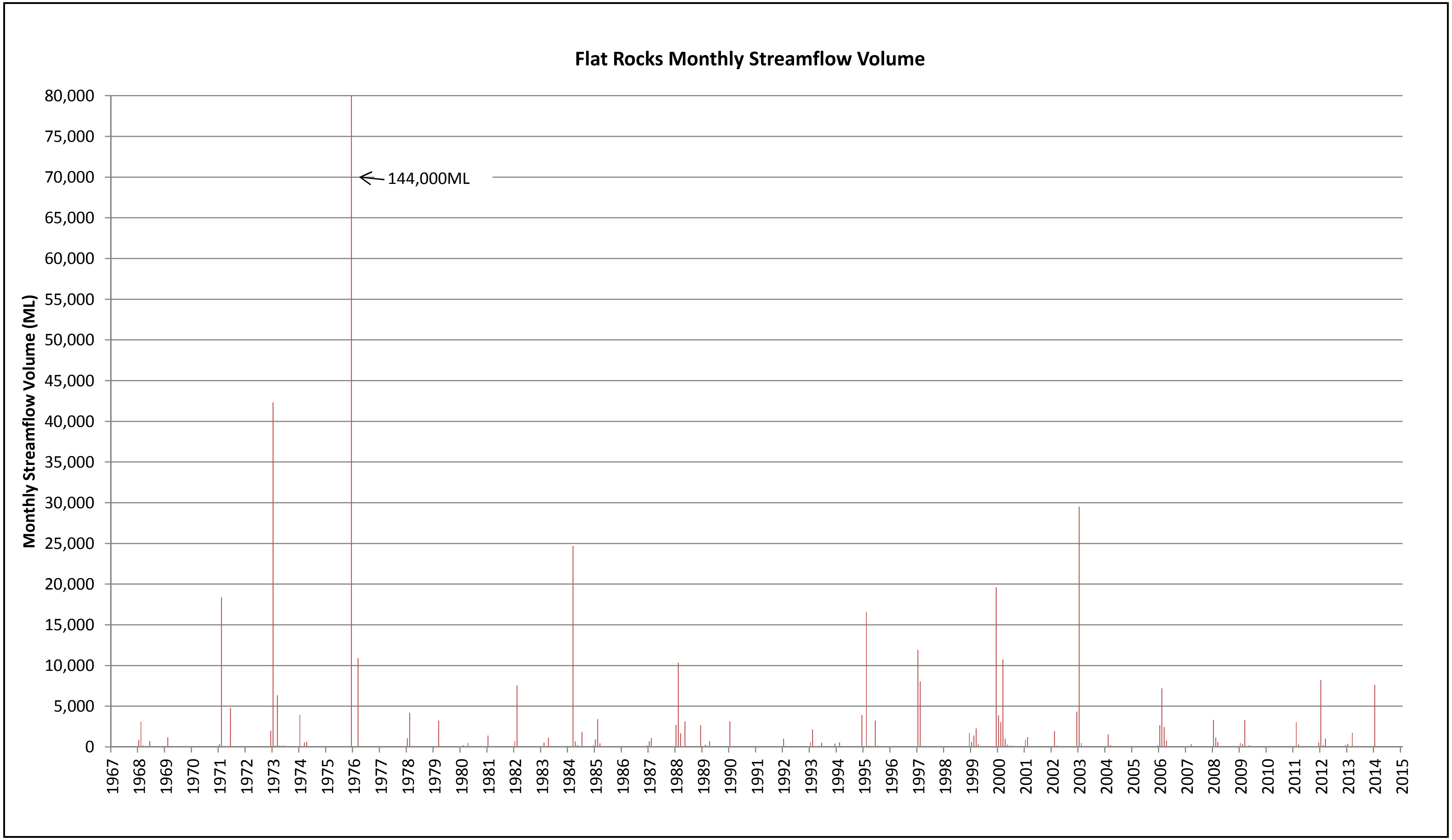
COONDEWANNA CATCHMENT LAND TYPES



RPS

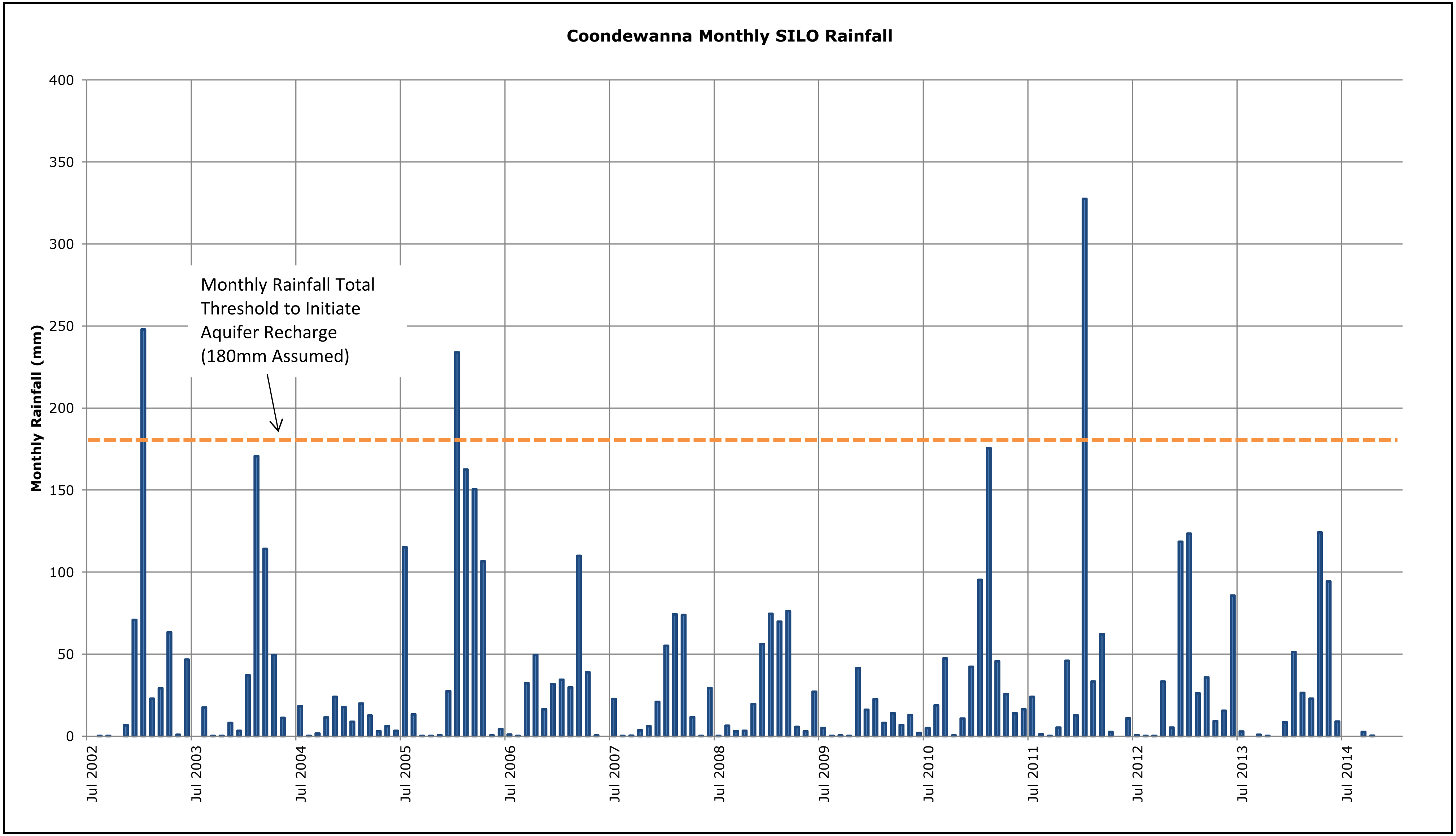
Coondewanna Catchment Annual Rainfall Data FIGURE 3

