Groundwater contribution to nutrient export from the Ellen Brook catchment

Olga Barron, Mike Donn, Susan Furby, Joanne Chia and Chris Johnstone

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Cover Photograph
Description: Inflow to nutrient stripping pond located on a western tributary to Ellen Brook (site number EBN14). Photo taken on 11th September 2008 during Ellen Brook snapshot sampling conducted by the Western Australian Department of Water and Ellen Brockman Integrated Catchment Group.
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EXECUTIVE SUMMARY

The Department of Water has identified the Ellen Brook catchment as one of the highest contributors of nitrogen and phosphorus to the Swan-Canning Estuary. It is believed that the main sources of nutrients in the catchment are associated with current and historical land use activities such as fertilisers, animal waste and soil-bound nutrients. The reported research, conducted between September 2007 and September 2008, was predominantly focused on the groundwater component of the water balance and baseflow in the Ellen Brook catchment. The effects of surface and, particularly, groundwater hydrology on nitrogen and phosphorus export from the catchment are still the subject of ongoing investigation; furthermore, the influence of groundwater and wetlands on the surface water regime is particularly uncertain.

Project aims and methods

The main goal of the project was to develop a conceptual groundwater model of the Ellen Brook catchment to improve understanding of the connectivity and travel times of water and nutrients in groundwater systems from different parts of the catchment, as well as their interaction with surface waters. The study area was delimited by the surface water catchment of Ellen Brook. Indirect indicators were used to identify the groundwater contribution to Ellen Brook, including analysis of baseflow, groundwater residence time and remotely sensed data to delineate groundwater discharge zones.

Review and analysis of water flow and quality data were conducted for the surface and groundwater of the Ellen Brook catchment. This was complemented with some additional field work designed to further understand the hydrogeological characteristics of the system.

Key findings from the project

Definition of the groundwater systems

The groundwater systems in the Ellen Brook catchment which are likely to influence river flow and (or) water quality at least during some period of an annual hydrological cycle may be grouped into six hydrogeological units.

- Gnangara Dune system
- Dandaragan Plateau
- Northern Dunes sub-catchment
- Ellen Brook valley
- Lower Ellen Brook sub-catchment
- Eastern sub-catchment

The extent of the units was only indicative and will require further clarification by more detailed spatial analysis, which was outside the current project scope. The preliminary delineation of the units was based on surface geology map, DEM analysis and interpretation of available monitoring data.

Groundwater discharge

Contribution of groundwater discharge to the river flow is most significant in two areas:

- the streams draining Dandaragan Plateau, particularly during winter months when discharge is contributing to surface inundation in the northern Ellen Brook sub-catchment
- the lower reaches of Ellen Brook during summer and autumn months (when groundwater is a sole source for the river flow). During other times,
Groundwater contribution at this location comprises a small portion of total river flow.

On an annual basis, baseflow accounts for (on average) 42% of annual river discharge. This percentage may be up to 57% during drier years and 31% in wetter years. Most of the baseflow (more than 80%) is generated in the northern sub-catchment. High baseflow rates are controlled by:

- substantial flow contribution from the streams draining Dandaragan Plateau (up to 17GL/year)
- surface inundation due to flat landscape and shallow groundwater occurrence within the river valley in the north
- some input of the local groundwater.

The northern sub-catchment also generates a large proportion of the total river flow, e.g. more than 50% of annual flow in 1992.

Groundwater discharge to the river in the southern sub-catchment is low and likely to be less than the potential evaporative losses estimated at 5000 ML/day during the spring baseflow period in 2007. This also confirms that the occurrence of Guilford clay provides a regional confining layer, restricting groundwater discharge from the deeper Superficial Aquifer to Ellen Brook and its tributaries.

In some areas groundwater discharge is continuous; however, discharge rates are not great enough to sustain continuous flow in the streams. The permanent presence of water, however, supports flourishing flora and fauna, which then influences the biological and chemical processes within the hypothetic zones and maintains the environment where organic matter and nutrient accumulation occurs. Such areas also attract human settlements and agricultural activities. The areas include:

a. the upper reaches of the western tributaries, receiving groundwater discharge from the Gnangara Dunes
b. the break in the slope areas along the northern hills sub-catchment at the foothill of Dandaragan Plateau.

These areas were delineated using the results of Landsat 7 data interpretation. This was proven to be a promising technique for groundwater discharge delineation, but will require further validation with on-ground information to support the interpretation of Landsat images.

Groundwater fluxes in these areas can promote surface primary productivity, influence sediment microbial activity and affect organic matter decomposition. This explains the high concentrations of dissolved organic carbon (DOC) and total organic nitrogen (TON) in the creeks downstream from these areas.

**Nutrient concentrations**

Groundwater contribution to nutrient load in Ellen Brook is suggested to be related to two factors:

- the contribution of groundwater discharge to baseflow
- the effect on the processes controlling nutrient accumulation and release to the water column in the areas where groundwater discharge is continuous throughout the year.

Nutrient concentrations in surface water during baseflow are lower than during peak flow. The nitrogen and phosphorus in surface water during baseflow appear to come from different sources. Total nitrogen is mainly associated with sources that generate dissolved organic carbon. Phosphorus, however, is not closely related to DOC.
Nutrient concentrations in the regional groundwater are generally low. The regional groundwater residence time is greater than 30-40 years and groundwater quality is unlikely to be significantly influenced by current land use activities.

Shallow groundwater in the areas of sand occurrence, such as in the northern sub-catchment, is likely to have high concentrations of phosphorous and organic nitrogen.

High nitrate concentration is detected in the Lennard Brook but not in the Ellen Brook. It is likely to be depleted from the water due to the denitrification processes in the waterlogged areas in the northern sub-catchment characterised by high organic carbon and anaerobic conditions.

**Future work**

A number of future research activities may advance the knowledge of nutrients transfer in the Ellen Brook catchment:

1. Identify the water balance and nutrient budget in the areas receiving groundwater discharge which potentially provide a substantial contribution on DOC and TON to the river load
2. Further validation of Landsat 7 data interpretation in relation to delineation of the groundwater discharge zones
3. Detailed studies of the groundwater fluxes in the northern sub-catchment which currently contributes large proportion of the annual river discharge
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1. INTRODUCTION

1.1. General

The Department of Water has identified the Ellen Brook Catchment as one of the highest contributors of nitrogen and phosphorus to the Swan-Canning Estuary. It is believed that the main sources of nutrients in the catchment include fertilisers, animal waste and soil-bound nutrients associated with the current and historical land use activities. However, the effects of surface and particularly groundwater hydrology on nitrogen and phosphorus export from the catchment are not well defined.

Ellen Brook is an ephemeral river with no flow recorded during summer and early autumn months. A large part of the catchment is inundated in the winter and spring either through rising regional groundwater levels or waterlogging of soils with low permeability. The influence of groundwater and wetlands on the surface water regime is particularly uncertain. The current research undertaken between September 2007 and September 2008 was predominantly focused on the groundwater component of the catchment water balance and baseflow in Ellen Brook.

In this section, the characteristics of the Ellen Brook catchment are described, data on water quality based on the literature is reported, and the project objectives and scope are described.

1.2. Project objectives and scope

The influence of groundwater and wetlands on the surface water regime is particularly uncertain. The most current research, undertaken between September 2007 and September 2008, was predominantly focused on the groundwater component of the catchment water balance and baseflow in Ellen Brook.

The Department of Water has identified the Ellen Brook catchment as one of the highest contributors of nitrogen (N) and phosphorus (P) to the Swan-Canning Estuary (Swan River Trust, 2009). It is believed that the main sources of nutrients in the catchment include fertilisers, animal waste and soil-bound nutrients associated with the current and historical land use activities. However, the effects of surface and particularly groundwater hydrology on N and P export from the catchment are not well-defined.

The main goal of the project was to develop a conceptual groundwater model of the Ellen Brook catchment to improve understanding of the connectivity and travel times of water and nutrients in groundwater systems from different parts of the catchment as well as their interaction with surface waters. The study area was delimited by the surface water catchment of Ellen Brook.

There are three questions of particular interest:

- What is the groundwater contribution (fluxes) to the Ellen Brook flow?
- What is the groundwater quality (particularly nutrients) within the Ellen Brook catchment?
- If the above are reasonably high, what is the residence time of groundwater and when may a possible change in land use practice influence nutrient loads received by the river through groundwater discharge?

The scope of research activities consisted of:

- interpreting available information on river flow and water quality
monitoring of stream flow and water quality monitoring during the spring and summer 2007-2008 baseflow period at a number of selected locations

- groundwater sampling for residence time analysis in selected available bores
- interpreting remotely sensed data.

1.3. Catchment location and available data

The Ellen Brook catchment is located 25 km east from the coastline of Western Australia. The surface water catchment area of Ellen Brook is 715 km², approximately 50 km long north-to-south (Figure 1-1). Ellen Brook drains both the hills in the east, with a maximum surface elevation of 270 m AHD, and the large dunes system in the west at 130 m AHD which flows south along flat terrains, joining the Swan River near Belhus at less than 5 m AHD. The three major physiographic units in the Ellen Brook catchment are the Swan Coastal Plain in the west, the uplands of the Dandaragan Plateau in the north and northeast, and the Darling Plateau in the east (Figure 1-2) (Shams and Smith, 2001). Many seasonal creeks flow eastward into the Ellen Brook and dissect the Pinjarra Plain. The Dandaragan Plateau is dissected by several perennial brooks which flow west and south-west into Ellen Brook. The Darling Plateau is drained by seasonal streams which flow west into Ellen Brook.

Land use is predominantly related to agriculture including livestock, vineyards, some horticulture and irrigated agriculture. The area also contains a few quarries and mining operations, and a number of urban developments.

Figure 1-1 Location map (courtesy of WA Department of Water)
There are some observation locations where surface water and groundwater are currently monitored by the Western Australia Department of Water and local natural resource management (NRM) groups (Figure 1-3 and Figure 1-4). These include the:

- gauging station at the outflow from the catchment (Railway Parade, 616189), where river discharge has been recorded since 1966 with reported accuracy of approximately 20%. Water quality in Ellen Brook at this station has been studied throughout the years
- gauging station at Lennard Brook (Molecap Hill, 617165), where river discharge has been recorded between 1962 and 2001
- Chittering Landcare Group surface water monitoring sites (Figure 1.3, 2005-2008), where samples have been collected for nutrient analysis
- groundwater monitoring bores reported to WIN database (predominantly Gnangara mound monitoring bores; (Figure 1-4). Groundwater monitoring was predominantly focused on groundwater levels and hydraulic heads. In some cases data were available over a period since the 1970s. Only limited data are available for groundwater quality data

In the following sections of the report we outlined the project methodology (section 2), provided information and data analysis supporting characterisation of the catchment hydrological and hydrogeological condition (section 3) and water quality (section 4). These allowed definition of the major hydrogeological units and definition of the conceptual groundwater model parameters.
Groundwater contribution to nutrient export from the Ellen Brook catchment

Figure 1-2 Surface geology map and surface water network (courtesy of WA Department of Water)
Figure 1-3 Surface water monitoring sites including stream gauge sites and Chittering Landcare Group sites (Data extracted from WIN database)
Figure 1-4 Groundwater sampling sites based on data extracted from the WIN database

Groundwater contribution to nutrient export from the Ellen Brook catchment
1.4. Nutrients in the Ellen Brook catchment

Water quality in Ellen Brook and its catchment has been investigated for a few decades. Ellen Brook contributes the highest amount of nutrients to Swan Estuary after Avon River; therefore, recent research has focused on the dynamics and sources of nutrients in surface water. A brief summary of the findings from the literature review is given below. More details are provided in Appendix 1.

1.4.1. Surface water

As outlined below, nutrient concentrations and nutrient speciation in surface water are highly variable throughout the Ellen Brook catchment. To the north-east of the catchment (Lennard Brook), horticultural fertilisers are the main nutrient sources, resulting in high inorganic nitrogen concentrations in the Lennard Brook with nitrate (NO$_3^{-}$) concentrations reaching up to 2 mg/L (Sharma et al, 1993). However P concentrations remain low with total phosphorus (TP) and soluble reactive phosphorus (SRP) both less than 0.1 mg/L (Sharma et al, 1994).

Average total nitrogen (TN) concentrations are generally consistent between Lennard Brook (1.3-1.6 mg/L; Sharma et al, 1993) and the gauging station (1.68-1.88 mg/L; Donohue, 1994); the speciation, however, changes from NO$_3^{-}$ dominant to dissolved organic nitrogen (DON) dominant. Average total phosphorus (TP) concentrations increase from <0.1 mg/L to 3.8 mg/L between Lennard Brook and the middle reaches of Ellen Brook (Sharma et al, 1994; Donohue, 1994; Horwood, 1997).

Daily measurements indicate that NO$_3^{-}$ and SRP concentrations in Ellen Brook’s main channel are strongly dependent on flow, which rises sharply with storm flow and declines during the flow recession (Sharma et al, 1996). This was attributed to greater interaction of surface runoff with the nutrient-rich soils during storm flow (Sharma et al, 1996). The SRP concentrations in the baseflow also vary seasonally, with higher concentrations in the mid-winter baseflow (0.3-0.5 mg/L) and lower concentrations in late winter baseflow (0.1-0.2 mg/L; Sharma et al, 1996). Sharma et al (1996) suggested that this was due to the change in the proportion of surface runoff to groundwater, with surface runoff being greater during the mid-winter period.

In the middle to lower reaches, the tributaries to the east and west of the Ellen Brook main channel have markedly different nutrient compositions (Donohue, 1994; Sharma et al., 1996; Horwood, 1997; Shams and Smith, 2001). The surface water draining from western subcatchments are characterised by high N and P concentrations (predominantly as DON and SRP), high dissolved organic carbon (DOC) and low salinity. In contrast, the eastern tributaries have high salinity, low P concentrations and a greater proportion of inorganic N (NO$_3^{-}$ plus ammonium).

1.4.2. Groundwater

Groundwater nutrient studies are limited to areas to the west of Ellen Brook, with studies conducted in both the areas of Bassendean Sand and Guildford Clay occurrences. The soils in these areas have limited capacity to retain P, especially the Bassendean Sands (Gerritse, 1994; Gerritse et al, 1995; Sharma et al, 1996). Similarly, high dissolved organic matter C:N ratios (20:40) have been observed in both Bassendean Sand leachates (Gerritse, 1994) and Ellen Brook surface water (Gerritse, 1994; Shams and Smith, 2001) indicating that soil organic matter is the probable source of DOC and DON in the surface water. Gerritse (1994) also suggested that the leaching of historical soil organic matter stores (accumulated under native vegetation) was a possible source of DOC and DON to the groundwater.
Nutrient concentrations in the shallow Superficial Aquifer, which has a depth to the water table of 1-7 m under horticultural areas within the Bassendean soil occurrence, can be significant due to fertiliser application (up to 38 mg/L TP and 100 mg/L NO$_3$; Lantzke 1997). However, the transport of fertiliser nutrients to the deeper aquifer is limited, possibly due to the adsorption of phosphate in impervious iron-cemented sands (coffee rock) and the high denitrification potential of the shallow aquifer (Lantzke, 1997).

West of the Ellen Brook main channel, in areas where the Guildford Clay formation is present, groundwater P concentrations tend to be lower than those observed in the seasonal creeks and the drains west of Ellen Brook (Sharma et al., 1993; Sharma et al., 1994; Shams and Smith, 2001). Phosphorus concentrations in the shallow groundwater within the Guildford Clay Formation are reported to be lower than those observed in the deeper groundwater (Shams and Smith, 2001). However, the high P concentrations in the deeper groundwater may be related to the high extractable P in the aquifer materials as observed by Shams and Smith (2001), rather than leaching of P fertiliser from the surface. Meanwhile, TN concentrations are higher in the shallow groundwater than in the seasonal creeks and drains (Sharma et al., 1993; Sharma et al., 1994; Shams and Smith, 2001). Nitrate is dominant (though highly variable) in the shallow groundwater while DON is dominant in the deeper groundwater (Shams and Smith, 2001). Groundwater nutrient concentrations to the east of the Ellen Brook main channel were not reported.

### 1.4.3 Conclusions on surface water and groundwater studies

Overall, surface water and groundwater studies reported in the literature predominantly focus on the middle and lower Ellen Brook catchment and also the Lennard Brook catchment which drains Dandaragan Plateau. Surface water quality, in terms of nutrient concentrations and speciation, appears to have a high degree of spatial variability throughout the catchment, with high N and P concentrations in the western tributaries.

Apart from Lennard Brook, DON is the dominant form of nitrogen in both surface water and, according to some authors, groundwater. Sources of DON are potentially linked to the soil organic matter which originated from native vegetation prior to clearing (Gerritse, 1994).

A high proportion of SRP in TP was reported in surface water, with particularly high concentrations in the western tributaries. Reported P seasonal pattern with higher concentrations during midwinter baseflow was linked to a potentially greater interaction between surface runoff and soils during the period of soil inundation.

Limited published information indicates that TN concentrations in groundwater were higher than in surface water, while P concentrations in shallow groundwater were lower.
2. PROJECT METHODS

2.1. Background

The project methods were developed to deliver the main project objectives and designed to investigate the effect of a groundwater system on:

- nutrient transfer within the catchment
- nutrient load in the river.

The project methods were based on a conceptual understanding of groundwater fluxes in the catchment. The original concept, based on literature review and discussion with WA Department of Water personnel, led to the conclusion that groundwater contribution in the Ellen Brook catchment may be linked to two possible scenarios: regional groundwater discharge and localised groundwater discharge.

Regional groundwater discharge is driven by catchment (or wider) hydrogeological conditions; groundwater fluxes are defined by regional groundwater recharge, hydraulic gradients, aquifer hydraulic properties and regional boundary conditions (Figure 2-1). The rates of regional groundwater discharge to the river are likely to be semi-constant throughout the year because the regional hydrogeological conditions (such as the regional groundwater gradients, large distance between recharge and discharge zones) are likely to change only marginally between seasons.

In the Ellen Brook catchment, the main aquifer contributing to the river flow is the Superficial Aquifer. Considering the presence of clay deposits in the river valley, the recharge is likely to occur outside of the area of clay occurrence. The groundwater discharge is likely to be associated with the river channel, where the channel incision is deep.

Localised groundwater discharge may occur in the area affected by shallow groundwater when the uppermost part of the aquifer is intercepted by drains or stream channels. In such circumstances, groundwater contribution to the surface water flow may occur only when the groundwater table is above the drain base; however, surface water channels become disconnected from groundwater when the water table subsides below the drain base during summer (Figure 2-2) The contribution from local groundwater under WA climatic conditions is likely to be limited to a period of a few months during winter – early spring and it is likely to be localised spatially. In the Ellen Brook catchment this is likely to occur in the flat, low-lying areas along the river valley. Local groundwater discharge is proportional to a hydraulic conductivity of the water-bearing strata and is greater for deeper channels.

The effect of land use on water quality is likely to be more significant and rapid for localised groundwater discharge. This is due to a significantly smaller groundwater residence time as a result of a proximity between groundwater recharge and discharge zones. This proximity is of the order of tens to hundreds of metres, while in the case of a regional groundwater system the distance may be tens to hundreds of kilometres.

There are a number of techniques which allow for estimation of groundwater contribution to a surface water flow. They are largely based on the investigation of a groundwater ‘signature’ in the receiving water body such as an increase in river flow gained from groundwater discharge or variation in surface water quality; water temperature, chemistry or isotopic signature; or at zones where groundwater discharge is expected. Application of complex
methods is more effective, however, when a conceptual groundwater model of the catchment is defined, which then allows an appropriate field experiment to be designed.

Figure 2-1 Conceptual west-east cross-section of the Ellen Brook catchment. The flow lines suggest the direction of the regional groundwater flow and potential regional groundwater discharge areas.

Figure 2-2 Local shallow groundwater table (GWT) and interaction with drain or river channel in winter and summer.
One of the common techniques for evaluating the groundwater contribution to the river flow is analysing river flow during baseflow period. It is widely expected that the baseflow is predominantly formed by groundwater contribution (Arnold and Allen, 1999; Chapman, 1999; Wittenberg, 1999; Wittenberg and Sivapalan, 1999); however, in some cases, the river flow during the baseflow period can also be influenced by a delayed discharge from wetlands or inundated areas (Griffiths and Clausen, 1997). This may be particularly relevant to a catchment like Ellen Brook.

Water quality in the river during the baseflow period may be indicative of groundwater quality if baseflow is formed by groundwater discharge. In-stream processes may also influence surface water quality during this time. Groundwater not only delivers the dissolved and colloidal forms of nutrient/organic compounds to rivers and wetlands, but may also influence the biological and chemical processes within the hyporheic zones (Boulton and Hancock, 2006). Upward fluxes of hyporheic water can promote surface primary productivity, influence sediment microbial activity and affect organic matter decomposition. There is evidence that groundwater contribution and its variation over time and under land use alteration may alter processes governing the biota and rates of many ecosystem processes (e.g. leaf decomposition). In addition, thermal and chemical conditions related to groundwater inputs have direct and indirect effects on riverine biota and rates or types of in-stream processes.
2.2. Project methods

The scope of project research activities was based on available data prior to the project commencement and data generated as a result of the project activities and included:

- analysis of river discharge data
- groundwater level monitoring data
- water quality data.

We also applied remotely sensed data to delineate groundwater discharge zones. A summary of the project methods is given below with more details on specific analyses in Appendixes 2-6.

2.2.1. Surface water flow and quality at the outflow from the Ellen Brook catchment

Analysis of river hydrograph and water quality data obtained at the Ellen Brook gauging station (AWRC Ref 616189) was to define the baseflow characteristics of the catchment and river water quality typical for the baseflow period. The analysis involved:

- Residual flow duration curve (FDC) analysis of the river flow which allowed for qualitative evaluation of groundwater contribution to river flow.
- Baseflow identification, which was based on separation of river hydrograph when sequential reduction of the hourly flow rates was the most typical for baseflow. This reduction was 20 l/sec or less. A MATLAB routine was developed and used to estimate baseflow for the period 1966 to 2006.
- Analysis of annual river discharge during baseflow period, when the proportion of the groundwater contribution to the river flow and its effect on the river water quality is greatest.
- Analysis of available water quality data for the Ellen Brook gauging station (WIN database), which included nutrients (N and P), electrical conductivity and major ions as well as their relationship with the river flow.

2.2.2. Surface water flow and quality in the Ellen Brook catchment

Assessment of surface water flow and quality variation within the catchment was based on limited data available prior to the project commencement and data collected by the project. Key data are summarised as follows:

- In addition to the records at the Ellen Brook gauging station, continuous discharge data for a middle reach of Ellen Brook was available for 1992 (AWRC Ref 616100, Figure 2-3 Surface water sampling locations Figure 2-3). Simultaneous analysis of the river discharge data for both observation stations allowed for the estimation of relevant contributions of the upper and lower sub-catchments to the river flow during 1992.
- Water quality data collected by Chittering Landcare Group, which included in situ pH, electrical conductivity (EC), temperature and nutrients (TN, TKN, TDN, NO3, NO2, NH3, TP, TDP, SRP). This data was used to investigate the spatial distribution of surface water nutrient concentrations and EC throughout the catchment.
### Figure 2-3: Surface Water Sampling Locations

#### Hydrography (DoE)

- Ellen Brook Catchment (DoE)
- Watercourse - major, perennial
- Watercourse - minor, perennial
- Watercourse - major, non-perennial
- Watercourse - minor, non-perennial
- Other waterbodies

#### CSIRO SW Monitoring Sites

<table>
<thead>
<tr>
<th>Site Code</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>EBN9</td>
<td></td>
</tr>
<tr>
<td>EBN14A</td>
<td></td>
</tr>
<tr>
<td>EBN14B</td>
<td></td>
</tr>
<tr>
<td>EBN16</td>
<td></td>
</tr>
<tr>
<td>EBN18</td>
<td></td>
</tr>
<tr>
<td>EBN20</td>
<td></td>
</tr>
<tr>
<td>EBN20A</td>
<td></td>
</tr>
<tr>
<td>EBN22</td>
<td></td>
</tr>
</tbody>
</table>

#### Sampling Interval

- Late winter baseflow
- Summer baseflow

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Groundwater contribution to nutrient export from the Ellen Brook catchment
• Baseflow monitoring in 2007-2008 was done including weekly flow metering and surface water sampling at eight locations within the catchment, and during September 2007-April 2008 to define the stream flow during the baseflow period as well as the rate of nutrient export from the sub-catchments (Figure 2-3). A summary of this sampling is as follows:

  o Four locations were monitored during September-December 2007 (stations EBN09, EBN16, EBN22 and EBN18). Their locations were chosen to be representative of the northern, western (reportedly characterised by high nutrient loads) and eastern sub-catchments, where generally low nutrient concentrations occur, and the catchment as a whole.

  o An additional four stations were included in the program in January-April 2008, which were monitored fortnightly (stations EBN14A, EBN14B, EBN20 and EBN20A). This extended summer sampling program was initiated to define surface water quality when groundwater discharge was the only source of the river flow.

  o Water samples were analysed in situ for pH, electrical conductivity (EC), dissolved oxygen, temperature and turbidity using a multi-parameter probe (Horiba U-10). Water samples were also sent to an accredited laboratory for analysis of pH, alkalinity, EC, TSS, major ions (Ca, Mg, K, Na, Al, Fe, Mn, Cl, SO\textsubscript{4}, HCO\textsubscript{3}, CO\textsubscript{3}, total S), nutrients (TN, TKN, TDN, NO\textsubscript{3}, NO\textsubscript{2}, NH\textsubscript{3}, TP, TDP, SRP), dissolved organic carbon (DOC) and trace elements (As, Cd). Dissolved organic N, particulate N, dissolved organic P and particulate P were derived from measured values. Arsenic and Cd were analysed as they have previously been used to trace agricultural chemicals and P (Gerritse, 1996).

  2.2.3. Groundwater residence time

Groundwater residence time in the local aquifers may be used for an approximate estimation of the timeframe for the impact of land use change on groundwater quality. Residence time in groundwater was estimated based on the chlorofluorocarbons (CFCs) analysis in groundwater samples. The method is based on the known rise in atmospheric CFCs, which allows for the identification of groundwater that is less than 50 years old.

Within the constraints of the project timeline and the budget, it was impossible to undertake a substantial drilling program to support groundwater sampling at various depths and within various geological strata along preferred transects. For this reason, only available bores screened within the Superficial Formation within an inlet length of no more than 5 m were included in the analysis (Fig. A5.1). Samples were also taken for nutrient analysis at the time of CFC sampling to investigate any links between groundwater age and nutrient concentrations and speciation.

  2.2.4. Application of Landsat 7 data for delineation of groundwater discharge zones

Groundwater discharge zones in the Ellen Brook catchment were also investigated using satellite data. Remotely sensed data analysis was based on the hypothesis that near-surface groundwater may be identified as anomalies in the vegetation signature, the surface thermal signature and the seasonal variation in these parameters acquired from the remotely sensed imagery.

The Landsat 7 Enhanced Thematic Mapper (ETM+), which provides a better quality of thermal data than Landsat 5 data, was used for analysis. Seven images were selected for

The groundwater discharge zones were identified using the following techniques:

- Greenness analysis identified the changes in reflectance of vegetation over the seven considered dates. This was based on calculation of a greenness index (ETM+ band 4 – ETM+ band 3) and its temporal summaries over time from late winter to late summer, which can produce linear and quadratic slopes from orthogonal polynomials as a function of time (Wallace et al, 2006 and Wallace and Furby, 1994) (see Figure 3 in Appendix 6). This technique relies on interpretation of intensity of greenness to identify the various types of vegetation responses:
  - The horizontal line (constant greenness) indicates that there are no changes in the greenness of the vegetation over the time period. This is most typical of perennial vegetation.
  - The downward sloping line (linear) and curve (quadratic) are typical of drying annual or ephemeral vegetation. Greenness decline in areas where there is no or little access to water is likely to be more sudden and is characterised by a ‘quadratic’ response, while areas with access to water (via groundwater but also irrigation) exhibit slower, more ‘linear’ rates of greenness decline.

- Thermal surface anomalies (as deviation from mean), based on the assumption that groundwater discharge may cause a number of thermal patterns, such as:
  - The discharge zones associated with deeper groundwater may be indicated by a warmer thermal anomaly during the winter months when groundwater is warmer than surface or surface water.
  - The discharge zones in summer reduce surface temperature and therefore can be identified by cooler surface anomalies.
  - Trees with access to groundwater may be detected by a cooler thermal anomaly potentially all year around due to high evapotranspiration rates rather than perennial vegetation without access to groundwater.

It is important to mention that application of Landsat 7 to delineation of groundwater discharge zones usefully complemented other analyses; this aspect of the research was exploratory and the adopted techniques may require further development and testing.

Details of individual activities as well as the results of the associated analysis are given in Appendixes 1-7.
3. GEOLOGY AND HYDROGEOLOGY

3.1. Geology

Hydrogeological systems, which may influence the Ellen Brook water regime, are related to the Superficial Aquifer, which is an aquifer hosted by the Cretaceous deposits in the Dandaragan Plateau and to some extent the water system within the Precambrian crystalline rock (Table 3-1, Figure 3-1).

Table 3-1 Geological and hydrogeological systems which may potentially influence the water balance in Ellen Brook

<table>
<thead>
<tr>
<th>Age</th>
<th>Geological Formation</th>
<th>Lithology</th>
<th>Aquifer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary</td>
<td>Guilford Clays, Bassendean Sands, Gnangara sands</td>
<td>Clays, Sand</td>
<td>Superficial Aquifer</td>
</tr>
<tr>
<td></td>
<td>Ascot Formation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cainozoic</td>
<td>Molecap Greensand, Gingin Chalk, Poison Hill Greensands</td>
<td>Sandstone, Shale, Chalk</td>
<td>Poison Hill Aquifer, Mirrabooka Aquifer</td>
</tr>
<tr>
<td>Cretaceous</td>
<td>Osborne Formation</td>
<td>Interbedded sandstone, siltstone and shales</td>
<td>Leederville – Parmelia Aquifer</td>
</tr>
<tr>
<td></td>
<td>Mariginiup Member, Wanneroo Member, Pinjar Member</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-Cambrian</td>
<td>Crystalline rocks (Gneiss, Magmatite, Granites)</td>
<td></td>
<td>Highly localised</td>
</tr>
</tbody>
</table>

3.1.1. Precambrian crystalline rocks

The Darling Plateau is a laterite-capped plateau formed over Precambrian crystalline rocks and is bound to the west by the Darling Scarp. Bedrock is close to the surface or overlain by highly weathered clays.

3.2.2. Cretaceous and Cainozoic deposits

The Dandaragan Plateau is gently undulating, sand and laterite covered plateau located at 200-300 m AHD. Its south western boundary is the Gingin Scarp. The Dandaragan Plateau is situated between the Darling and Gingin Faults and forms over a large syncline, built in the upper profile by Cretaceous and Cainozoic deposits. The descriptions of the stratigraphic sequence in the region are given in Kay and Diamond (2001) and shown in Figure 3-3. There is little surface runoff from the plateau due to permeable surface cover.

The geological sequence defines a number of formations which host the regional aquifers (Poison Hill Aquifer, Mirrabooka Aquifer, and Leederville – Parmelia Aquifer) and two major regional aquitards: Otorowiri Member (Jurassic) and Osborne Formation (Cretaceous), which form the base and overlay of the Leederville – Parmelia Aquifer, respectively (Table 3-1).

The Leederville – Parmelia Aquifer is hosted by Cretaceous deposits, including Mariginiup Member (siltstone and shales), Wanneroo Member (interbedded sandstone, siltstone and shales) and Pinjar Member (interbedded siltstone and shales). The Wanneroo Member extends towards Ellen Brook catchment where it is overlain by Superficial Formation.
Poison Hill Aquifer and Mirrabooka Aquifer are hosted by a Cainozoic Formation formed by Molecap Greensand, Gingin Chalk and Poison Hill Greensands, which appear to be less consolidated formations than Cretaceous sedimentary rocks. Molecap Greensand is fine to coarse, grey to dark greenish-grey silty, glauconitic sandstone, weathered to yellow-brown.