F:\Jobs\1733B\Report\[005a Figure 3.xls]005a Fig 3



Flat Rocks Monthly Runoff 1967 - 2014 FIGURE 4

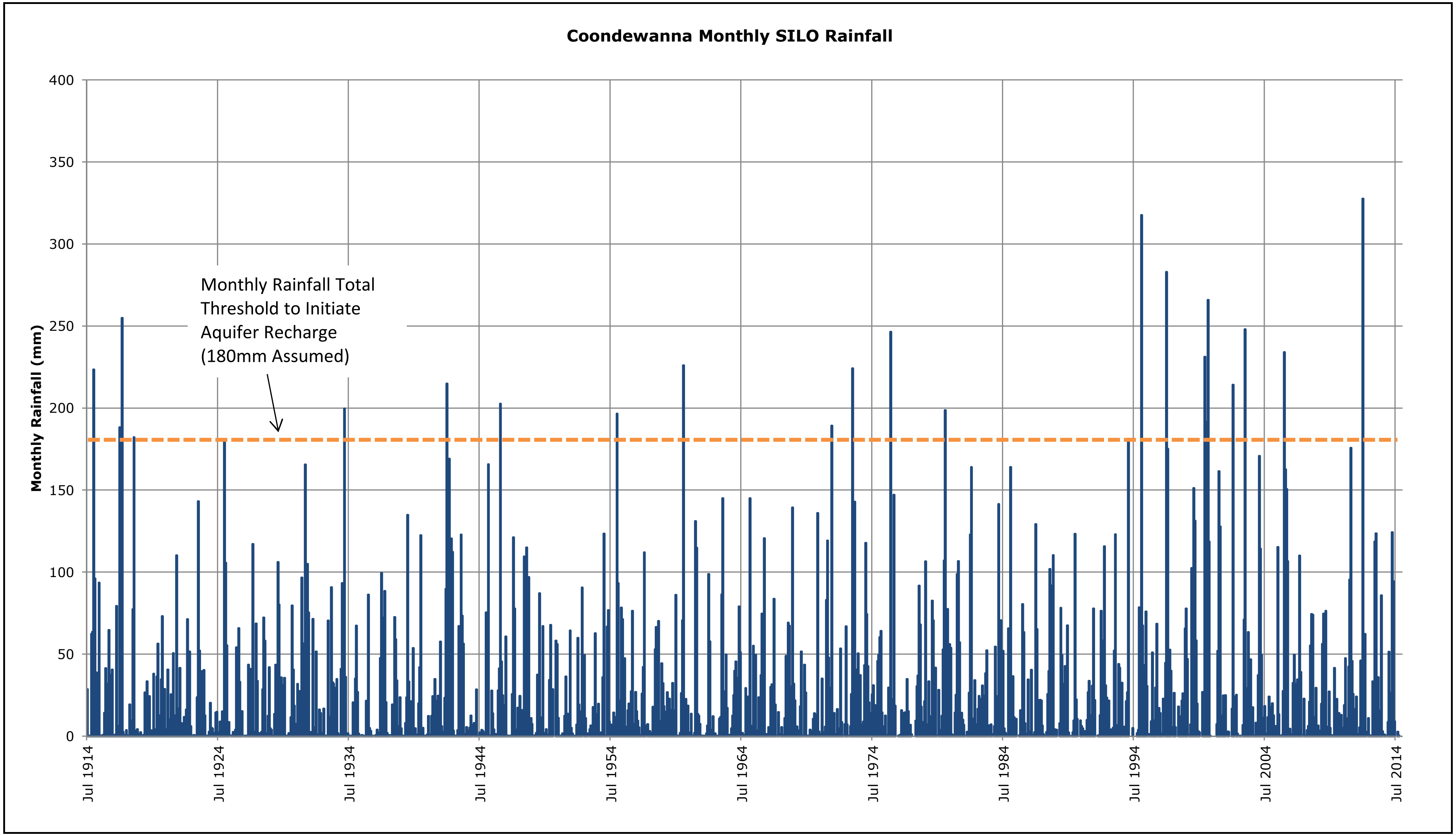
F:\Jobs\1733B\Calcs\[Flat Rocks Streamflow.xlsx]005a Fig 4