The unit outcrops in the study area and may reach a thickness of up to 85 m. Gingin Chalk is a weak-to-moderate consolidated white-to-grey slightly glauconitic chalk occasionally containing thin beds of greensands. Poison Hill Greensands consists of weathered, poorly consolidated, ferruginous clayey greensand and glauconitic sandstone with thin, intercalated shaley beds. The formations are known for P deposits which are used as fertiliser by local farmers.
3.3.3. Quaternary deposits

Data from available bore logs suggest that the thickness of Quaternary deposits increases from north-east to south-west, from less than 10 m to more than 60 m. The Quaternary deposits include Ascot Formation, Gnangara sands, Bassendean Sands and Guilford Clays. Further information about the Quaternary deposits is provided below:

- The Northern part of sub-catchment is predominantly underlain by sand deposits (e.g. WIN Bore 5294).
- More detailed information on Quaternary deposits in the middle sub-catchment was provided by Shams and Smith (2001). In this area of the catchment, the Guilford formation overlays Bassendean Sands. The clay deposits are typically plastic in texture and contain 10% sand to a thickness of 6 m and more. The underlying Bassendean Sands contain up to 20% clay.
- The lower profile is predominantly built by sandy deposits (e.g. WIN Bore 5403).

The geological structure of the catchment defines catchment topography as illustrated in Figure 3-2. The ridged relief in the Precambrian bedrocks is replaced by flatter, but elevated surfaces of the Dandaragan Plateau. The surface depressions in the river valley are more common in the northern sub-catchment, but are also detected along the river channel in the middle and lower sub-catchment. Further to the west, the Gnangara dune system is indicated by a high surface elevation and multiple surface depressions within the dune formation.
Figure 3-2 Catchment relief based on DEM analysis (courtesy of CMIT, Jeremy Wallace): blue colour indicates the area of surface depressions.
3.2. Hydrogeology

Figure 3-3 shows west-east hydrogeological transact in the area of Gingin, located just north of the Ellen Brook catchment. It also identifies the key aquifers in the areas.

3.2.1. Precambrian crystalline rocks

Precambrian crystalline rocks are not considered to contain any substantial groundwater resources; however, groundwater may be found locally hosted by the weathered profile or fissure systems.

3.2.2. Cretaceous and Cainozoic deposits

The aquifer recharge takes place north of the Ellen Brook catchment boundary (Kay and Diamond, 2001). The groundwater discharges to streams that flow to the east of the Dandaragan Plateau, including perennial Lennard Brook. Mirrabooka Aquifer discharges to the streams such as Gingin and Lennard Brooks; Leederville Aquifer discharge occurs in places along the foot of the Gingin Scarp, for instance into Gingin Brook, and therefore potentially in the creeks within Ellen Brook Catchment. Discharge may possibly occur within the ‘break of slope’ areas, generating a ‘seepage zone’ at the base of the hills. In addition, the perennial creeks may provide groundwater recharge sources when streams flow across the sand deposits of the valley in the northern part of sub-catchment.

Considering the low rates of runoff generation within the plateau, Lennard Brook annual discharge may be indicative of the groundwater discharge rates from the Dandaragan Plateau. Table 3-2 shows the estimated total discharge from the plateau, which is 9.1-16.5 GL/year.

Table 3-2 Groundwater discharge to the stream in Dandaragan Plateau

<table>
<thead>
<tr>
<th>Description</th>
<th>Range for observation period 1962-2001</th>
<th>Data for 1992</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lennard Brook annual discharge, GL/year</td>
<td>4.7-8.6</td>
<td>8.2</td>
</tr>
<tr>
<td>Lennard Brook length, km</td>
<td>39.3</td>
<td></td>
</tr>
<tr>
<td>Lennard Brook annual discharge rate per unit length, MG/m/year</td>
<td>120-218</td>
<td>208</td>
</tr>
<tr>
<td>The total length of the streams receiving groundwater discharge as identified by Landsat 7 data analysis, km</td>
<td>75.8</td>
<td></td>
</tr>
<tr>
<td>Total annual discharge, GL/year</td>
<td>9.1-16.5</td>
<td>15.8</td>
</tr>
</tbody>
</table>
Figure 3-3 West-east hydrogeological transect in the area of Gingin (just north to the Ellen Brook catchment)
For the available bores on the plateau, water levels indicate a substantial hydraulic head, approximately 30-40 m higher than the surface elevation in the valley. However, due to the geological structure (a syncline indicated on Figure 3-3) and presence of the regional aquitard, a direct discharge from the Cretaceous aquifers to the Ellen Brook is not likely. Both Poison Hill Aquifer and Mirrabooka Aquifer may produce yields up to 60-100 m$^3$/day.

### 3.3.3. Quaternary deposits

According to the Department of Water (DoW) monitoring data, the water table in the dune system to the north-west of the catchment is lower than in the Ellen Brook valley (Figure 3-4 and Figure 3-5). Steady water table reduction in Superficial Aquifer (2-4 m over a 30-year period) is likely to be related to groundwater abstraction within the Gnangara Mound (Figure 3-6). The monitoring data for the bores to the east of the dune system in the northern sub-catchment also show a reduction in the groundwater level, but the water table subsidence begins at a later stage (1990s) compared to more western areas (1970s). This suggests that there is a propagation of the Gnangara mound drawdown to the east. At this stage, however, the water levels and their seasonal variations remain unchanged in the valley area, as indicated by the groundwater level monitoring in the bores (Figure 3-7).

The groundwater gradient in the middle catchment is toward the river (Figure 3-8). The groundwater level reduction over the monitoring period is observed within the Gnangara dunes system, where the water level dropped about 3 m over 30 years. Groundwater abstraction is more likely to occur in the southern sub-catchment where land use is more intensive, such as urban or vineries where water is used for intensive irrigation (Figure 3-9 and Figure 3-10).

The Guildford Clays located along the river valley are likely to provide a local confining layer for the deeper Superficial Aquifer. Though the deeper Superficial Aquifer can be locally characterised by the hydraulic heads above datum (e.g. Bores 5393 and 5424), most of the records suggest that the hydraulic heads are below the surface, but could be lower or higher than the free water table. For instance, Sharma and Smith (2001) reported the upward gradients defined by up to 0.5 m difference between the hydraulic heads in the deep bores (<20 m) and the groundwater table. However, in accordance with the Darcy’s Law, such gradients may produce limited upward fluxes, up to 0.001 m$^3$/m$^2$/day (or 1 mm/day) if the vertical hydraulic conductivity of the Guildford Clays is less than 0.01 m/day. The spatial and temporal variabilities in the vertical hydraulic gradients provide evidence for the variability in interaction between the deep and shallow groundwater units within the river valley underlined by Guildford Clays. These units are likely to be linked to spatial variability in the hydraulic properties of Guildford formation and the effect of local groundwater abstraction.

Regional groundwater recharge in Superficial Aquifer is likely to occur along the perimeter of the Ellen Brook valley in the:

- west (Gnangara Dunes) as rainfall infiltration, which currently is less than abstraction rates
- north (sand deposits) and north-east (along Dandaragan Plateau) as rainfall infiltration and potentially as a discharge from the Dandaragan Plateau
- south-east along the foothill in the area of colluvial deposits, which is likely to be limited.
Figure 3-4 West-east transect across the Ellen Brook catchment in the northern, middle and southern sub-catchments
Groundwater contribution to nutrient export from the Ellen Brook catchment

Figure 3-5 West-east transect across northern sub-catchments and groundwater levels in 1970s and currently based on WIN data

Figure 3-6 Groundwater table variation in the Superficial Aquifer in the Gnangara Dunes area within northern sub-catchment (WIN data)
Figure 3-7 Groundwater table variation in the Superficial Aquifer in the proximity of the Ellen Brook Channel within northern sub-catchment (WIN data).

Figure 3-8 West-east transect across middle sub-catchments and groundwater levels in 1970s and currently based on WIN data.
Figure 3-9 West-east transect across southern sub-catchments and groundwater levels in winter and summer (current) based on WIN data.

Figure 3-10 Groundwater table variation in the Superficial Aquifer in the southern sub-catchment in the proximity of a golf course, where groundwater abstraction is evident (WIN data).
3.3. Groundwater discharge zones

Landsat 7 data analysis identified the groundwater discharge areas. Results from the analysis are detailed below.

3.3.1. Precambrian crystalline rocks

Though it is expected that only limited groundwater resources are hosted by this formation, groundwater seepage may occur along stream lines and at the base of the hills. Figure 3-11 and Figure 3-12 show the results of Landsat data analysis, indicating that there are areas where groundwater discharge may be found (e.g. red colour in Figure 3-12a). However, field data may be required to confirm the delineated zones.

3.3.2. Cretaceous and Cainozoic deposits

Figure 3-13 and Figure 3-14 show potential seepage zones along the foothill of the Dandaragan Plateau. The discharge zones were identified by a trend in vegetation greenness (Figure 3-13b), warmer thermal anomalies in September (Figure 3-14a) and consistently cooler anomalies for the vegetation class. Cool thermal anomalies detected for March 2001 are clearly related to Lennard Brook, and are indicative of the groundwater discharge, which is confirmed by Brook flow monitoring data (Figure 3-15).

3.3.3. Quaternary deposits

Groundwater discharge zones, shown in Figure 3-16 and Figure 3-17, are mainly associated with the seepage from the Gnangara Dunes. The trends in vegetation greenness (Figure 3-16b and c) and warmer thermal anomalies in September 2000 (Figure 3-17a) are particularly useful for zones delineation in this area.

3.3.4. Conclusions

- Groundwater discharge zones were identified along the eastern slope of Gnangara dunes, streams draining Dandaragan Plateau.
- Other groundwater discharge zones identified by Landsat 7 data analysis are potentially associated with ‘break of slope’ areas and a number of wetlands located in the northern sun-catchment of Ellen Brook.
- The Landsat 7 data analysis shows good potential for investigation of groundwater systems that have shallow groundwater occurrence. However, on-ground validation of some findings are further required. More details related to this analysis are given in Appendix 6.
Figure 3-11 Visual multi-spectral image (a) and groundwater discharge zones indicated by Landsat 7 data analysis in the South-east of the catchment: greenness (green colour on (b)). The residential areas were also masked: hard surfaces and irrigation may potentially influence the LANDSAT images interpretation.
Figure 3-12 Groundwater discharge zones indicated by Landsat 7 data analysis in the south-east of the catchment: the deeper groundwater discharge zone (red colour on (a)); potential access of vegetation to groundwater (blue (b) and blue/green and orange c)). The cooler signature on (b) and (c) images may be influence by the slope exposure, and the high elevation area was masked. The residential areas were also masked: hard surfaces and irrigation may potentially influence the Landsat 7 images interpretation.
Figure 3-13 Visual multi-spectral image (a) and groundwater discharge zones indicated by Landsat 7 data analysis in the north-east of the catchment: greenness (green colour on (b)). The residential areas were also masked: hard surfaces and irrigation may potentially influence the LANDSAT images interpretation.
Figure 3-14 Groundwater discharge zones indicated by Landsat 7 data analysis in the north-east of the catchment: the deeper groundwater discharge zone (red colour on (a)); potential access of vegetation to groundwater (blue (b) and blue/green and orange (c)). The cooler signature on (b) and (c) images may be influenced by the slope exposure, and the high elevation area was masked. The residential areas were also masked: hard surfaces and irrigation may potentially influence...
Figure 3-15 Cooler surface anomaly along the Lennard Brook and other streams draining Dandaragan Plateau (including Gingin Brook to the north), which are potentially evident of groundwater discharge (a) and geomorphologic wetlands identified by WA Department of Water (formally DoE) (b)
Figure 3-16 Visual multi-spectral image (a) and groundwater discharge zones indicated by Landsat 7 data analysis in the west of the catchment: greenness (green colour on b) and c), as zoom-in to the southern past of the area). Red colour on b) and c) indicates deviation from natural drying pattern poetically indicating area of irrigation. The residential areas were also masked: hard surfaces and irrigation may potentially influence the LANDSAT images interpretation.
Figure 3-17 Groundwater discharge zones indicated by Landsat 7 data analysis in the west of the catchment: the deeper groundwater discharge zone (red colour on (a)); potential access of vegetation to groundwater (blue (b) and blue/green and orange (c)). The residential areas were also masked: hard surfaces and irrigation may potentially influence.
4. CHARACTERISTICS OF THE CATCHMENT HYDROLOGICAL AND HYDROGEOLOGICAL CONDITIONS

4.1. Climate

As is typical for the Mediterranean climate, rainfall within the catchment mainly occurs during winter months, while summers are usually dry and warm. The average annual rainfall for 1989-2006 was 662 mm (Figure 4-1) as recorded at the RAAF meteorological station (Bureau of Meteorology station 9053) located in the middle of the catchment. There was a trend in annual rainfall reduction over the last few decades similar to other regions in the southwest of Western Australia.

Annual potential evaporation exceeds annual rainfall, and on average was 1988 mm/year during 1970-2007. However, monthly data (Figure 4-2) show higher potential evaporation than rainfall, except for June-August. More information on meteorological conditions of the catchment is given in Appendix 7.

![Figure 4-1 Annual rainfall at RAAF meteorological station (BoM station 9053)](image)

![Figure 4-2 Monthly average rainfall and evaporation at RAAF meteorological station for 1970-2006](image)
4.2. Hydrology

Ellen Brook is an ephemeral river with river flows only during winter and spring, commonly from the end of May to November. In summer, the river flow upstream from the gauging station 616189 (EBN18) contains unusual, isolated water pools which are permanent at several locations (such as in the Bullsbrook area) (Shams and Smith, 2001).

Some waterways in the catchment do have continuous annual flow, which is indicative of the regional groundwater discharge; these include:

- Lennard Brook, which drains the Cretaceous and Cainozoic formations of the Dandaragan Plateau
- the lower reaches of Ellen Brook receiving groundwater contribution from the regional Superficial Aquifer
- the upper reaches of the streams in the western sub-catchments which drain Gnangara Dunes.

Drainage density of the surface water network is greatest within Guildford Formation (the area of the clay-rich formation occurrence) and smaller in the hills (Table 4-1). Drainage density is particularly low in the sandy formation in the northern part of the catchment. It appears that the drainage density in Ellen Brook catchment is indicative of the areas with high (sand) and low (clay) infiltration rates, which is inversely related to overland flow characteristics.

Note that high infiltration potential in the large part of the catchment, such as Western Bassendean Dunes or Northern sub-catchments, limits overland flow generation, but increases groundwater recharge.

Table 4-1 Drainage density (analysis is limited to the extent of Environmental Geology map, which does not cover the north sub-catchment)

<table>
<thead>
<tr>
<th>River Valley</th>
<th>Total</th>
<th>Gnangara Dunes, S8*</th>
<th>Sand over clay, S10*</th>
<th>Guilford Clays, Mgs1</th>
<th>Hills</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area, km²</td>
<td>445.2</td>
<td>122.2</td>
<td>102.1</td>
<td>83.0</td>
<td>137.8</td>
</tr>
<tr>
<td>Length, km</td>
<td>622.3</td>
<td>25.9</td>
<td>171.2</td>
<td>246.9</td>
<td>178.0</td>
</tr>
<tr>
<td>Drainage density, km/km²</td>
<td>1.4</td>
<td>0.2</td>
<td>1.7</td>
<td>3.0</td>
<td>1.3</td>
</tr>
</tbody>
</table>

* Soil Code in accordance with Environmental Geology map (DoW)

Long-term annual river discharge over 1966-2006, as recorded at the Ellen Brook gauging station (AWRC Ref 616189), is 31 GL/yr (Figure 4-3) with the highest flows recorded for July and August (Figure 4-4). In the beginning of an annual cycle, the river flow occurs when the cumulative rainfall reaches 250-300 mm (Figure 4-5), indicating that the catchment can provide a substantial storage for rainwater. Additionally, a threshold of 300 mm of annual rainfall was identified when correlation between total annual rainfall and total annual river discharge was considered (Figure 4-6).

Though there are no flow data available for the majority of the streams, it appears that flow contribution from the eastern and western tributaries varies with time. The flow in the hill sub-catchments starts and ceases earlier than in the western sub-catchments, which are
adjacent to Gnangara dunes (personal communication, Chittering Group). This was confirmed during the monitoring program over 2007-2008, when the Eastern Creek at monitoring station EBN22 ceased to flow in October 2007, while the Western stream at monitoring station EBN16 continued to flow until mid-November. This also coincided with the river flow termination at the gauging station.