RPS

Coondewanna Catchment Monthly Rainfall 2002-2014 FIGURE 5

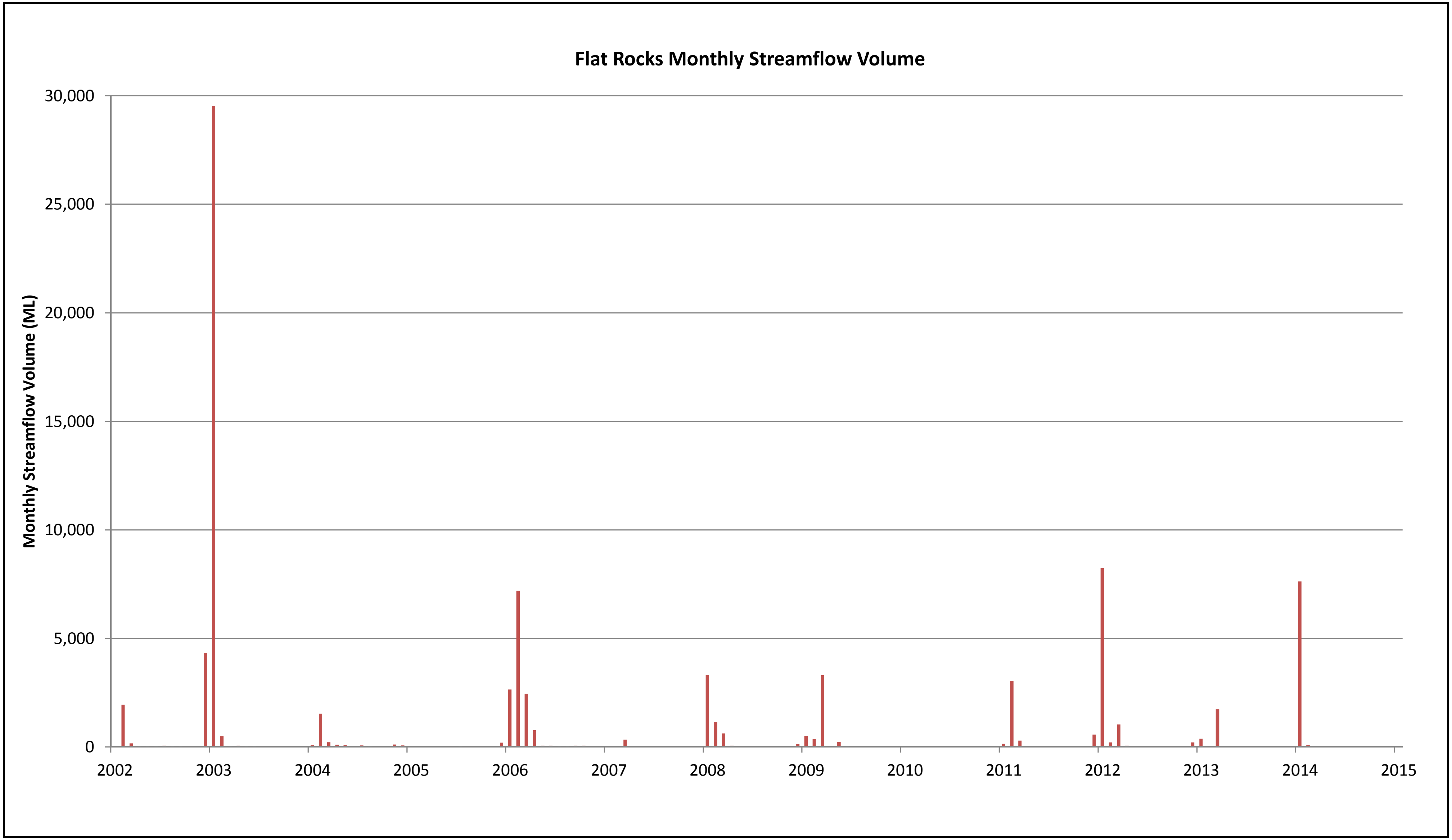
F:\Jobs\1733B\Calcs\[SILO Data - Coond Flats Catchment Centroid.xls]005a Fig 5



RPS

Coondewanna Catchment Monthly Rainfall 1914 - 2014 FIGURE 6

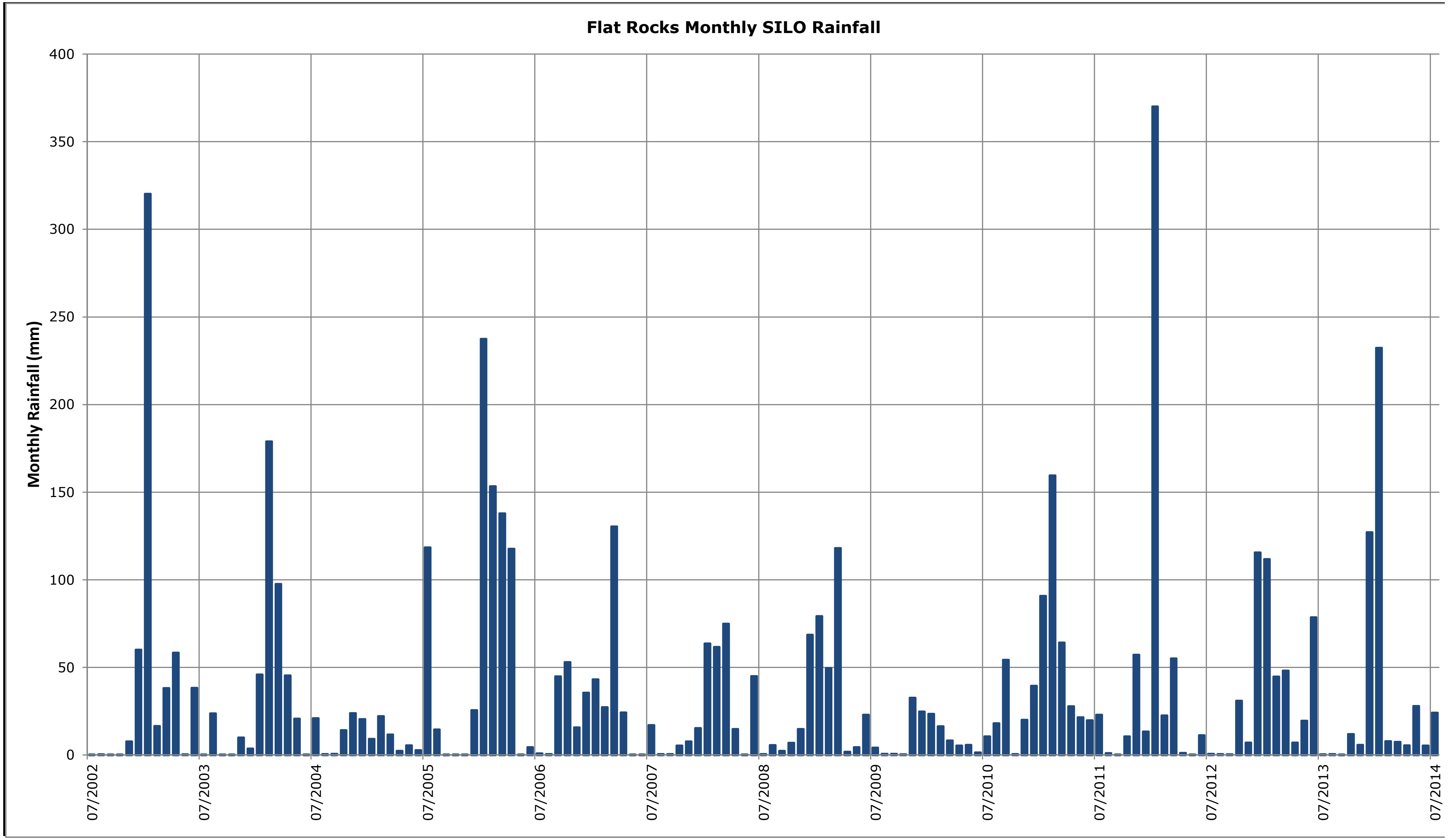
F:\Jobs\1733B\Calcs\[SILO Data - Coond Flats Catchment Centroid.xls]005a Fig 6



RPS

Flat Rocks Monthly Runoff 2002 - 2014 FIGURE 7

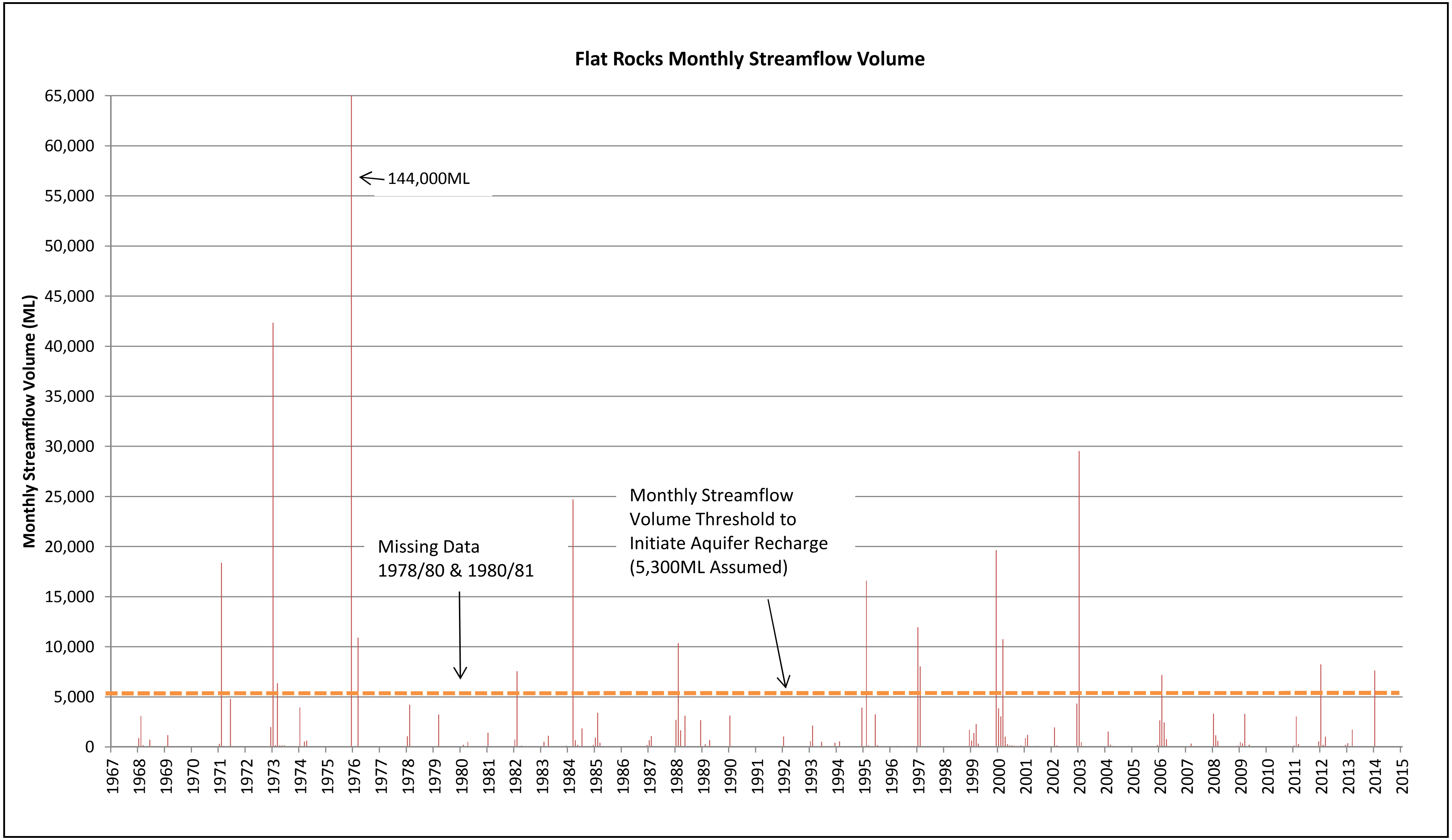
F:\Jobs\1733B\Calcs\[Flat Rocks Streamflow.xlsx]005a Fig 7



RPS

Flat Rocks Catchment Monthly Rainfall 2002 - 2014 FIGURE 8

F:\Jobs\1733B\Report\[005a Figure 8.xlsx]005a Fig 8



RPS

Flat Rocks Monthly Runoff 1967 - 2014 FIGURE 9

F:\Jobs\1733B\Calcs\[Flat Rocks Streamflow.xlsx]005a Fig 9

PLATES

RPS

LAKE ROBINSON INUNDATION (JANUARY 2012) PLATE 1

f:\jobs\1733b\report\005a plate 1.docx

APPENDIX 4

Chloride Balance Calculation

Chloride Balance - Outflow from Coondewanna Flats

Ref	Item	No.	Chloride Conc	Units	Remarks/Formula
	Concentrations				
1	Rainfall		0.5	mg/L	Hedley et al 2009
2	GW throughflow conc		43	mg/L	URS (2013) and average from ioWater
3	Surface Water Flood Concentration		0	mg/L	n/a - no surface water outflow
	Measured Parameters				
5	Catchment Area	860		km^2	RPS (2014)
6	rainfall	328		mm/yr	Longterm silo average (RPS 2014)
7	Rainfall Volume	282,080,000		m^3/year	6*5
8	Surface Water Outflow	0		m^3/year	n/a - no surface water outflow
	Chloride Movement				
9	Chloride inflow from rain		1.4104E+11	mg/year	1*5*6
10	Cl outflow - surface water flood		0.0000E+00	mg/year	8*3
	Unaccounted for Chloride - groundwater outflow				
11	(Cl rain) - (Cl surface water)		1.4104E+11	mg/year	9-10 Balance of Cl flux
	Water Balance				
12	**calculated GW outflow from Coondewanna Flats**	**8,980**		**m^3/d**	11/2; Volume required to remove (11)Cl at 43mg/L

Steady State Groundwater Balance

Coondewanna Flats

Feature	kL/d	Remarks
Groundwater Recharge		
GW Inflow from Mudlark/Tandanya	250	inflow through CID aquifer
Recharge on the FlatsAlluvial aquifer	11,000	CPH estimate
In direct recharge - remainder of catchment / soil moisture	0	accounted for in Cl balance
Total Groundwater Recharge	**11250**	
Groundwater Discharge		
ET - Coondewanna Vegetation	2270	Calculated by difference; exceeds theoretical max
Total Groundwater Outflow	8,980	Fixed from Cl balance
Total Groundwater Discharge	**11250**	
Water Balance Analysis - Coondewanna Flats		
Total recharge as % Rainfall	1.46%	cf CPH o/all estimate 0.8%
Phreatophytic area	6850020	sq.m
Riparian water Use	0.121	m

Chloride Balance - Outflow at Weeli Wolli

Ref	Item	No.	Chloride Conc	Units	Remarks/Formula
	Concentrations				
1	Rainfall		0.5	mg/L	
2	GW throughflow conc		75	mg/L	measured HD & MAC EIA
3	Surface Water Flood Concentration		6	mg/L	Based on data from EG/WW
4	Spring Flow Concentration		75	mg/L	measured HD & MAC EIA
	Measured Parameters				
5	Catchment Area	2307		km^2	RPS (2013)
6	rainfall	328		mm/yr	Longterm silo average (RPS 2014)
7	Rainfall Volume	756,696,000		m^3/year	6*5
8	Surface Water Outflow	13,500,000		m^3/year	Gauged at Weeli Wolli and Tarina
9	Spring Baseflow	7200		m^3/d	Gauged Weeli Wolli
	Chloride Movement				
10	Chloride inflow from rain		3.7835E+11	mg/year	1*5*6
11	Cl outflow - spring baseflow		1.9710E+11		9*4
12	Cl outflow - surface water flood		8.1000E+10	mg/year	8*3
	Unaccounted for Chloride - groundwater outflow				
13	(Cl rain) - (Cl surface water)		1.0025E+11	mg/year	10-11-12 Balance of Cl flux
	Water Balance				
14	**calculated GW outflow @ Spring**	**3,660**		**m^3/d**	13/2; Volume required to remove (13)Cl at 75mg/L