Figure 4-3 Annual Ellen Brook discharge

Figure 4-4 Ellen Brook average, maximum and minimum monthly discharge
Figure 4-5 Relationship between cumulative rainfall and monthly river discharge

Figure 4-6 Relationship between annual rainfall and annual river discharge

$R^2 = 0.8545$
According to flow duration curves (FDC) (see Appendix 2 for details) and data for the entire observation period 1966-2006, the river discharge at the gauging station occurs on average over 63% days.

FDC shape is typical for an intermittent stream (see Figure A2-1 in Appendix 2). The steep shape of the curve for the lower discharge rates suggests that the regional groundwater contribution to Ellen Brook in the river reach upstream from the gauging station is limited. The flat FDC shape for the high flow rates indicates that the catchment response to high rainfall events is moderate and the river is not prone to frequent flooding, which is indicative of high storage capacity of the catchment.

Despite the low groundwater contribution indicated by FDC, total annual baseflow is comprised of, on average, 42% annual river discharge and may be up to 57% during drier years and 31% in wetter years (see Figures A2-3 and A2-4 in Appendix 2). The baseflow is closely related to annual rainfall and is greater during the wetter years (Figure 4-6).

![Figure 4-7 Relationship between annual rainfall and annual river baseflow](image)

Figure 4-7 also shows the variability in annual river baseflow between the years with similar annual rainfall. It appears that in addition to total annual rainfall, the baseflow variability is also related to the rainfall pattern during the individual years. For instance for the years when annual rainfall was 750-800 mm, the annual total baseflow was greater during the years where rainfall intensity was greater (Figure 4-8). Such a close relationship between baseflow and rainfall pattern suggests that baseflow at catchment scale is likely to be linked with surface or pre-surface processes (surface inundation, or compensation effect of wetlands on the river flow), rather than regional groundwater processes. Some of the analysis which follows will illustrate these effects.
Available data indicate that the baseflow is predominantly generated in the northern sub-catchment. The conclusion was based on the analysis of three data sets:

- river discharge analysis for 1992
- baseflow monitoring during spring 2007
- satellite data analysis for spring 2000 images.

During 1992 the flow contribution from the northern sub-catchment during the baseflow periods was more than 80% of the total baseflow (as measured at AWRC station 616189) (Figure 4-9).

The travelling time between the monitoring stations is approximately 32 hours\(^1\), and the discharge data for these two stations was compared with 1 day lag time. Figure 4-10 shows the river discharge within northern sub-catchments (429 km\(^2\)) (as measured at AWRC station 616100) and southern sub-catchments (286 km\(^2\)) as a flow gain between the two stations. The data is expressed as a discharge per unit catchment area (m\(^3\)/km\(^2\)/day) for a direct comparison. The southern part of the Ellen Brook catchment shows a quick response to storm events and quick flow recession with limited baseflow. The runoff per unit area during baseflow period in 1992 is much greater in the northern sub-catchment; however, runoff is generally lower during storm events. indicating the likely presence of some type of compensation storage.

\(^1\) Manning’s formula was used to estimated flow velocity in an open channel using a Manning’s friction coefficient of 0.07 for conditions with some weds, and heavy brush on banks (Featherstone and Nalluri, 1988).
Figure 4-9 River discharge at the gauging station and the proportion of the northern sub-catchment contribution during 1992: (a) on daily basis and (b) as average for daily flow intervals.
Similarly, during the spring 2007 baseflow monitoring program, it was observed that the river does not gain any significant flow between the EBN9 (gauging station 616100) and EBN18 (gauging station 616189), and the flow measurements at the gauging station were consistently lower than at EBN9 during October – November 2007 (Figure 4-11a). Presuming comparable accuracy of the flow measurements at both stations at about 20%, the reduction in the river flow can be adequately attributed to the effect of evaporative losses along the river channel, which can also account for some additional inflow between the stations. This is discussed further below.

The evaporative losses from the river channel and its immediate surroundings were estimated to be within a range of 4000 – 5000 m$^3$/day or 46-57 L/sec in terms of the river discharge (Figure 4-11b). The estimation was based on the following assumptions:

- a river length between the two stations of approximately 27 km
- 10-20 m wide area contributes to evaporation along the river channel
- evaporation rate is equal to a potential daily evaporation
- travel time between stations is 1.4 days (32 hours).

Considering minimum gain in river flow after EBN9 (gauging station 616100), it is likely that any baseflow contribution to river flow in the southern part of the catchment between stations EBN9 and EBN18 during October – November is likely to be less than the evaporative losses along the river channel, or less than 5000m$^3$/day.
Spring baseflow in the main channel is mainly related to the time when analysis of the thermal data from Landsat 7 Enhanced Thematic Mapper (ETM+) indicates well-defined thermal anomalies in the surface thermal images. It is important to mention that such thermal anomalies may indicate areas of managed forestry, steep western-faced slopes or open water. Since the northern sub-catchment is generally flat and absent of managed forestry plantations, the anomaly was interpreted to be surface water occurrence or surface inundation. The anomalies were clearly identified for images acquired in spring 2000 (Figure 4-12a). The evidence of surface inundation was confirmed by a site inspection in October 2008, when a similar baseflow condition was expected (Figure 4-13).

Figure 4-12b also shows the river hydrograph recorded for the year 2000 at gauging station 616189, indicating the dates when the images were acquired. The river flow appears to cease when the images indicate significant reduction in the inundated area and disconnection among individual waterlogged areas.

Waterlogging plays an important role in hydrology of the Northern sub-catchment, and is likely to be caused by:

- low surface gradients
- potentially greater than elsewhere groundwater recharge rate due to contribution from the perennial streams flowing from Dandaragan Plateau
- excessive recharge results in a much shallower groundwater table in this area than elsewhere in Ellen Brook catchment and development of wetlands.

These factors combined define the high baseflow associated with this part of the catchment.
Figure 4-12 Thermal anomalies in the northern sub-catchment, which correspond to a ‘waterlike’ signature, in September 2000 (a), October 2000 (b) and December 2000 (c) and river daily discharge in 2000 (d)
Figure 4-13 Photo indicating waterlogging in the northern region of Ellen Brook catchment: a) left bank area (Breera Road); b) and c) – right bank area (Nambung Road)
In summer, when groundwater is the only source for surface water flow, baseflow was observed in the lower reaches of Ellen Brook downstream from the gauging station and along the eastern slope of Gnangara dunes, where stream flow was measured during January-March 2008.

River flow at the confluence with Swan River during the summer months 2007-2008 ranged from 2.5 - 29 L/sec (35-40 ML in total during January-March). It is unlikely that evaporative losses from the stream, due to the high stream flow velocity and low residence time, influenced the river flow here. The high stream flow velocity and low residence time are defined by a steep decline in the river bed from 15 m to 5 m within a 3 km river reach. Riparian vegetation, however, is likely to intercept some groundwater which otherwise could discharge to the river.

Lennard Brook baseflow is consistent throughout the year and is predominately from groundwater sources as discussed in a previous section.

Along the eastern slope of Gnangara Dunes (EBN14A), the stream discharge rates were recorded as 1 - 9 L/sec (16-20 ML in total during January-March). The flow ceases within a short distance from the discharge zone, where plentiful vegetation forms an ‘oasis’ in mostly dry surrounds. The stream discharge is likely to be lost to evapotranspiration associated with dense vegetation. These areas are well-defined by greenness analysis of the Landsat 7 data. Figure 3-10c shows that the vegetation remains greener much longer within the stream reaches receiving groundwater discharge. More detailed interpretation of the Landsat 7 data may potentially provide more quantitative data on water balance in these areas, including evaporative losses, which may allow estimation of groundwater discharge rates.

A summary of the flow distribution in the catchment is shown in Table 4-2. From the analysis, it appears that the drainage from the Dandaragan Plateau is significant and is likely to be the main contributor to Ellen Brook baseflow. A large portion of this discharge is potentially recharging Superficial Aquifer in the northern sub-catchment and may also be lost to evaporation in the inundated areas.

### 4.3. Conclusions

The analysis indicates that the hydrological regime of the catchment which may be linked to groundwater characterisation can be outlined as follows:

- Ellen Brook annual baseflow significantly contributes to the river flow (up to 57% annual river discharge)
- baseflow is sensitive to both annual rainfall and rainfall intensity and its distribution during the year
- more than 80% baseflow is generated in the northern sub-catchment
- baseflow solely sustained by the regional groundwater is generated within Dandaragan creeks throughout the year and also in Ellen Brook downstream from the gauging station during summer months.
<table>
<thead>
<tr>
<th>Contributor</th>
<th>Annual flow</th>
<th>% total annual flow</th>
<th>% total baseflow</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Annual flow, GL</strong></td>
<td>13.6&lt;sup&gt;1&lt;/sup&gt;</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td><strong>Baseflow, GL</strong></td>
<td>Total</td>
<td>6.0&lt;sup&gt;2&lt;/sup&gt;</td>
<td>44</td>
</tr>
<tr>
<td>Northern sub-catchment</td>
<td>4.8&lt;sup&gt;3&lt;/sup&gt;</td>
<td>35</td>
<td>80</td>
</tr>
<tr>
<td>Dandaragan Creeks</td>
<td>15.8&lt;sup&gt;4,7&lt;/sup&gt;</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Baseflow below the gauging station (this is in addition to the baseflow estimated at the gauging station)</td>
<td>0.3&lt;sup&gt;5&lt;/sup&gt;</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Discharge from Gnangara dunes</td>
<td>&lt;sup&gt;1&lt;/sup&gt;&lt;sup&gt;6&lt;/sup&gt;</td>
<td>&lt;sup&gt;7&lt;/sup&gt;7</td>
<td>&lt;sup&gt;7&lt;/sup&gt;7</td>
</tr>
<tr>
<td>Groundwater discharge over area covered by Guilford Clays (122km&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>44.5&lt;sup&gt;8&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>1</sup> as measured at the gauging station 616189
<sup>2</sup> outcome of baseflow estimation (hydrograph separation)
<sup>3</sup> as 80% of catchment baseflow
<sup>4</sup> flow estimation based on data in Table 3-2
<sup>5</sup> as measured over 49 days period and extrapolated to annual discharge
<sup>6</sup> based on the Donnan Equation, defining daily discharge rate from groundwater to 1 m drain; the following parameters were used: sand hydraulic conductivity K=10 m/day, hydraulic gradient 0.002 and the length of groundwater discharge zone 30 km.
<sup>7</sup> the value indicate stream discharge, but not all discharge is contributed to Ellen Brook
<sup>8</sup> approximate estimation based on the assumption that groundwater discharge may be 1 mm/day as suggested in the previous section
5. WATER QUALITY

5.1. Groundwater quality

Groundwater quality data discussed in this section was mainly obtained from the WIN database as groundwater sampling under the scope of the current project was limited only to the deeper bores where groundwater was sampled for CFC analysis. More detailed analysis of water quality data is given in Appendixes 3-5.

5.1.1. Nutrients

According to WIN data, nutrient concentrations in groundwater are generally low (Figure 5-1 and Figure 5-2). Aside from the data reported by Shams and Smith (2001) elevated phosphorus concentrations (>0.1 mg/L) was found in 11 out of 41 bores, for which data was available (circles in Figure 5-1). Six of these bores are located in the shallower groundwater (<17 m deep) in the northern sub-catchment where water-bearing strata is mainly sand and the groundwater table is less than 0.5 m from the surface in the winter. In the south elevated phosphorus concentrations are observed in three shallow bores found in the vicinity of wetlands.

Shams and Smith (2001) observed high TP concentrations in the deeper Superficial Aquifer in the middle of the catchment, however high phosphorus concentrations (up to 3800 mg/kg TP) were also reported for the aquifer materials and were likely to influence the observed phosphorus concentrations in the deeper Superficial Aquifer.

Based on the WIN data, groundwater nitrogen concentrations are low (<1.0 mg/L) within the shallow and deep Superficial Aquifer (Figure 5-2). However for the majority of sites only inorganic nitrogen has been analysed. For the few sites with TN measurements, DON appears to be the dominant nitrogen in the groundwater, which is consistent with reports by Shams and Smith (2001). As a consequence the groundwater nitrogen concentrations may be expected to exceed 1.0 mg/L over a greater proportion of the catchment than currently suggested by the WIN dataset.

The low groundwater nutrient concentrations were confirmed with the limited sampling conducted as part of the CFC groundwater aging (15 sites). High TP concentrations were observed in some bores; however total dissolved P concentrations tended to be low with only four samples exceeding 0.1 mg/L. Those samples are collected from bores used in the Shams and Smith (2001) study with depths of 4.7-10.5 m; Table A5-1, Appendix 5). Total N concentrations were <1.0 mg/L for the majority of samples (93%) with DON the dominant species (on average 53%; Table A5-1, Appendix 5).

5.1.2. Major ion composition

Groundwater in Ellen Brook catchment in Superficial Aquifer is mainly characterised by Na-Cl, Ca-Na-HCO$_3$-Cl and Ca-HCO$_3$ compositions with some minor variations. The distribution of the groundwater type is given on a Piper Diagram, using available data from the WIN database (Appendix 3; Figure A3-2). Considering that the main source of groundwater originates from rainwater which is Na-Cl type, the deviation from this type indicates that groundwater quality was affected by rock/soil/water interactions. Na-Cl groundwater type is more typical for shallow groundwater, where a greater proportion of bores (75% of 44) with inlets <15 m BGL had this water type.

Groundwater Ca-Na-HCO$_3$-Cl and Ca-HCO$_3$ types suggest that calcium carbonate is likely to be present or was present in the aquifer materials, which is typical for the Ascot Formation.
(Davidson, 1995). In addition, calcium carbonate was possibly present in the Bassendean Dunes, prior to weathering as suggested by Bastian (1996). The deeper bores with inlets greater than 15 m BGL are more likely to be characterised by Ca-Na-HCO$_3$-Cl and Ca-HCO$_3$ types (67% of 21).

This suggests that the shallow groundwater quality is mainly influenced by rainwater recharge and evaporation processes. The deeper groundwater quality is influenced by interaction with aquifer materials.

Na-Cl water type is more typical for the north and west of the Ellen Brook catchment, while the groundwater in south-east area of the catchment is predominantly Ca-Na-HCO$_3$-Cl and Ca-HCO$_3$ type. Therefore if Ellen Brook receives some groundwater contribution to the river flow in the southern sub-catchment, some Ca enrichment in surface water may be expected.

### 5.1.3. Groundwater residence time

According to CFC analysis groundwater residence time is likely to be longer than 30 years (Appendix 5). No spatial patterns were observed in the groundwater age to suggest areas of recent recharge. One bore in the west of the catchment (AWRC Ref 61611021; NR2C) where groundwater age is the youngest (1976) had high groundwater ammonia concentration (6.5 mg/L). Such high groundwater ammonia concentration may indicate human activity affecting recent recharge near this location (e.g. septic systems, fertilisers). The relationship between groundwater nutrient concentration and identified age could not be determined.
Figure 5-1 Groundwater phosphorus concentration; each point represents the maximum total phosphorus or soluble reactive phosphorus if total P was not available for that site; SCCP long term targets for TP concentration were used for concentration cut-off.
Figure 5-2 Groundwater nitrogen concentration; each point represents the maximum total nitrogen or NO₃, NH₃ or TKN if total was not available for that site; SCCP long term targets for TN were used for concentration cut-off.

Groundwater contribution to nutrient export from the Ellen Brook catchment
5.2. Surface water quality

5.2.1. Ellen Brook gauging station

Nutrient concentrations at the Ellen Brook gauging station (AWRC Ref 616189, EBN18) show a close relationship with river discharge rates with nutrient concentration increasing with flow. Typically high nutrient concentrations are observed during storm events and lower concentrations during baseflow. This relationship is influenced by temporal factors as shown on (Figure 5-3) with key features as follows:

- Nutrient concentrations at the beginning of the wet season may be affected by ‘first flush’. During this period, there is also greater variability in nutrient concentrations, which is likely to be the result of the mobilisation of nutrients upon the onset of the winter rains from river bed or landscape, which is common for phosphorus and nitrogen seasonal dynamics (Baldwin and Mitchell, 2000; Peters and Donohue, 2001).

- Nutrient concentrations are elevated at the end of the flow season potentially due to the effect of evaporative concentration in the water pool at the gauging station; which was noted during the baseflow monitoring program in 2007 (Appendix 4).

Nutrient concentrations measured at the gauging station show an overall annual variation in median concentration of 2-2.5 times and a well-defined seasonal pattern (Figure 5-3).