Steady State Groundwater Balance

Weeli Wolli Spring

Feature	kL/d	Remarks
Groundwater Recharge		
GW Inflow from Coondewanna	8980	inflow through CID aquifer
Recharge in the Weeli Wolli area	2,500	CPH estimate
In direct recharge - remainder of catchment / soil moisture	1189	0.3mm/yr
Total Groundwater Recharge	**12669**	
Groundwater Discharge		
ET - Weeli Wolli & Ben's Oasis	1810	Calculated by difference
Spring Baseflow	7,200	Estimated from hydrographs and guage
Groundwater throughflow	3,660	Fixed through Cl balance
Total Groundwater Discharge	**12669**	
Water Balance Analysis - Total Weeli Wolli Catchment		
Total recharge as % Rainfall	0.61%	Previous CPH Estimate 0.8%
Total Recharge	14939	Previous CPH Estimate 15000
ET loss	4080	kL/d across entire catchment
GW Outflow (spring and throughflow)	10,860	calculated
Phreatophytic area - Total	14350020	sq.m
Phreatophytic area - Weeli Wolli	7500000	sq.m
Riparian water Use - Total	0.104	m
Riparian water Use - Weeli Wolli	0.088	m

Notes:

a. Recharge at Coondewanna based on hydrograph analysis during SEA (RPS 2014)
b Outflow from Coondewanna constrained by Cl balance calculation
c Recharge at Weeli Wolli based on hydrograph analysis during SEA (RPS 2014)
d Outflows from catchment constrained by measured values and Cl balance calculation
e ET fluxes un-constrained and calculated by difference to remove "excess" water based on above

Chloride Balance - Outflow from Coondewanna Flats

Ref	Item	No.	Chloride Conc	Units	Remarks/Formula
	Concentrations				
1	Rainfall		0.5	mg/L	Hedley et al 2009
2	GW throughflow conc		43	mg/L	URS (2013) and average from ioWater
3	Surface Water Flood Concentration		0	mg/L	n/a - no surface water outflow
	Measured Parameters				
5	Catchment Area	860		km^2	RPS (2014)
6	rainfall	328		mm/yr	Longterm silo average (RPS 2014)
7	Rainfall Volume	282,080,000		m^3/year	6*5
8	Surface Water Outflow	0		m^3/year	n/a - no surface water outflow
	Chloride Movement				
9	Chloride inflow from rain		1.4104E+11	mg/year	1*5*6
10	Cl outflow - surface water flood		0.0000E+00	mg/year	8*3
	Unaccounted for Chloride - groundwater outflow				
11	(Cl rain) - (Cl surface water)		1.4104E+11	mg/year	9-10 Balance of Cl flux
	Water Balance				
12	**calculated GW outflow from Coondewanna Flats**	**8,980**		**m^3/d**	11/2; Volume required to remove (11)Cl at 43mg/L

Steady State Groundwater Balance

Coondewanna Flats

Feature	kL/d	Remarks
Groundwater Recharge		
GW Inflow from Mudlark/Tandanya	250	inflow through CID aquifer
Recharge on the FlatsAlluvial aquifer	11,000	CPH estimate
In direct recharge - remainder of catchment / soil moisture	0	accounted for in Cl balance
Total Groundwater Recharge	**11250**	
Groundwater Discharge		
ET - Coondewanna Vegetation	1070	Calculated by difference; exceeds theoretical max
Total Groundwater Outflow	10,180	Fixed from Cl balance
Total Groundwater Discharge	**11250**	
Water Balance Analysis - Coondewanna Flats		
Total recharge as % Rainfall	1.46%	cf CPH o/all estimate 0.8%
Phreatophytic area	6850020	sq.m
Riparian water Use	0.057	m

Chloride Balance - Outflow at Weeli Wolli

Ref	Item	No.	Chloride Conc	Units	Remarks/Formula
	Concentrations				
1	Rainfall		0.5	mg/L	
2	GW throughflow conc		75	mg/L	measured HD & MAC EIA
3	Surface Water Flood Concentration		6	mg/L	Based on data from EG/WW
4	Spring Flow Concentration		75	mg/L	measured HD & MAC EIA
	Measured Parameters				
5	Catchment Area	2307		km^2	RPS (2013)
6	rainfall	328		mm/yr	Longterm silo average (RPS 2014)
7	Rainfall Volume	756,696,000		m^3/year	6*5
8	Surface Water Outflow	13,500,000		m^3/year	Gauged at Weeli Wolli and Tarina
9	Spring Baseflow	7200		m^3/d	Gauged Weeli Wolli
	Chloride Movement				
10	Chloride inflow from rain		3.7835E+11	mg/year	1*5*6
11	Cl outflow - spring baseflow		1.9710E+11		9*4
12	Cl outflow - surface water flood		8.1000E+10	mg/year	8*3
	Unaccounted for Chloride - groundwater outflow				
13	(Cl rain) - (Cl surface water)		1.0025E+11	mg/year	10-11-12 Balance of Cl flux
	Water Balance				
14	**calculated GW outflow @ Spring**	**3,660**		**m^3/d**	13/2; Volume required to remove (13)Cl at 75mg/L

Steady State Groundwater Balance

Weeli Wolli Spring

Feature	kL/d	Remarks
Groundwater Recharge		
GW Inflow from Coondewanna	10180	inflow through CID aquifer
Recharge in the Weeli Wolli area	2,500	CPH estimate
In direct recharge - remainder of catchment / soil moisture	1189	0.3mm/yr
Total Groundwater Recharge	**13870**	
Groundwater Discharge		
ET - Weeli Wolli & Ben's Oasis	3010	Calculated by difference
Spring Baseflow	7,200	Estimated from hydrographs and guage
Groundwater throughflow	3,660	Fixed through Cl balance
Total Groundwater Discharge	**13870**	
Water Balance Analysis - Total Weeli Wolli Catchment		
Total recharge as % Rainfall	0.67%	Previous CPH Estimate 0.8%
Total Recharge	14939	Previous CPH Estimate 15000
ET loss	4080	kL/d across entire catchment
GW Outflow (spring and throughflow)	10,860	calculated
Phreatophytic area - Total	14350020	sq.m
Phreatophytic area - Weeli Wolli	7500000	sq.m
Riparian water Use - Total	0.104	m
Riparian water Use - Weeli Wolli	0.146	m

Notes:

a. Recharge at Coondewanna based on hydrograph analysis during SEA (RPS 2014)
b Outflow from Coondewanna unconstrained
c Recharge at Weeli Wolli based on hydrograph analysis during SEA (RPS 2014)
d Outflows from catchment constrained by measured values and Cl balance calculation
e ET flux at Weeli Wolli calculated by difference
f ET flux at Coondewanna based on maximum potential

Chloride Balance - Outflow from Coondewanna Flats

Ref	Item	No.	Chloride Conc	Units	Remarks/Formula
	Concentrations				
1	Rainfall		0.5	mg/L	Hedley et al 2009
2	GW throughflow conc		43	mg/L	URS (2013) and average from ioWater
3	Surface Water Flood Concentration		0	mg/L	n/a - no surface water outflow
	Measured Parameters				
5	Catchment Area	860		km^2	RPS (2014)
6	rainfall	328		mm/yr	Longterm silo average (RPS 2014)
7	Rainfall Volume	282,080,000		m^3/year	6*5
8	Surface Water Outflow	0		m^3/year	n/a - no surface water outflow
	Chloride Movement				
9	Chloride inflow from rain		1.4104E+11	mg/year	1*5*6
10	Cl outflow - surface water flood		0.0000E+00	mg/year	8*3
	Unaccounted for Chloride - groundwater outflow				
11	(Cl rain) - (Cl surface water)		1.4104E+11	mg/year	9-10 Balance of Cl flux
	Water Balance				
12	**calculated GW outflow from Coondewanna Flats**	**8,980**		**m^3/d**	11/2; Volume required to remove (11)Cl at 43mg/L

Steady State Groundwater Balance
Coondewanna Flats

Feature	kL/d	Remarks
Groundwater Recharge		
GW Inflow from Mudlark/Tandanya	1070	inflow through CID aquifer
Recharge on the FlatsAlluvial aquifer	9,500	CPH estimate
In direct recharge - remainder of catchment / soil moisture	0	accounted for in Cl balance
Total Groundwater Recharge	**10570**	
Groundwater Discharge		
ET - Coondewanna Vegetation	1070	Calculated by difference; exceeds theoretical max
Total Groundwater Outflow	9,500	Fixed from Cl balance
Total Groundwater Discharge	**10570**	
Water Balance Analysis - Coondewanna Flats		
Total recharge as % Rainfall	1.37%	cf CPH o/all estimate 0.8%
Phreatophytic area	6850020	sq.m
Riparian water Use	0.057	m

Chloride Balance - Outflow at Weeli Wolli

Ref	Item	No.	Chloride Conc	Units	Remarks/Formula
	Concentrations				
1	Rainfall		0.5	mg/L	
2	GW throughflow conc		75	mg/L	measured HD & MAC EIA
3	Surface Water Flood Concentration		6	mg/L	Based on data from EG/WW
4	Spring Flow Concentration		75	mg/L	measured HD & MAC EIA
	Measured Parameters				
5	Catchment Area	2307		km^2	RPS (2013)
6	rainfall	328		mm/yr	Longterm silo average (RPS 2014)
7	Rainfall Volume	756,696,000		m^3/year	6*5
8	Surface Water Outflow	13,500,000		m^3/year	Gauged at Weeli Wolli and Tarina
9	Spring Baseflow	7200		m^3/d	Gauged Weeli Wolli
	Chloride Movement				
10	Chloride inflow from rain		3.7835E+11	mg/year	1*5*6
11	Cl outflow - spring baseflow		1.9710E+11		9*4
12	Cl outflow - surface water flood		8.1000E+10	mg/year	8*3
	Unaccounted for Chloride - groundwater outflow				
13	(Cl rain) - (Cl surface water)		1.0025E+11	mg/year	10-11-12 Balance of Cl flux
	Water Balance				
14	**calculated GW outflow @ Spring**	**3,660**		**m^3/d**	13/2; Volume required to remove (13)Cl at 75mg/L

Steady State Groundwater Balance
Weeli Wolli Spring

Feature	kL/d	Remarks
Groundwater Recharge		
GW Inflow from Coondewanna	9500	inflow through CID aquifer
Recharge in the Weeli Wolli area	2,500	CPH estimate
In direct recharge - remainder of catchment / soil moisture	1189	0.3mm/yr
Total Groundwater Recharge	**13189**	
Groundwater Discharge		
ET - Weeli Wolli & Ben's Oasis	2330	Calculated by difference
Spring Baseflow	7,200	Estimated from hydrographs and guage
Groundwater throughflow	3,660	Fixed through Cl balance
Total Groundwater Discharge	**13189**	
Water Balance Analysis - Total Weeli Wolli Catchment		
Total recharge as % Rainfall	0.64%	Previous CPH Estimate 0.8%
Total Recharge	14259	Previous CPH Estimate 15000
ET loss	3400	kL/d across entire catchment
GW Outflow (spring and throughflow)	10,860	calculated
Phreatophytic area - Total	14350020	sq.m
Phreatophytic area - Weeli Wolli	7500000	sq.m
Riparian water Use - Total	0.086	m
Riparian water Use - Weeli Wolli	0.113	m

Notes:

a. Recharge at Coondewanna between SEA max and Cl balance
b Outflow from Coondewanna unconstrained
c Recharge at Weeli Wolli based on hydrograph analysis during SEA (RPS 2014)
d Outflows from catchment constrained by measured values and Cl balance calculation
e ET flux at Weeli Wolli calculated by difference
f ET flux at Coondewanna based on maximum potential

Chloride Balance - Outflow from Coondewanna Flats

Ref	Item	No.	Chloride Conc	Units	Remarks/Formula
	Concentrations				
1	Rainfall		0.5	mg/L	Hedley et al 2009
2	GW throughflow conc		43	mg/L	URS (2013) and average from ioWater
3	Surface Water Flood Concentration		0	mg/L	n/a - no surface water outflow
	Measured Parameters				
5	Catchment Area	860		km^2	RPS (2014)
6	rainfall	328		mm/yr	Longterm silo average (RPS 2014)
7	Rainfall Volume	282,080,000		m^3/year	6*5
8	Surface Water Outflow	0		m^3/year	n/a - no surface water outflow
	Chloride Movement				
9	Chloride inflow from rain		1.4104E+11	mg/year	1*5*6
10	Cl outflow - surface water flood		0.0000E+00	mg/year	8*3
	Unaccounted for Chloride - groundwater outflow				
11	(Cl rain) - (Cl surface water)		1.4104E+11	mg/year	9-10 Balance of Cl flux
	Water Balance				
12	**calculated GW outflow from Coondewanna Flats**	**8,980**		**m^3/d**	11/2; Volume required to remove (11)Cl at 43mg/L