![Box plots of TN and TP concentrations and river flow for the gauge station 616189 over 1987-2008 period](image)

**Figure 5-3** Box plots of TN and TP concentrations and river flow for the gauge station 616189 over 1987-2008 period; boxes represent the 25th and 75th percentiles, the error bars the 10th and 90th percentiles and the points the 5th and 95th percentiles for TN, TP and river flow for months from May to December

During July–August, when the river discharge is generally high, TP and TN concentrations are less variable as well as during the baseflow period from September–November. Concentrations of TP and TN consistently decrease during September–November .

A strong linear relationship is observed between average monthly TN/TP concentrations and the log of the total winter monthly discharge for 1996-1999 (Figure 5-4). This is based on the high frequency data for 1996-1999, where the data for the time of year when nutrient concentration is affected by ‘first flush’ and by evaporative concentration are excluded.
The relationship between nutrient concentration and river discharge varies depending on seasonality and flow rates as illustrated by the TP concentration-discharge curves in Figure 5-6. Three storm events were considered:

- In the early part of the wet season high TP concentrations are associated with the rising limb of the hydrograph when TP reaches high concentrations, e.g. up to 0.6 mg/l in the example given in Figure 5-5a. This is in agreement with the earlier comment related to the potential effect of ‘first flush’ on TP transfer from the catchment to the river.

- Later in the winter, the peak in nutrient concentration during storm event is observed after the peak in the discharge and during the recession of the river hydrograph (Figure 5-5b). Considering the flow distribution analysis described above and higher input from the northern sub-catchment during the recession period of the river hydrographs (Figure 4-10), the pattern of TP and flow may indicate that higher nutrient contributions are related to the discharge from the northern sub-catchment. Furthermore, the baseflow TP concentration is also higher than in the earlier wet season.

- For the high flow events, such as shown in Figure 5-5c, the relationship between TP and river discharge is poor due to dilution effect, particularly evident after river discharge reaches 8 m$^3$/s.

It was also noticed that the nutrient concentrations were higher during mid-winter baseflow than during spring baseflow. Furthermore, for winter baseflow, nutrient concentrations were higher during the wetter years than during the drier years (Figure 5-6).
Figure 5-5 Total phosphorus (TP) concentration and river discharge hysteresis curves for individual storm events (a) early wet season (20/6/96 to 26/6/96), (b) mid-winter (20/8/96 to 23/8/96) and (c) for high flow events (3/8/97 to 9/8/97).

Figure 5-6 Average TP and TN concentrations during winter baseflow for 1996, 1997 and 1999 and their relationship with total annual baseflow estimated for those years.
5.2.2. Nutrient concentrations in the waterways within the Ellen Brook catchment

Spatial variability of TP and TN concentrations in the Ellen Brook catchment is evident from the snapshot data collected from the main Ellen Brook channel, the eastern and western tributaries by Horwood (1996) and the Chittering Landcare group in 2005-2008. The EC and nutrient concentrations recorded for the eastern and western tributaries indicate large differences in water quality for these areas. (e.g. Figure 5-8). A substantially higher EC is found in the surface water of the eastern tributaries, while nutrient concentrations are greater in the western tributaries.

A summary of the water quality within various waterways in Ellen Brook catchment is given in Table 5-1.

5.2.2.1. Eastern tributaries

Nitrogen concentration is generally lower in the eastern tributaries than in the western tributaries and the main Ellen Brook channel; however, when it is greater than 1-1.5 mg/L it is mostly associated with inorganic fractions of the nitrogen pool. A particularly high proportion of inorganic nitrogen (more than 60%) was detected in the sampling locations EBN1 (Lennard Brook) and EBN5, where sampling points are located within the Dandaragan Plateau, elevated above the river valley. There are two locations (EBN6 and EBN8) where TN is greater than 1 mg/L and organic N dominates; they are associated with the streams flowing along the Guilford Formation within the river valley. These sites drain a wetland identified as a groundwater discharge zone (EBN8) or intensive farm land (EBN6).

Average TP concentration is less than 0.08 mg/L for all eastern tributaries except Lennard Brook (EBN1). The highest EC values were detected in the areas identified as groundwater discharge zones (EBN7, EBN8 and EBN 10).

5.2.2.2. Western tributaries

Western tributaries are characterised by higher TN and TP concentrations; however, EC is much lower than in both the eastern tributaries and the main Ellen Brook channel. Average TN concentrations are in a range 2.5 - 4.6 mg/L and average TP concentrations varied between 0.5-3.2 mg/L (Figure 5-8 and Figure 5-9). For all sites, inorganic nitrogen concentration comprises less than 20% and more often less than 10% (in 62% samples). Headwaters of all the streams are associated with the groundwater discharge zones, springs and wetlands developed at the foot of the Gnangara Dunes. Groundwater discharge to some springs is continuous throughout the year.

The highest nutrient concentrations are associated with the streams monitored at EBN11 and EBN12 which are related to more intensive land use in these sub-catchments.

It was initially thought that the spatial differences in water quality could be used as a natural tracer for sources of contributions to the surface water fluxes. However, although large differences in water quality are observed between the eastern and western sub-catchments (up to 20 times for TP) variability in the main channel is small (<2.5 times).

During the baseflow analysis for spring 2007, enrichment in TN, TP and DOC concentrations was observed between middle river reach (EBN9) and the gauging station (EBN18) (Appendix 4). This may suggest that nutrient input is occurring between these two stations, most likely from the high nutrient western sub-catchments (nutrient concentrations at EBN16 greater than at EBN9 or EBN18). Increases in Ca and HCO₃ concentrations between EBN9 and EBN18 also support inputs from the western sub-catchments (see Figure A4-4 in Appendix 4). However, prior to mid-November the flow, EC, other major ion concentrations
and major ion compositions are similar for these two stations (see Figures A4-2, A4-3, A4-4 and A4-6 in Appendix 4). As described in Section 3.3, evaporation from the main channel may account for the contribution to flow from the western sub-catchments. Thus the slight diluting effect of the western sub-catchments is lost even though there are increased inputs of the nutrients, Ca and HCO₃.

During the 2007 spring baseflow period the TN and DOC concentrations (see Figures A4-7, A4-8, A4-13 and A4-14, respectively, in Appendix 4) are observed to decrease for all monitored sites, while TP remains relatively stable (see Figure A4-10 and A4-11 in Appendix 4). Nitrogen speciation remains linked to DOC (average DON/TN > 75%) during the spring baseflow period, while the SRP/TP ratio decreases in the main channel and the western tributary. As N and P behave differently both in terms of concentration and speciation, the processes influencing N and P transport over the spring baseflow period appears to be different but not resolvable. Furthermore, the reduction in TP in the middle of the monitoring period at EBN9 may indicate changes to the contribution of different source areas upstream of this site. As the northern sub-catchment (i.e. upstream of EBN9) contributes the greatest proportion of the flow during the spring baseflow period, further information is needed to determine the source of the TP reduction.

In the lower reaches of the catchment downstream from the gauging station TN, TP, DOC and EC are lower in summer than in the main channel during the spring baseflow period. In fact, the nutrient concentrations in the lower reaches (average TN = 0.71 mg/L and average TP = 0.12 mg/L) are more closely related to the groundwater nutrient concentrations (Figures 4-1 and 4-2).

Nutrient concentrations measured in groundwater discharge at the head of a western sub-catchment (EBN14A; see Figure A4-17 in Appendix 4) during summer are also lower than the Chittering Landcare group monitoring site downstream of Railway Parade (EBN14; Figure 5-8) and also the neighbouring western tributary monitored during CSIRO spring baseflow monitoring (EBN16; see Figures A4-7, A4-10 and A4-13 in Appendix 4). Assuming that groundwater nutrient concentrations in discharge at the head of the western tributaries remains consistent throughout the year, the increase in concentration downstream is related to a source in the valley area.

Total N has a strong correlation with DOC, whereas TP is not closely related to DOC at all stations. Total P concentration increased during late spring baseflow at EBN9, where groundwater contribution is greater. This suggests that nitrogen is likely to be related to the organic matter sources and TP is not (Figure 5-7).

It appears that the nutrient concentrations in monitored sub-catchments varied in absolute values, yet retained similar patterns: the N/P concentrations remained greater in the west, lower in the east and intermediate in the main channel throughout the hydrological cycle.

The surface water DOC:DON ratio during the spring baseflow is lower than during the summer baseflow (see Figs A4.15 and A4.18 in Appendix 4). During the spring baseflow this ratio is approximately 20 indicating that slow release of N could occur upon degradation of the dissolved organic matter as a result of microbial activity. Furthermore DOC:DON ratio during the summer baseflow is higher (~40), suggesting that N release from dissolved organic matter is even more limited.
Figure 5-7 Relationship between total nitrogen (TN) (a) and total phosphorus (TP) (b) with dissolved organic carbon (DOC) during the baseflow period 2007 at three monitoring locations.
Figure 5-8 Mean electrical conductivity (EC), total nitrogen (TN) and total phosphorus (TP) for snapshot sampling by the Chittering Landcare Group (2005-2008) for the main Ellen Brook channel and tributaries; error bars represent the standard deviation on the mean.
Figure 5.9 Mean electrical conductivity (EC), total nitrogen (TN) and total phosphorus (TP) for snapshot sampling by the Chittering Landcare Group for September, October and November (2005-2008) for the main Ellen Brook channel and tributaries; error bars represent the standard deviation on the mean.
Table 5-1 Water quality in various waterways in Ellen Brook catchment

<table>
<thead>
<tr>
<th>Location</th>
<th>Unit scale</th>
<th>Seasonality</th>
<th>Nitrogen (as TN)</th>
<th>Phosphorus (as TP)</th>
<th>DOC</th>
<th>Comments</th>
<th>Baseflow contribution to Ellen Brook</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>GW(^2)</td>
<td>SW</td>
<td>SW</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(&lt;40 m)</td>
<td>(&lt;40 m)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Gnangara Dunes</td>
<td>Regional</td>
<td>Intermittent</td>
<td>0.016-2.8</td>
<td>1.00 - 1.70</td>
<td>0.35 - 0.40</td>
<td>30 - 33</td>
<td>68-79 (74)% DON 68-97 (84)% SRP(^3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>as NO(_x)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dandaragan Plateau</td>
<td>Regional</td>
<td>Continuous</td>
<td>0.17-13</td>
<td>0.7-3.0</td>
<td>0.03-0.36 (0.19 av)</td>
<td>4.8-19.3</td>
<td>38-87 (65)% SRP 4-98 (34)% DON</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>as NO(_x)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northern sub-catchment</td>
<td>Local</td>
<td>Intermittent</td>
<td>1.5-13.0</td>
<td>0.64 - 2.80</td>
<td>0.17 - 0.42</td>
<td>13 - 62</td>
<td>29-75 (43) % SRP 39-100 (74)% DON(^4)</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>as NO(_3)</td>
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<td></td>
<td></td>
<td></td>
<td>0.02-0.84</td>
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</tr>
<tr>
<td>Ellen Brook valley (clay)</td>
<td>Local</td>
<td>Intermittent</td>
<td>0.003-6.6</td>
<td>1.60 - 3.30</td>
<td>0.24 - 0.84</td>
<td>27 - 63</td>
<td>50-91 (70) % SRP 64-96 (85)% DON(^5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.09-5.1(^*)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>0.07-3.2(^**)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>0.01-0.6</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>as SRP</td>
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<td></td>
<td></td>
<td></td>
<td>0.004-1.32</td>
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<td></td>
<td>0.01-0.2(^*)</td>
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<td></td>
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<td></td>
<td>0.01-0.67(^**)</td>
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<td></td>
<td></td>
<td></td>
<td>0.01-0.36</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>0.01-0.03</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Lower Ellen Brook sub-</td>
<td>Regional</td>
<td>Continuous</td>
<td>0.02-0.37</td>
<td>0.44 - 1.20</td>
<td>6.5 - 13</td>
<td>15-36 (25) % SRP 58-93 (74)% DON(^6)</td>
<td>100% during summer months</td>
</tr>
<tr>
<td>catchment</td>
<td></td>
<td></td>
<td>(n=2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eastern sub-catchment</td>
<td>Regional</td>
<td>Intermittent</td>
<td>0.27</td>
<td>0.09</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(as NH(_3)</td>
<td>(as SRP</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>n=1)</td>
<td>n=1)</td>
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</tr>
</tbody>
</table>
* from Shams and Smith (2001) shallow groundwater quality monitoring, with depth to bore inlet <5 m
** from Shams and Smith (2001) deeper groundwater quality monitoring, with depth to bore inlet >5 m

2 GW – groundwater and SW – surface water
3 Station EB14
4 Station EB9
5 Station EB16
6 Station EB20
7 Station EB22
5.3. Conclusions

The main findings, based on the data and analysis presented in Chapter 5, can be summarised as follows:

- The major ion composition in groundwater and surface water is similar and as such cannot be used for investigation of groundwater contribution to the river flow with exception to the river reaches which receive deeper groundwater in the southern sub-catchment. Some Ca enrichment was observed during spring baseflow analysis in 2007 between monitoring station EBN9 and EBN18.

- The residence time of groundwater in the deep Superficial Aquifer was estimated to be greater than 30 years; thus the deep groundwater quality is unlikely to be influenced by current land use.

- According to available data nutrient concentrations are low in the deeper Superficial Aquifer, and it is reflected in the low nutrient concentrations during summer baseflow downstream from the EBN18 (gauging station 616189).

- High P concentrations observed for some bores in the deeper Superficial Aquifer may be related to P in the aquifer matrix (Sham and Smith 2001) and not to land use.

- Nutrient concentrations may be high in the shallow (or perched) groundwater in the northern Ellen Brook sub-catchment, where nutrient concentrations during spring baseflow are high.

- Throughout the annual hydrological cycle nutrient concentrations increase with the river flow, showing a linear relationship with the log₁₀(discharge). Though nutrient concentrations are always lower during baseflow, they tend to be higher during years when baseflow is high.

- There is evidence that N and P may have different sources or pathways from the catchment to surface water during spring baseflow. It was found that N is closely linked to DOC, while the relationship between P and DOC is poor. At some locations (such as EBN9), P concentration increases during the low flow, while N and DOC concentrations decrease.

- Higher organic N concentrations are related to those streams where groundwater discharge was identified.
6. CONCEPTUAL GROUNDWATER MODEL

Based on the available information, the groundwater systems in the Ellen Brook catchment, which are likely to influence river flow and (or) water quality at least during some period of an annual hydrological cycle, may be grouped into six hydrogeological units (Figure 6-1):

- Gnangara Dune system
- Dandaragan Plateau
- Northern Dunes sub-catchment
- Ellen Brook valley
- Lower Ellen Brook sub-catchment
- Eastern sub-catchment.

The extent of the units was only indicative and will require further clarification by more detailed spatial analysis, which was outside the current project scope. The preliminary delineation of the units was based on Surface Geology map, DEM analysis and interpretation of available monitoring data. The description of the units and the effect of hydrogeological and hydrological conditions on Ellen Brook flow are given below.

Groundwater contribution to nutrient load in Ellen Brook is related to two factors (Figure 6-2):

- the contribution of groundwater discharge to baseflow in Dandaragan Plateau, Northern dunes sub-catchment and Lower Ellen Brook sub-catchment
- the effect on the processes controlling nutrient accumulation and release in the areas where groundwater discharge is continuous throughout the year, such as Northern dunes sub-catchment and Ellen Brook valley.

On an annual basis, most of the baseflow (> 80%) is generated in the Northern Dunes sub-catchment upstream from EBN9 (Figure 6-3), contributing to a large proportion of the total river flow (e.g. more than 50% of annual flow in 1992). High baseflow rates in this area are controlled by:

- substantial flow contribution from the streams draining Dandaragan Plateau (up to 17GL/year)
- surface inundation due to flat landscape and shallow groundwater occurrence within the river valley in the north (groundwater levels are at the surface in winter)
- some input of the local groundwater.

Although river discharge is low (<20 L/sec) during summer baseflow downstream from the EBN18 (gauging station 616189), it enables continuous nutrient contribution to Swan River throughout the year. However, the concentrations and loads are low during summer baseflow. Residence time in regional groundwater is more than 30 years and groundwater quality is unlikely to be affected by recent land use in the catchment.