Steady State Groundwater Balance

Coondewanna Flats

Feature	kL/d	Remarks
Groundwater Recharge		
GW Inflow from Mudlark/Tandanya	250	inflow through CID aquifer
Recharge on the FlatsAlluvial aquifer	9,500	CPH estimate
In direct recharge - remainder of catchment / soil moisture	0	accounted for in Cl balance
Total Groundwater Recharge	**9750**	
Groundwater Discharge		
ET - Coondewanna Vegetation	770	Calculated by difference; exceeds theoretical max
Total Groundwater Outflow	8,980	Fixed from Cl balance
Total Groundwater Discharge	**9750**	
Water Balance Analysis - Coondewanna Flats		
Total recharge as % Rainfall	1.26%	cf CPH o/all estimate 0.8%
Phreatophytic area	6850020	sq.m
Riparian water Use	0.041	m

Chloride Balance - Outflow at Weeli Wolli

Ref	Item	No.	Chloride Conc	Units	Remarks/Formula
	Concentrations				
1	Rainfall		0.5	mg/L	
2	GW throughflow conc		75	mg/L	measured HD & MAC EIA
3	Surface Water Flood Concentration		6	mg/L	Based on data from EG/WW
4	Spring Flow Concentration		75	mg/L	measured HD & MAC EIA
	Measured Parameters				
5	Catchment Area	2307		km^2	RPS (2013)
6	rainfall	328		mm/yr	Longterm silo average (RPS 2014)
7	Rainfall Volume	756,696,000		m^3/year	6*5
8	Surface Water Outflow	13,500,000		m^3/year	Gauged at Weeli Wolli and Tarina
9	Spring Baseflow	7200		m^3/d	Gauged Weeli Wolli
	Chloride Movement				
10	Chloride inflow from rain		3.7835E+11	mg/year	1*5*6
11	Cl outflow - spring baseflow		1.9710E+11		9*4
12	Cl outflow - surface water flood		8.1000E+10	mg/year	8*3
	Unaccounted for Chloride - groundwater outflow				
13	(Cl rain) - (Cl surface water)		1.0025E+11	mg/year	10-11-12 Balance of Cl flux
	Water Balance				
14	**calculated GW outflow @ Spring**	**3,660**		**m^3/d**	13/2; Volume required to remove (13)Cl at 75mg/L

Steady State Groundwater Balance

Weeli Wolli Spring

Feature	kL/d	Remarks
Groundwater Recharge		
GW Inflow from Coondewanna	8980	inflow through CID aquifer
Recharge in the Weeli Wolli area	2,500	CPH estimate
In direct recharge - remainder of catchment / soil moisture	1189	0.3mm/yr
Total Groundwater Recharge	**12669**	
Groundwater Discharge		
ET - Weeli Wolli & Ben's Oasis	1810	Calculated by difference
Spring Baseflow	7,200	Estimated from hydrographs and guage
Groundwater throughflow	3,660	Fixed through Cl balance
Total Groundwater Discharge	**12669**	
Water Balance Analysis - Total Weeli Wolli Catchment		
Total recharge as % Rainfall	0.61%	Previous CPH Estimate 0.8%
Total Recharge	13439	Previous CPH Estimate 15000
ET loss	2580	kL/d across entire catchment
GW Outflow (spring and throughflow)	10,860	calculated
Phreatophytic area - Total	14350020	sq.m
Phreatophytic area - Weeli Wolli	7500000	sq.m
Riparian water Use - Total	0.066	m
Riparian water Use - Weeli Wolli	0.088	m

Notes:

a. Recharge at Coondewanna between SEA max and Cl balance
b Outflow from Coondewanna constrained by Cl balance calculation
c Recharge at Weeli Wolli based on hydrograph analysis during SEA (RPS 2014)
d Outflows from catchment constrained by measured values and Cl balance calculation
e ET flux at Weeli Wolli calculated by difference
f ET flux at Coondewanna calculated by difference

Chloride Balance - Outflow from Coondewanna Flats

Ref	Item	No.	Chloride Conc	Units	Remarks/Formula
	Concentrations				
1	Rainfall		0.5	mg/L	Hedley et al 2009
2	GW throughflow conc		43	mg/L	URS (2013) and average from ioWater
3	Surface Water Flood Concentration		0	mg/L	n/a - no surface water outflow
	Measured Parameters				
5	Catchment Area	860		km^2	RPS (2014)
6	rainfall	328		mm/yr	Longterm silo average (RPS 2014)
7	Rainfall Volume	282,080,000		m^3/year	6*5
8	Surface Water Outflow	0		m^3/year	n/a - no surface water outflow
	Chloride Movement				
9	Chloride inflow from rain		1.4104E+11	mg/year	1*5*6
10	Cl outflow - surface water flood		0.0000E+00	mg/year	8*3
	Unaccounted for Chloride - groundwater outflow				
11	(Cl rain) - (Cl surface water)		1.4104E+11	mg/year	9-10 Balance of Cl flux
	Water Balance				
12	**calculated GW outflow from Coondewanna Flats**	**8,980**		**m^3/d**	11/2; Volume required to remove (11)Cl at 43mg/L

Steady State Groundwater Balance
Coondewanna Flats

Feature	kL/d	Remarks
Groundwater Recharge		
GW Inflow from Mudlark/Tandanya	250	inflow through CID aquifer
Recharge on the FlatsAlluvial aquifer	8,980	CPH estimate
In direct recharge - remainder of catchment / soil moisture	0	accounted for in Cl balance
Total Groundwater Recharge	**9230**	
Groundwater Discharge		
ET - Coondewanna Vegetation	0	Calculated by difference; exceeds theoretical max
Total Groundwater Outflow	9,230	Fixed from Cl balance
Total Groundwater Discharge	**9230**	
Water Balance Analysis - Coondewanna Flats		
Total recharge as % Rainfall	1.19%	cf CPH o/all estimate 0.8%
Phreatophytic area	6850020	sq.m
Riparian water Use	0.000	m

Chloride Balance - Outflow at Weeli Wolli

Ref	Item	No.	Chloride Conc	Units	Remarks/Formula
	Concentrations				
1	Rainfall		0.5	mg/L	
2	GW throughflow conc		75	mg/L	measured HD & MAC EIA
3	Surface Water Flood Concentration		6	mg/L	Based on data from EG/WW
4	Spring Flow Concentration		75	mg/L	measured HD & MAC EIA
	Measured Parameters				
5	Catchment Area	2307		km^2	RPS (2013)
6	rainfall	328		mm/yr	Longterm silo average (RPS 2014)
7	Rainfall Volume	756,696,000		m^3/year	6*5
8	Surface Water Outflow	13,500,000		m^3/year	Gauged at Weeli Wolli and Tarina
9	Spring Baseflow	7200		m^3/d	Gauged Weeli Wolli
	Chloride Movement				
10	Chloride inflow from rain		3.7835E+11	mg/year	1*5*6
11	Cl outflow - spring baseflow		1.9710E+11		9*4
12	Cl outflow - surface water flood		8.1000E+10	mg/year	8*3
	Unaccounted for Chloride - groundwater outflow				
13	(Cl rain) - (Cl surface water)		1.0025E+11	mg/year	10-11-12 Balance of Cl flux
	Water Balance				
14	**calculated GW outflow @ Spring**	**3,660**		**m^3/d**	13/2; Volume required to remove (13)Cl at 75mg/L

Steady State Groundwater Balance
Weeli Wolli Spring

Feature	kL/d	Remarks
Groundwater Recharge		
GW Inflow from Coondewanna	9230	inflow through CID aquifer
Recharge in the Weeli Wolli area	2,500	CPH estimate
In direct recharge - remainder of catchment / soil moisture	1189	0.3mm/yr
Total Groundwater Recharge	**12919**	
Groundwater Discharge		
ET - Weeli Wolli & Ben's Oasis	2060	Calculated by difference
Spring Baseflow	7,200	Estimated from hydrographs and guage
Groundwater throughflow	3,660	Fixed through Cl balance
Total Groundwater Discharge	**12919**	
Water Balance Analysis - Total Weeli Wolli Catchment		
Total recharge as % Rainfall	0.62%	Previous CPH Estimate 0.8%
Total Recharge	12919	Previous CPH Estimate 15000
ET loss	2060	kL/d across entire catchment
GW Outflow (spring and throughflow)	10,860	calculated
Phreatophytic area - Total	14350020	sq.m
Phreatophytic area - Weeli Wolli	7500000	sq.m
Riparian water Use - Total	0.052	m
Riparian water Use - Weeli Wolli	0.100	m

Notes:

a. Recharge at Coondewanna based on Cl balance
b Outflow from Coondewanna unconstrained
c Recharge at Weeli Wolli based on hydrograph analysis during SEA (RPS 2014)
d Outflows from catchment constrained by measured values and Cl balance calculation
e ET flux at Weeli Wolli calculated by difference
f Zero flux at Coondewanna calculated by difference

Chloride Balance - Outflow from Coondewanna Flats

Ref	Item	No.	Chloride Conc	Units	Remarks/Formula
	Concentrations				
1	Rainfall		0.5	mg/L	Hedley et al 2009
2	GW throughflow conc		43	mg/L	URS (2013) and average from ioWater
3	Surface Water Flood Concentration		0	mg/L	n/a - no surface water outflow
	Measured Parameters				
5	Catchment Area	860		km^2	RPS (2014)
6	rainfall	328		mm/yr	Longterm silo average (RPS 2014)
7	Rainfall Volume	282,080,000		m^3/year	6*5
8	Surface Water Outflow	0		m^3/year	n/a - no surface water outflow
	Chloride Movement				
9	Chloride inflow from rain		1.4104E+11	mg/year	1*5*6
10	Cl outflow - surface water flood		0.0000E+00	mg/year	8*3
	Unaccounted for Chloride - groundwater outflow				
11	(Cl rain) - (Cl surface water)		1.4104E+11	mg/year	9-10 Balance of Cl flux
	Water Balance				
12	**calculated GW outflow from Coondewanna Flats**	**8,980**		**m^3/d**	11/2; Volume required to remove (11)Cl at 43mg/L

Steady State Groundwater Balance

Coondewanna Flats

Feature	kL/d	Remarks
Groundwater Recharge		
GW Inflow from Mudlark/Tandanya	250	inflow through CID aquifer
Recharge on the FlatsAlluvial aquifer	8,730	total outlfow Cl balance; calc by difference
In direct recharge - remainder of catchment / soil moisture	0	accounted for in Cl balance
Total Groundwater Recharge	**8980**	
Groundwater Discharge		
ET - Coondewanna Vegetation	0	Calculated by difference; exceeds theoretical max
Total Groundwater Outflow	8,980	Fixed from Cl balance
Total Groundwater Discharge	**8980**	
Water Balance Analysis - Coondewanna Flats		
Total recharge as % Rainfall	1.16%	cf CPH o/all estimate 0.8%
Phreatophytic area	6850020	sq.m
Riparian water Use	0.000	m

Chloride Balance - Outflow at Weeli Wolli

Ref	Item	No.	Chloride Conc	Units	Remarks/Formula
	Concentrations				
1	Rainfall		0.5	mg/L	
2	GW throughflow conc		75	mg/L	measured HD & MAC EIA
3	Surface Water Flood Concentration		6	mg/L	Based on data from EG/WW
4	Spring Flow Concentration		75	mg/L	measured HD & MAC EIA
	Measured Parameters				
5	Catchment Area	2307		km^2	RPS (2013)
6	rainfall	328		mm/yr	Longterm silo average (RPS 2014)
7	Rainfall Volume	756,696,000		m^3/year	6*5
8	Surface Water Outflow	13,500,000		m^3/year	Gauged at Weeli Wolli and Tarina
9	Spring Baseflow	7200		m^3/d	Gauged Weeli Wolli
	Chloride Movement				
10	Chloride inflow from rain		3.7835E+11	mg/year	1*5*6
11	Cl outflow - spring baseflow		1.9710E+11		9*4
12	Cl outflow - surface water flood		8.1000E+10	mg/year	8*3
	Unaccounted for Chloride - groundwater outflow				
13	(Cl rain) - (Cl surface water)		1.0025E+11	mg/year	10-11-12 Balance of Cl flux
	Water Balance				
14	**calculated GW outflow @ Spring**	**3,660**		**m^3/d**	13/2; Volume required to remove (13)Cl at 75mg/L

Steady State Groundwater Balance

Weeli Wolli Spring

Feature	kL/d	Remarks
Groundwater Recharge		
GW Inflow from Coondewanna	8980	inflow through CID aquifer
Recharge in the Weeli Wolli area	2,500	CPH estimate
In direct recharge - remainder of catchment / soil moisture	1189	0.3mm/yr
Total Groundwater Recharge	**12669**	
Groundwater Discharge		
ET - Weeli Wolli & Ben's Oasis	1810	Calculated by difference
Spring Baseflow	7,200	Estimated from hydrographs and guage
Groundwater throughflow	3,660	Fixed through Cl balance
Total Groundwater Discharge	**12669**	
Water Balance Analysis - Total Weeli Wolli Catchment		
Total recharge as % Rainfall	0.61%	Previous CPH Estimate 0.8%
Total Recharge	12669	Previous CPH Estimate 15000
ET loss	1810	kL/d across entire catchment
GW Outflow (spring and throughflow)	10,860	calculated
Phreatophytic area - Total	14350020	sq.m
Phreatophytic area - Weeli Wolli	7500000	sq.m
Riparian water Use - Total	0.046	m
Riparian water Use - Weeli Wolli	0.088	m

Notes:

a. Recharge at Coondewanna based on Cl balance
b Outflow from Coondewanna constrained by Cl balance calculation
c Recharge at Weeli Wolli based on hydrograph analysis during SEA (RPS 2014)
d Outflows from catchment constrained by measured values and Cl balance calculation
e ET flux at Weeli Wolli calculated by difference
f Zero flux at Coondewanna calculated by difference