High nitrate concentration is detected in the Lennard Brook, but not in the Ellen Brook, and is likely to be depleted due to the denitrification processes in the waterlogged areas in the Northern Dunes sub-catchment, characterised by high organic carbon and anaerobic conditions.

Groundwater also sustains multiple wetlands. In addition to anthropogenic nutrient input, organic matter, nitrogen and potentially phosphorus are likely to accumulate over time within wetlands and upper reaches of the streams draining wetlands. Constant water availability, due to continuous groundwater discharge throughout the year, supports diverse and plentiful vegetation, but also provides preferable conditions for the higher rate of organic matter decomposition. A more detailed description of the hydrogeological units is given below.
Figure 6-1 Hydrogeological units in the Ellen Brook catchment according to adopted conceptual groundwater model
Figure 6-2 The stream reaches which receive groundwater discharges: red – groundwater discharge significantly influence the river baseflow, blue – groundwater discharge influence the processes controlling nutrient accumulation and organic matter decomposition
Figure 6-3 Catchment area contribution to baseflow
## Hydrogeological units

<table>
<thead>
<tr>
<th><strong>Gnangara Dunes systems</strong></th>
<th><strong>Role in nutrient contribution to Ellen Brook</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>The hydrogeological unit is formed by a dune deposits in the western part of Ellen Brook catchment. Groundwater here is recharging from the direct rainwater infiltration and does not generate stormwater, which is indicated by the extremely low drainage density within this area. The recharge rate was estimated to be up to 40% rainfall (Silberstein et al, 2008)</td>
<td>The groundwater discharge from the dunes composes small portion in the water balance of Ellen Brook, however it is likely to be an important factor in nutrient generation in the catchment. The continuous flow and high yielding aquifers attract agricultural activities within a close proximity to the wetlands and springs resulted in high nutrient input. Sands are also characterised by low nutrient retention.</td>
</tr>
<tr>
<td>The groundwater discharge from the unit within the Ellen Brook catchment occurs where the sand deposits overlays Guilford clays, forming springs and wetlands with 30 km along eastern and southern edges. Based on available information (water levels in the monitoring bores and published data on hydraulic properties of Bassendean Sands) the groundwater discharge is likely to be $q=1\text{GL/year}$</td>
<td>In addition to anthropogenic nutrient input, organic matter, Nitrogen and potentially Phosphorus are likely to accumulate over time within wetlands and upper reaches of the streams draining wetlands. Constant water availability due to continuous groundwater discharge throughout the year supports diverse and plentiful vegetation, but also provides preferable conditions for the higher rate of organic matter decomposition.</td>
</tr>
<tr>
<td>The groundwater abstraction in the Gnangara area resulted in the groundwater table drawdown, which cause reduction or loss of the groundwater discharge to a number of springs.</td>
<td>Groundwater system is classified as regional.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Dandaragan Plateau</strong></th>
<th><strong>Role in nutrient contribution to Ellen Brook</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>The recharge in the aquifer hosted by Cretaceous deposits in the Dandaragan plateau is associated with areas outside of the Ellen Brook surface water catchment. The aquifer is confined and discharge zones are likely to be associated with the streams flowing from the plateau towards the river valley. Some of these streams (such as Lennard Brook) are perennial, which generates 4.7-8.6 ML/year(^8). The additional discharge zone from this hydrogeological unit is associated with the “break of the slop” area, which was confirmed by remote sensing data analysis. According to available information it is unlikely (however possible) that the Cretaceous aquifer(s) is hydraulically connected to the Superficial Aquifer. However a continuous flow in the stream receiving groundwater discharge from Cretaceous aquifer(s) is likely to contribute to</td>
<td>As in the case Gnangara Dunes discharge, the continuous flow in the streams attracts agricultural activities with close proximity to the stream lines. As a result surface water quality in the streams along the slopes of Dandaragan plateau (e.g. Lennard Brook above EBN1) is characterised by high Nitrogen as Nitrate (85%TN) but low DOC concentration (&lt;15 mg/L). TP concentration is also high in contrarily to reported earlier in Shams and Smith, 2001.</td>
</tr>
<tr>
<td>The additional discharge zone from this hydrogeological unit is associated with the “break of the slop” area, which was confirmed by remote sensing data analysis. According to available information it is unlikely (however possible) that the Cretaceous aquifer(s) is hydraulically connected to the Superficial Aquifer. However a continuous flow in the stream receiving groundwater discharge from Cretaceous aquifer(s) is likely to contribute to</td>
<td>Similarly to the Gnangara springs the continuous flow of the Dandaragan plateau streams resulted in development of wetland in the foothill area, and it appears that water quality on the outflow from those</td>
</tr>
</tbody>
</table>

\(^8\) However it is not clear if all discharge from Lennard Brook is directed to the Ellen Brook or partly may be flowing to the north from the Ellen Brook catchment
the Superficial Aquifer recharge in the Northern sub-catchment of Ellen Brook.  

*Groundwater system is classified as regional.*

<table>
<thead>
<tr>
<th>Groundwater system is classified as regional.</th>
<th>Northern Dunes sub-catchment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low nutrient retention capacity of the sand deposit, high water table, high sand permeability, low surface gradient and intensive land use (livestock) cause accumulation of nutrients in shallow groundwater. The flat landscape and low groundwater gradients resulted in a low rate of groundwater fluxes, and water balance is likely to be dominated here by recharge and evaporative losses. During the period when the groundwater table is above the drainage base the shallow groundwater contributes to the creek flow and high nutrient loads in surface water. High water table during winter months reduces the opportunities for infiltration and therefore cause an increase in stormwater generation in this area, which is otherwise provide a storage for rainfall infiltration. Low P retention capacity of sands and preferable condition denitrification process associated with water logging resulted in high concentration of TP/SRP and low concentration of Nitrate with overall high TN concentrations. Available data suggests that TP and TN concentration in the Ellen Brook main channel in this area is constantly higher than elsewhere.</td>
<td>Based on limited information available from the bore logs and also by low drainage density, Northern Dunes sub-catchment is likely to be underlined by Quaternary sand deposits. Bore logs indicate that in some area “coffee rock” has been developed within first meters from the ground surface, suggesting a historically high water table in this area. The groundwater table along the creek line is close to the surface varying from 0.2 m in the winter to 2 m in the summer. The area is prone to inundation, which has also identified by Landsat imagery analysis. According to available monitoring data the hydraulic gradient in this area is influenced by the drawdown in the groundwater table in the Gnangara dunes (Banksia area), where the water table is lower than in the valley. This implies that this area is likely to be the recharge zone for northern Gnangara groundwater resources. The high position of groundwater table in the valley may also be due a higher groundwater recharge rates in this area than further to the west, associated with discharge from Dandaragan plateau. Ellen Brook baseflow is greatly dependent on discharge from this area both in terms of the baseflow duration and volumes. It was shown that the spring baseflow in Ellen Brook (2000 data) exists when the surface inundation occurs in the northern sub-catchment. High nutrient concentrations were detected in some monitoring bores.</td>
</tr>
</tbody>
</table>

**Ellen Brook valley**

Ellen Brook valley further to the south is underlined by Guildford clays which are less permeable than other Quaternary deposits and are likely to provide a local aquitard for the deeper Superficial Aquifer and therefore limit the recharge to the Superficial Aquifer. Drainage density along the valley implies a higher rate of stormwater generation than elsewhere in the catchment, indicating a low rate of

| Groundwater contribution to nutrient export from the Ellen Brook catchment | 67 |

|  | Groundwater contribution to nutrient export from the Ellen Brook catchment | 67 |
Groundwater contribution to nutrient export from the Ellen Brook catchment

<table>
<thead>
<tr>
<th>Sub-catchment</th>
<th>Description</th>
<th>Nutrient concentrations during the baseflow period within this hydrogeological unit are lowest among the records and are close to the SCCP targets. The observed concentration in the river during summer time is likely to be affected by in-stream processes and/or livestock input, where animals have a direct access to the stream. However during the summer months groundwater discharge provides a media for the nutrient transfer to Swan River, and as such contributing to the summer nutrient loads.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Ellen Brook sub-catchment</td>
<td>Lower Ellen Brook sub-catchment is located downstream from the gauging station, where the river channel cut deep into superficial deposits (e.g. up to 15 m upstream from the confluence with Swan River). Groundwater discharge here is sufficient to provide continues river flow throughout the summer months, and is likely to be related to regional groundwater discharge.</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Groundwater system is classified as local.</em></td>
<td></td>
</tr>
<tr>
<td>Eastern sub-catchment</td>
<td>Eastern sub-catchment formed by Precambrian rocks is not likely to provide groundwater contribution to Ellen Brook and its tributaries. Spring baseflow period is shorter than in the western tributaries; however there is indication of groundwater discharge zones in this area identified by remotely sensed data analysis and observation during spring 2007 monitoring program, when a water pool at EBN22 was maintained after the flow ceased. According to the available surface water</td>
<td>This area provides low groundwater contribution to Ellen Brook and overall low nutrient loads. Streams receiving groundwater discharge are characterised by higher organic nitrogen concentrations, but overall high salinity.</td>
</tr>
<tr>
<td></td>
<td><em>Groundwater system is classified as local.</em></td>
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</tr>
</tbody>
</table>

Groundwater contribution to nutrient export from the Ellen Brook catchment
quality data, which is gravitated to salinity affected areas, these tributary are characterised by low TP concentrations, but TN concentration are 1-2 mg/L.

*Groundwater system is classified as regional.*
7. CONCLUSIONS

This research project was developed to develop a conceptual groundwater model for the Ellen Brook catchment. The scope of the work involved the review of previous reports and the water flow and quality data in the surface and groundwater. It was complemented with some additional field work designed to verify the initial understanding of the hydrogeological workings of the system.

Key outcomes of the project are summarised:

1. Groundwater contribution to nutrient load in Ellen Brook is related to two factors:
   a. the contribution of groundwater discharge to baseflow and
   b. the effect on the processes controlling nutrient accumulation and release in the areas where groundwater discharge is continuous throughout the year.

2. Contribution of groundwater discharge to the river flow is most significant in two areas:
   a. in the streams draining Dandaragan Plateau, particularly during winter months when discharge is contributing to surface inundation in the northern Ellen Brook sub-catchment
   b. in the lower reaches of Ellen Brook during summer and autumn months (when groundwater is a sole source for the river flow). During other times, groundwater contribution at this location composes a small portion of total river flow.

3. On an annual basis, baseflow accounts for (on average) 42% of annual river discharge. This percentage may be up to 57% during drier years and 31% in wetter years. Most of the baseflow (more than 80%) is generated in the northern sub-catchment upstream from EBN9. High baseflow rates are controlled by:
   a. substantial flow contribution from the streams draining Dandaragan Plateau (up to 17GL/year)
   b. surface inundation due to flat landscape and shallow groundwater occurrence within the river valley in the north
   c. some input of the local groundwater.

4. The Northern sub-catchment also generates a large proportion of the total river flow, e.g. more than 50% of annual flow in 1992.

5. Groundwater discharge to the river in the Southern sub-catchment is low and likely to be less than potential evaporative losses estimated as 5000ML/day during the spring baseflow period in 2007. This also confirms that the occurrence of Guilford clay provides a regional confining layer restricting groundwater discharge from the deeper Superficial Aquifer to Ellen Brook and its tributaries.

6. In some areas groundwater discharge rates are not large enough to generate a continuous stream flow. The permanent presence of water however, supports flourishing flora and fauna, which then influences the biological and chemical process within the hypothetic zones and maintains the environment where organic matter and nutrient accumulation occurs. Such areas also attract human settlements and agricultural activities. The areas include the:
   a. upper reaches of the western tributaries, receiving groundwater discharge from the Gnangara Dunes
b. break in the slope areas along the northern hills sub-catchment at the foothill of Dandaragan Plateau.

7. Groundwater fluxes in these areas can promote surface primary productivity, influence sediment microbial activity and affect organic matter decomposition. This explains the high concentrations of DOC and TON in the creeks downstream from these areas.

8. Nutrient concentrations in surface water during baseflow are lower than during peak flow. It appears that the N and P in surface water during baseflow may be related to the difference sources. Total nitrogen is mainly associated with the sources which also generate dissolved organic carbon but phosphorus does not closely relate to DOC.

9. Nutrient concentrations in the regional groundwater are generally low. The regional groundwater residence time is greater than 30-40 years and groundwater quality is unlikely to be significantly influence by current land use activities.

10. Shallow groundwater in the areas of sand occurrence, such as in the northern sub-catchment, is likely to have high concentrations of P and organic N.

11. High nitrate concentration detected in the Lennard Creek, but not in the Ellen Brook, is likely to be lost from the water due to the denitrification processes in the waterlogged areas characterised by high organic carbon and anaerobic conditions.

A number of future research activities may advance the knowledge of nutrients transfer in the Ellen Brook catchment:

1. Identify the water balance and nutrient budget in the areas receiving groundwater discharge which potentially provide a substantial contribution on DOC and TON to the river load

2. Further validate Landsat 7 data interpretation in relation to delineation of the groundwater discharge zones

3. Conduct detailed studies of the groundwater fluxes in the northern sub-catchment which currently contributes large proportion of the annual river discharge
8. REFERENCES


Lantzke N (1997) ‘Phosphorus and nitrate loss from horticulture on the Swan Coastal Plain.’ Agriculture Western Australia, Miscellaneous Publication 16/97, Perth.


1. Surface water quality

1.1 Catchment outlet
Surface water quality data has been collected at the Ellen Brook gauging station since 1987. Donohue et al. (2001) and Peters and Donohue (2001) presented the trends in nutrient concentrations and nutrient transport from the Ellen Brook catchment for the period 1987 to 1998. No long term trends were observed for total nitrogen (TN) concentrations though total phosphorus (TP) concentrations decreased between 1994 and 1998 (Donohue et al., 2001). TP was also shown to be positively related to discharge, particularly during the flow rate below 6 m$^3$/s (Donohue et al., 2001).

Surface water TP concentrations show a strong seasonal variation. TP concentrations increase rapidly with the onset of the wet season and slowly decrease towards the end of the season (Peters and Donohue, 2001). Soluble Reactive Phosphorus (SRP) is a large proportion of TP (70%) and its seasonal variations are similar to those for TP.

Dissolved Organic Nitrogen (DON) is the dominant form of TN in surface water (Peters and Donohue, 2001). The low proportion of nitrate ($\text{NO}_3^-$) was attributed to high denitrification potential of the soils within the catchment and low in-stream biological production due to limited light penetration in the highly coloured waters (Peters and Donohue, 2001).

1.2 Within the catchment
A number of different studies and monitoring programs of surface water quality within the catchment have been conducted over the years (Donohue, 1994; Gerritse 1994; Sharma et al. 1993; Sharma et al., 1994; Sharma et al., 1996; Horwood, 1997; Shams and Smith, 2001). These studies focused on the nutrient concentrations and salinity in the Ellen Brook main channel and also in the tributaries. The tributaries considered include the horticulture dominated Lennard Brook in the north and the eastern and western tributaries in the middle to lower catchment. It was reported that nutrient concentrations and salinity vary both spatially and temporarily.

Similar average TN concentrations are observed in the Lennard Brook and Ellen Brook main channel above the Ellen Brook gauging station and are generally greater than 1 mg/L, reportedly 1.3-1.6 mg/L (Sharma et al, 1993) and 1.68-1.88 mg/L (Donohue, 1994). Lower TN concentrations were observed in the upper Lennard Brook (0.7 mg/L) and downstream of the Ellen Brook gauging station, e.g. 0.85 – 1.2 mg/L (Sharma et al, 1993). In the Ellen Brook main channel organic N species are dominant (Donohue, 1994; Sharma et al, 1993; Sharma et al 1994).

Nitrate concentrations ($\text{NO}_3^-$) are high in Lennard Brook (~0.5-2 mg/L) and generally NO$_3^-$ is the major N species in Lennard Brook, though it varies seasonally (Sharma et al, 1993). Daily water quality data showed sharp increases in NO$_3^-$ concentrations in the Ellen Brook main channel at the beginning of storm flow declining during recession (Sharma et al, 1996). The enhanced NO$_3^-$ in storm runoff was attributed to greater interaction of surface runoff with the nutrient rich soils (Sharma et al, 1996).

Generally TN concentrations in western tributaries discharging to Ellen Brook in its middle and lower reaches are higher than TN concentrations the eastern tributaries (Horwood, 1997). DON is the dominant N species in the western tributaries (Donohue, 1994; Shams and Smith, 2001), while according to Sharma et al (1996) NO$_3^-$ contribution to Ellen Brook was higher from the eastern tributaries. Inorganic N (NO$_3^-$ and ammonium) concentrations in both the eastern and western tributaries also vary seasonally with greater concentrations at
the beginning of winter (first rainfall events) and progressively decreasing concentrations later (Sharma et al., 1996).

It was reported that Phosphorus concentrations in Lennard Brook are generally low (TP and SRP < 0.1 mg/L) with the SRP/TP ratio reasonably constant (0.8) (Sharma et al., 1994). TP concentrations are higher in the Ellen Brook main channel in its middle to lower reaches, and could be as high as 3.8 mg/L (Donohue, 1994; Horwood, 1997). SRP is the dominant P species in the Ellen Brook main channel however the SRP/TP ratio varies seasonally (Donohue, 1994; Sharma et al. 1994). Daily measurements indicate that SRP concentrations rise sharply with storm flow and decline during the flow recession which has been attributed to greater interaction of surface runoff with the nutrient rich soils (Sharma et al, 1996). The SRP concentrations in the baseflow have also been shown to vary seasonally, with higher concentrations in the mid-winter baseflow (0.3-0.5 mg/L) and lower concentrations in late winter baseflow (0.1-0.2 mg/L; Sharma et al, 1996). Sharma et al (1996) suggested that this was due to the change in proportion of surface runoff and groundwater, surface runoff having a greater proportion during the mid-winter baseflow.

In the middle to lower Ellen Brook catchment the western tributaries typically have higher TP concentrations than those to the east (Horwood, 1997). Little SRP is observed in the eastern tributaries (<0.1 mg/L) while in the western tributaries SRP concentrations (up to 4 mg/L) are often greater than observed in the Ellen Brook main channel (Sharma et al., 1994). Baseflow SRP concentrations from the western tributaries show little seasonal variability remaining relatively constant over the winter period (Sharma et al, 1996). SRP concentrations were reported to be higher during storm events than during baseflow period.

Both chloride concentration and electrical conductivity (EC) have been used to trace the sources of surface water salinity in the Ellen Brook catchment (Sharma et al, 1996; Horwood, 1996; Horwood, 1997). Sharma et al (1996) observed that chloride (Cl) concentrations were four folds greater in the eastern tributaries compared to the western tributaries. Similarly, Horwood (1996, 1997) noted that the EC was higher in eastern tributaries. Chloride concentrations in the eastern tributaries showed a seasonal pattern with higher EC reported during early winter (up to 1800 mg/L) before decreasing in the middle to late winter (~300 mg/L). Cl concentrations in the western tributaries were lower and no seasonal patterns were reported (~100 mg/L).

Dissolved Organic Carbon (DOC) concentrations in the Ellen Brook main channel ranged from 40-60 mg/L (Gerritse, 1994) with DOC concentrations in the seasonal creeks to the west of Ellen Brook ranging from 50-89 mg/L (Shams and Smith, 2001).

2. Groundwater quality

2.1 Nutrient leaching and soil properties

High N and P concentrations have been observed in the shallow groundwater associated with horticultural production on the Gnangara mound (Lantzke, 1997; Salama et al., 2005). The leaching of fertilisers from horticultural production (turf, vegetables, and flowers) on Bassendean soils has lead to an increase in nutrient concentrations in the shallow groundwater beneath and immediately down gradient of production areas. TP and NO\textsubscript{3} in the upper 2 m of the Superficial Aquifer was reported to be up to 38 mg/L TP and 100 mg/L NO\textsubscript{3} (Lantzke 1997). However the deeper layers of the Superficial Aquifer were not greatly affected by high nutrient concentrations.

In horticultural production areas on Bassendean soils fertiliser NO\textsubscript{3} leached to the deeper Superficial Aquifer at two of the nine monitored sites (Lantzke, 1997). Low NO\textsubscript{3} concentration in the deeper Superficial Aquifer was attributed to three factors: (i) presence of impervious iron-cemented sands (known as “coffee rock”) limiting vertical movement of NO\textsubscript{3} rich water,
(ii) denitrification processes in the upper aquifer and/or (iii) the dilution by unaffected groundwater from outside the horticultural production area.

In leaching experiments, Gerritse (1996) observed dissolved organic matter in the soil leachates with carbon to nitrogen (C/N) ratios between 20 and 40. Similar C/N ratios have been observed in the Ellen Brook main channel (Gerritse, 1994) and in the seasonal creeks discharging to Ellen Brook from the west tributaries (Shams and Smith, 2001). The authors suggested that the soil organic matter is the probable source of dissolved organic C and DON in surface water and groundwater. Due to the high C/N ratio the dissolved organic matter is most likely to be derived from native vegetation accumulated in the grey sandy soils prior to catchment clearance (Gerritse, 1994).

Most soils within the Ellen Brook catchment have a limited capacity to retain P with only 12% of surface soils and 25% of subsoil having medium P sorption capacity $K_d > 15$ (Sharma et al, 1996). Soils to the west of Ellen Brook are characterised by lower P sorption capacity while soils to the east of Ellen Brook tended to have the highest P sorption capacity due to the greater iron oxide content (Gerritse, 1994; Gerritse et al. 1995; Sharma et al., 1996). Gerritse (1996) and Sharma et al. (1996) observed high groundwater P concentrations in areas of virgin (unfertilised) soils and suggested transport could occur via surface water and/or groundwater pathways.

Phosphorus concentrations in the deeper Superficial Aquifer under horticultural areas on Bassendean soils are generally low. In the Bassendean soils a layer of indurate sand comprised of humus and iron oxides (or “coffee rock”) is formed at the depth of the minimum groundwater level (Lantzke, 1997). Where the layer of indurate sand was present under horticultural areas P concentrations were low in the deeper Superficial Aquifer (Lantzke, 1997). It was suggested that this layer may provide high P sorption where it was permeable, or the impermeable coffee rock may also act as a physical barrier to vertical movement of water and P. Additionally Lantzke (1997) proposed that P leached below the coffee rock into the deeper Superficial Aquifer may also be diluted by low P groundwater from outside of the horticultural production area may also contribute to the low P concentration in the deeper groundwater.

2.2 Groundwater quality measurement

Within the Ellen Brook Catchment most of the investigations into groundwater nutrient concentrations were focused on areas to the west of the Ellen Brook main channel within the middle to lower catchments underlined by the Guildford Formation. Groundwater nutrient concentrations and speciation vary spatially, vertically and temporally (Sharma et al., 1993 1994; Shams and Smith, 2001). Nitrogen concentrations can be very high, mainly in the shallow groundwater (TN up to 17 mg/L) which is greater than observed in the seasonal creeks/drains to the west of Ellen Brook. Nitrate ($NO_3$) is dominant in the shallow Superficial Aquifer (within the Guildford Clay Formation) however $NO_3$ concentration is highly variable (<0.005-16 mg/L). Generally $NO_3$ concentrations are low in the lower Superficial Aquifer (Bassendean and Gnangara Sands) with DON dominating.

Groundwater P concentrations are generally lower than observed in the seasonal creeks/drains discharging to Ellen Brook from the west (Sharma et al., 1993; Sharma et al., 1994; Shams and Smith, 2001). Groundwater P was dominated by SRP although speciation varied seasonally at some locations and for some depths. In the shallow Superficial Aquifer within the Guildford Clay Formation P concentrations are generally low due to the high P retention capacity of the clay (Shams and Smith, 2001). However, in the deeper Superficial Aquifer P concentrations are high due to the low P retention capacity of the sandy aquifer.

Groundwater EC and Cl concentration was also highly variable both spatially and with depth, e.g. EC= 43-2300 mS/m and Cl=5-6100 mg/L, however temporal variability was low. Generally the groundwater EC in the shallow Superficial Aquifer is greater than observed in the deeper Superficial Aquifer (Shams and Smith, 2001). The average groundwater EC and
Cl concentration (410 mS/m and 1215 mg/L respectively) are an order of magnitude greater than observed in the seasonal creeks/drains, where average EC and Cl concentration are 44 mS/m 94 mg/L respectively (Shams and Smith, 2001).

To date no studies have been conducted on groundwater nutrients to the east of Ellen Brook or in the north of the catchment apart from the Lennard Brook catchment.
APPENDIX 2. BASEFLOW ANALYSIS

The baseflow analysis was undertaken by Flow Duration Curve (FDC) analysis and hydrograph separation for the gauging station (AWRC 616189) where flow data was available for the period 1966-2006. In addition, weekly flow metering and surface water sampling were undertaken at a number of locations within the catchment during September 2007-March 2008. These stations are shown in Figure 1-3 and Figure 2-3 in the main report.

Flow Duration Curves
The FDC is a plot that shows the percentage of time that flow in a stream is likely to equal or exceed some specified value of interest. FDC analysis allowed qualitative evaluation of groundwater contribution to river flow. The shape of a FDC in its upper and lower regions is particularly significant in evaluating the stream and basin characteristics. The shape of the low-flow region characterises the ability of the basin to sustain low flows during dry seasons. A very steep curve (high flows for short periods) would be expected for rain-caused floods on small watersheds. In the low-flow region, an intermittent stream would exhibit periods of no flow, whereas, a very flat curve indicates that moderate flows are sustained throughout the year due to natural (or artificial) streamflow regulation, or due to a large groundwater capacity which sustains the baseflow to the stream.

The stream flow records over the observation period were included in the FDC analysis both on an annual basis and for the entire data set. Following discussion above Figure A2-1 suggests that the contribution of the regional groundwater to the river flow is limited. At the gauging station and on annual basis the river flows only for 63% days. In comparison Figure A2-1 also shows FDC for the Southern River, where the groundwater contribution has been established.
Hydrograph separation

Separation of the river hydrograph was based on the partition of the periods with hourly flow increment less than 20 L/sec (or nearly 1800 m$^3$/day). The baseflow was estimated for each year between 1966 and 2006. As an example, Figure A2-2 shows the baseflow separation for 1980 river flow data, where baseflow was estimated as 8.7GL. Comparison between total flow, baseflow and meteorological conditions allowed analysis of rainfall effects on the river discharge and duration of the flow.

Figure A2-2 – An example of baseflow separation during a selected year (1980)

Figure A2-3 – Baseflow and storm runoff distribution during the entire observation period
According to analysis of all river hydrographs over the 30 years observation period (Figure A2-3), the annual baseflow is proportional to annual rainfall and increase from 4.5GL/yr during low rainfall years to more than 20GL/yr during high rainfall years (Figure A2-4). Accordingly the proportion of the baseflow in total annual river discharge varies between 50% and 30% for low and high rainfall years, respectively.

![Figure A2-4 – Relationship between total annual river discharge and baseflow with annual rainfall](image)

It appears that baseflow deviation from long-annual average baseflow is sensitive to rainfall (Figure A2-5): 10% reduction (or increase) in annual rainfall causes approximately 20% reduction (or increase) in baseflow which is comparable with variation in the total annual river discharge (26%).

![Figure A2-5 – Effect of variation in annual rainfall on variation in baseflow](image)
APPENDIX 3. WIN DATA ANALYSIS

1. Major Ion Composition
Based on the major ion composition (Ca, Mg, K, Na, Cl, SO\(_4\), HCO\(_3\)) of available surface and groundwater samples Piper diagrams were constructed to investigate how the major ion composition altered both spatially and temporally. A Piper diagram allows the examination of water samples through groupings of common cation and anion assemblages or water types with clusters of samples indicating a common source. For example if a sample is in contact with limestone (CaCO\(_3\)) it would be expected that Ca HCO\(_3\) water types to dominate.

1.2 Surface Water
The analysis of major ion composition for the gauging station (AWRC 616189) was limited by the availability of samples containing all seven major ions. Of the 64 samples 51 were collected between May 1981 and October 1982. Although there is limited data there is very little variation in the major ion composition at the gauging station with the data falling into the Na-Cl water type (Fig. A3.1). All other surface water data available also indicates that Na-Cl water type is dominant.

Based on the available surface water data, the small temporal variability observed at the gauging station and the lack of data from end-members (e.g. eastern tributaries) it is difficult to distinguish between surface water sources. Small differences exist between the gauging station and (i) Lennard Brook indicating a slight enrichment of Ca and (ii) the western tributaries which show greater Ca and HCO\(_3\) enrichment.

1.2. Groundwater
Groundwater major ion composition shows much greater variability compared to surface water (Fig. A3.2). The data falls into three main water types, Na-Cl, Ca-Na-HCO\(_3\)-Cl and Ca-HCO\(_3\) with about 50% of the samples falling into the Na-Cl class over all depths. This range of water types suggest that calcium carbonate may be or have been present in the aquifer materials to give the Ca-HCO\(_3\) end member. This is consistent with calcium carbonate of the Ascot Formation and possibly with the Bassendean Dunes if calcium carbonate was present prior to weathering as theorised by Bastian (1996). The other end member composition Na-Cl is related to rain water inputs and possibly saline soils. A greater proportion of sites (75% of 44) had with inlets <15 mBGL had a Na-Cl water type as compared to sites with inlets >15 mBGL (33% of 21). Of all sites, three had repeated measurements showing a Na-Cl water type and another water type. These results suggest that the shallow groundwater is influenced by rainwater recharge and evaporation giving the Na-Cl water type while calcium carbonate in the aquifer matrix influences the deeper groundwater to a greater extent.

Groundwater to the north and west of the catchment tends to have a greater proportion of Na-Cl water type. This may be related to the depth to the Ascot Formation in these areas since the sites are at a greater elevation (greater quaternary sediment thickness) than bore closer to Ellen Brook in the south of the catchment.

Based on the current WIN dataset the use of major ion composition to differentiate different groundwater and surface water end-members contributing to the Ellen Brook discharge is limited. The first limitation is that the surface water data all falls under the Na-Cl water type and hence the source water is also likely to be of the same water type, for example rainwater or the shallow groundwater. The few samples from the western tributaries indicate that there may be a calcium influence at least in the south of the catchment where these sites are located.
Figure A3.1 – Piper diagram showing the major ion compositions for the Ellen Brook gauging station (AWRC Ref 616189), Lennard Brook (AWRC Ref 617165), two other Ellen Brook main channel sites (AWRC Ref 6162261 & 6162262) and 4 samples from western tributaries (AWRC Ref 6161050, 6161052, 6161053, & 6160060). All units are in %meq/L. The other water type category includes Ca-Na-HCO$_3$-Cl and Ca-HCO$_3$ water types.
Figure A3.2 – Piper diagram showing the major ion compositions in the groundwater in the Ellen Brook catchment. All units are in %meq/L.
Figure A3.3 – Shallow Superficial groundwater (inlet <15 mBGL) major ion composition separated on water type. The other water type category includes Ca-Na-HCO₃-Cl and Ca-HCO₃ water types.
Figure A3.4 – Deep Superficial groundwater (inlet >15 mBGL) major ion composition separated on water type. The other water type category includes Ca-Na-HCO$_3$-Cl and Ca-HCO$_3$ water types.
2. Nutrients concentrations in surface water

2.1. Outflow from the catchment

High frequency TP and TN data were available for the period 1996 - 1999 at the gauging station (AWRC 616189). Example of relationship between flow and nutrient concentrations for 1997 is shown on Figure A3-5, which shows a close relationship between TN and TP and the river flow, when river discharge is plotted in a logarithmic scale.

Figure A3-5 Variation in flow (note log scale), total nitrogen (TN; a) and total phosphorus (TP; b) for 1997 illustrating the relationship between nutrient concentrations and river discharge
2.2 Catchment wide

Available water quality data suggests that there exists a strong relationship between nutrient concentration and EC (Figures A3-6 and A3-7). This is largely reflects the differences between nutrient concentration and EC distribution in eastern and western Ellen Brook tributaries. Water quality measured at the outlet of the Ellen Brook catchment (gauging station 616189) is less variable than for sites distributed throughout the catchment (Figure A3-7) suggesting that extremes in nutrient concentrations and EC are diluted prior to the gauging station. There is a need for individual stream discharge data to determine the influence of the various tributaries to the flow at the gauging station and thus nutrient contribution.

Figure A3-6 – Comparison of total nitrogen (TN) and total phosphorus (TP) with electrical conductivity for the Ellen Brook surface water snapshots sites (Chittering Landcare group and DoW, 2005-2008); data points represent the average for each site and the error bars represents the standard deviation
Figure A3-7 Comparison of total nitrogen (TN) and total phosphorus (TP) with electrical conductivity (EC) for the Ellen Brook gauging station (616189) and sites distributed throughout the catchment. Greater variability is observed in the water quality measured at the sites distributed throughout the catchment than at the catchment outlet (i.e. the gauging station).
APPENDIX 4. RIVER FLOW AND WATER QUALITY DURING BASEFLOW PERIOD 2007-2008

1. Monitoring methodology - baseflow during the period 2007-2008

Four sites were initially selected to undertake flow and water quality analysis during the baseflow period:

- two sites on the Ellen Brook main channel (in the middle of the river reach, EBN09 and at the gauging station, EBN18),
- one on the western (EBN16) and
- one on the eastern tributary (EBN22; Figure A4-1).

The sampling sites were selected from the current Chittering Landcare group and DoW catchment monitoring program to provide consistency between the monitoring programs. Sites on the eastern and western tributaries were chosen to provide examples of baseflow nutrient concentrations for the eastern and western sub-catchments.

The sampling commenced on 28th September 2007, and was undertaken weekly until the flow in the river ceased (early December 2007). In January the sampling program was expanded to four additional sites, where stream flow was recorded throughout the summer months on fortnightly basis between January-March 2008. Two sites were located in the low reach of Ellen Brook (EBN20 and EBN20A) and two other sites at the foot of the dune system in the western sub-catchment (EBN14A and EBN14B), where groundwater-fed springs occur. The western monitoring sites are located in a different sub-catchment to EBN16, but were selected due to easy access to sampling sites and continuous stream flow. These stations allowed monitoring discharge in a groundwater spring (EBN14A) and in the creek collecting groundwater discharge (EBN14B). Flow in the monitored creek ceased before reaching the Ellen Brook main channel.

At each location the discharge was recorded, in-situ parameters measured with a Horiba U-10 metre (pH, EC, DO, temperature, turbidity) and a water sample was collected. A duplicate sample was collected at one of the four locations during each sampling event.

Samples were further analysed for

- nutrients (Total N (TN), total dissolved N (TDN), ammonia (NH₃), nitrite (NO₂), nitrate (NO₃), total P (TP), total dissolved P (TDP), soluble reactive P (SRP)),
- major ions (Na, K, Ca, Mg, Fe, Al, Cl, HCO₃, SO₄),
- trace metals (Cd, As),
- dissolved organic C (DOC),
- electrical conductivity (EC), pH, total suspended solids (TSS) and total alkalinity.

Only results on nutrients, EC, pH and some major ions are presented in this report.
Groundwater contribution to nutrient export from the Ellen Brook catchment
2. Spring baseflow: discharge and water quality

2.1 Stream flow

The duration of Ellen Brook baseflow as recorded at the gauging station (EBN18) during spring 2007 was about 2 months. During this time river discharge at the gauging station reduced from ~750 L/s in September to no flow in mid-November. During this time 64mm rainfall was recorded, resulted in three well defined hydrograph peaks in the river flow (Figure A4-2).

Ellen Brook discharge in the middle of the river reach (EBN9) was similar to the discharge observed at the gauging station or at least within the error of the flow estimation. This suggests that the river has a limited recharge between these two points. Due to high flow and due to staff safety considerations, discharge measurement at EBN09 was only possible from 23 October. Flow decreased from 167 L/s to 7.6 L/s at the end of the monitoring period (13 December).

The flow in the Eastern tributary (EBN22) subsided within 3 weeks of monitoring from 21.6 L/sec to 2L/sec and ceased completely by week 4. However, a pool of standing water was remained until mid-December. The Western tributary baseflow (EBN16) was observed until mid December 2007, though flow was only measureable until mid-November.

![Figure A4-2 Stream flow at observation stations](image-url)
2.2 Water quality

Electrical conductivity (EC) at the Ellen Brook gauging station remains (EBN18) relatively constant in the early spring baseflow however from early November the EC is affected by evaporative concentration (Figure A4-3a). The EC in the middle reach also remains relatively constant initially though decreases from mid-November. The lowest EC was observed in the western tributary (Figure A4-3b). The general decrease in EC in the eastern tributary and the low flow may indicate that the area contributing to the flow is small and does not include areas of high salinity. The slight increase in EC for the eastern site might also be attributed to evaporative concentration from the end of October. Generally pH increases during the spring baseflow period at all sites (Figure A4-3c and A4-3d). The pH is lowest in the middle reach of Ellen Brook (EBN09) and increases slightly downstream (0.5 pH units) to the gauging station (EBN18). The pH of the tributaries tends to be higher than the main channel especially in the later spring baseflow.

The major ion concentrations follow a similar pattern to the EC (Na, Mg, K, Cl and SO$_4$) with the exception of Ca and HCO$_3$ (Figure A4-4). This is also reflected in the variation of ion concentrations with chloride concentration where Na, Mg and K follow the seawater dilution line while Ca and HCO$_3$ concentrations are enriched compared to seawater ratios (Figure A4-5). This indicates that surface Ca and HCO$_3$ is derived from sources other than rainwater, e.g. soil or groundwater. Calcium concentrations are greatest in the western tributary and increases during the spring baseflow. While the Ellen Brook middle reach had the lowest Ca concentration which decreases with time. Bicarbonate is also lowest in the Ellen Brook middle reach and remains constant for the spring baseflow period. Bicarbonate concentrations at the other three sites remain relatively constant for the first half of the spring baseflow period and increases in late October/early November.

Figure A4-3 Surface water EC and pH during baseflow at four monitoring stations on the main channel (a, c) and the tributaries (b, d).
Figure –A4-4 Surface water Ca and HCO₃ concentrations during baseflow at four monitoring stations on the main channel (a, c) and the tributaries (b, d).
Figure A4-5 Variation in surface water major ion concentration with chloride concentration. Here chloride is assumed to be conservative and deviation of samples above the seawater dilution line indicate that surface water ion concentrations are enriched compared to the seawater ionic ratios. Deviation below the line indicates that ions are removed from surface water via precipitation reactions.
The composition of the major ions (Ca, Mg, Na, K, HCO$_3^-$, SO$_4^{2-}$ and Cl) can be used to indicate changes in water sources contributing to surface water. Evaporative concentration does not alter the composition of the major ions if all remain in solution (i.e. precipitates do not form). The major ion composition of the baseflow surface water is shown in Figure A4-6. The major ion composition does not vary greatly at the Ellen Brook main channel sites (EBN09 and EBN18) with a strong dominance of Na and Cl ions. The major ion composition of the eastern and western tributaries varies over the monitoring period with an increasing proportion of Ca and HCO$_3^-$ present (see Figure A4-6, arrows represent increasing time).

The initial eastern tributary (EBN22) composition is similar to that observed in the main channel and is likely to represent water from the hills. As flow ceases by week 4 at this site the change in composition is likely to arise from a shift in the balance of water from the hills and low discharge from local groundwater from the more clay rich soils. However the local groundwater discharge is not great enough for flow to be maintained.

The major ion composition of the western tributary (EBN16) is different to that of the main channel over the whole monitoring period. Similar compositions were observed by Shams and Smith (2001) for both winter and spring samples. The shift in composition at EBN16 indicates a change in the water source to one which is more Ca/HCO$_3^-$ rich or the reduction of a more Na/Cl rich water source.

Figure A4-6 Piper diagram showing surface water major ion compositions. All units are in %meq/L. The bold arrows in the three sections of the graph indicate the change in composition observed over the monitoring period.
Total Nitrogen (TN) concentrations decrease at all sites during the spring baseflow period (excluding the periods effected by evaporation; Figure A4-7 and A4-8). In the Ellen Brook main channel, TN concentrations increase downstream from EBN09 to EBN18. Greater TN is observed in the western tributary than in the main channel and the eastern tributary. Dissolved organic N (DON) is the dominant nitrogen species at all sites (Figure A4-9), average 75% of total N (standard deviation 17%). Dissolved inorganic N (DIN) is low at all sites contributing less than 5% to total N.

Figure A4-7 Total Nitrogen (TN) in surface water during baseflow at four monitoring stations, (a) main channel and (b) tributaries.

Figure A4-8 Variation of Total Nitrogen with flow during the spring baseflow monitoring period with the highest flows at the beginning of this period. Note difference in the flow axis for (a) Ellen Brook main channel and (b) the eastern and western tributaries.
Groundwater contribution to nutrient export from the Ellen Brook catchment

Figure A4-9 Nitrogen speciation in surface water during baseflow at (a) EBN09, (b) EBN18, (c) EBN22, (d) EBN16. DON – dissolved organic nitrogen, NH3-N – ammonia/ammonium nitrogen, NO3-N – nitrate nitrogen

Total P concentrations are relatively constant at all stations during the baseflow period until 7 November, followed by concentration increase later in November and December. This is likely due to evaporative concentration affecting water quality at EBN18 and EBN16 as flow substantially dropped (Figure A4-10). Total P also varies little as flow decreases except for EBN09 where the concentration decreases between 200 and 160 L/s before increasing as flow decreases (Figure A4-11).

Total P concentrations in the main channel increase between stations EBN09 and EBN18 during all sampling events, while the SRP concentrations did not vary. In the Ellen Brook main channel the SRP/TP ratio in the first half of the spring baseflow period (25 September – 7 November) is greater and SRP composes 50% TP (Figure A4-12). The SRP/TP ratio decreases to 40% and 12% during November and December at EBN09 and at EBN18, respectively. The increase in particulate P at the gauging station (EBN18) may be the result of sorption reactions occurring in the pool upstream of the weir.

The total P concentration in the western tributary falls between that of the Ellen Brook middle reach and the gauging station, however the SRP concentrations in the western tributary are generally greater than in the Ellen Brook main channel. Decreases in the SRP/TP ratio (from ~90% to 55%) in the western tributary do not appear until the late spring baseflow.

Total P concentration in the eastern tributary was less than 0.05 mg/L for the entire spring baseflow period.

Despite the reported link between fertilisers and Cd and As and previous suggestion that Cd and As may be useful as tracers for surface water quality, no detectable concentration was measured in any samples collected during the project.

Dissolved Organic Carbon (DOC) concentration varies widely both spatially and temporally (Figure A4-13). DOC concentration varies little for the first three measurements and then...
Groundwater contribution to nutrient export from the Ellen Brook catchment decreases when flow falls below 200 L/s in the main channel and below 60 L/s in the western tributary (Figure A4-14). The DOC concentration increased downstream in the Ellen Brook main channel. The lowest concentrations were observed in the eastern tributary (6.5 to 13 mg/L) and the highest in the western tributary (30 to 64 mg/L). Increases in DOC concentration in November/December 2007 can be attributed to evaporative concentration during low flow (or no flow) period. The DOC:DON ratio for all sites is generally around 20 indicating that microbial release of N from the dissolved organic matter would be slow (Figure A4-15). Sharp increases in DOC:DON ratio for EBN09 and EBN22 later in the base flow indicate period of low nitrogen content in the dissolved organic matter.

![Figure A4-10 Total Phosphorous (TP) in surface water during baseflow at four monitoring stations, (a) main channel and (b) tributaries.](image1)

![Figure A4-11 Variation of total P with flow during the spring baseflow monitoring period with the highest flows at the beginning of this period. Note differences in the flow axis for (a) Ellen Brook main channel and (b) the eastern and western tributaries.](image2)
Figure A4-12 Phosphorous speciation in surface water during baseflow at (a) EBN09, (b) EBN18, (c) EBN22, (d) EBN16. SRP – soluble reactive phosphorus and DOP – dissolved organic phosphorus.

Figure A4-13 Dissolved Organic Carbon (DOC) in surface water during baseflow at four monitoring stations, (a) main channel and (b) tributaries.
Figure A4-14 Variation of Dissolved Organic Carbon (DOC) with flow during the spring baseflow monitoring period with the highest flows at the beginning of this period. Note differences in the flow axis for (a) Ellen Brook main channel and (b) the eastern and western tributaries.

Figure A4-15 Variation in DOC:DON ratio during the spring baseflow monitoring period showing similar dissolved organic matter carbon to nitrogen ratio for all sites.
3. Summer baseflow: water quality

3.1 Ellen Brook main channel
Two sites were sampled on the lower reaches of Ellen Brook (EBN20 and ENN20A), the EC was slightly lower than the two Ellen Brook sites (EBN09 and EBN18) included in the spring baseflow monitoring upstream (Figure A4-16a). The summer pH tended to be equivalent or higher than the pH observed at the upstream sites (Figure A4-16c).

Total nitrogen concentrations are in the lower range of the spring baseflow observations (≤1.2 mg/L; Figure A4-17a). DON is the dominant N species (average 74%, standard deviation 12%). Total P concentrations at EBN20 and ENN20A are lower than measured at the sites on the Ellen Brook main channel during the spring baseflow (Figure A4-17c). The P speciation in the lower reaches is dominated by particulate P (average 61%, standard deviation 25%) similar to what was observed at EBN18 in the latter spring baseflow. DOC concentrations are reasonably consistent during the summer baseflow ranging from 13 to 19 mg/L (Figure A4-17e), but lower than during the spring baseflow at EBN18 (prior to the effects of evaporation are observed). DOC: DON ratio is greater than observed during the spring baseflow (Figure A4-18a), indicating that the dissolved organic matter is of different composition in the groundwater discharge compared to the other surface water and potentially less available.

Figure A4-16 EC and pH at four monitoring stations
3.2 Western Tributary

The two sites monitored represent groundwater discharge zone, either as spring (EBN14A) or groundwater flow in the drain (EBN14B). The EC at both sites is very low (<24 mS/m) compared to all other sites monitored (Figure A4-16b). The pH at EBN14A is also low (5.2 to 5.4) compared to all other sites (Figure A4-16d). The pH in the drain (EBN14B) was at the lower range of the spring baseflow sampling.

Total N concentration in the groundwater discharge is higher than in the creek, with both sites lower than observed in the western tributary for the spring baseflow monitoring (Figure A4-17b). DON remains the dominant N species averaging 67% of total N (standard deviation 10%). At these two sites NH3-N is high compared to all other sites monitored (0.09-0.27 mg/L) with higher concentrations at EBN14A. NH3-N is the second most abundant species of N with an average of 18% of total N (standard deviation 7%). Total P concentrations in the groundwater discharge (0.35 to 0.40 mg/L; Figure A4-17d) are similar to the early spring baseflow P concentrations for the western tributary. Total P concentrations are lower in the drain (0.18 to 0.24 mg/L; Figure A4-17d). SRP is the dominant P species at these two sites, average 81% (standard deviation 14%). DOC concentrations observed in the groundwater discharge (30 to 33 mg/L; Figure A4-17f) are similar to that observed in the later spring baseflow in the western tributary. The DOC: DON ratio of the dissolved organic matter is similar to that measured in the lower reaches of Ellen Brook (Figure A4-18b).
Figure A4-17 Total N, Total P and Dissolved Organic Carbon (DOC) at four monitoring stations

Figure A4-18 Dissolved organic carbon (DOC) to dissolved organic nitrogen (DON) ratio for the four summer baseflow monitoring stations.
4. Outcomes of surface water quality analysis for the baseflow 2007-2008

During baseflow monitoring in spring 2007 baseflow duration is less than 3 months, supported by 3 major rainfall events (total rainfall 64mm). There was no noticeable inflow to the river in the low reaches between monitoring stations EBN09 and EBN18. Groundwater discharge occurs downstream from the gauging station sustaining minimum river flow (<20 L/sec) throughout the summer.

Water quality was monitored for the spring (September to December) and summer (February to March) baseflow periods. The spatial distribution of nutrients described in the literature, i.e. high N, P and DOC and low EC in the western tributaries, and low N and P and high EC in the eastern tributaries, was confirmed. In addition the DOC in the eastern tributaries was observed to be lower than the western tributaries. During the spring baseflow period the water quality generally improves with time, with the exception of P which remains relatively constant. Hence as the proportion of flow attributed to groundwater increases an improvement in water quality is observed.

During the groundwater sustained summer baseflow in the lower reaches of Ellen Brook water quality also remains consistent with nutrient concentrations generally lower than observed during the spring baseflow in other parts of the catchment. During summer groundwater discharge from springs at the base of the Gnangara dunes also maintains flow in the upper reaches of the western tributaries. The water quality from the springs is enriched in TP compared to surface water during the spring baseflow, while TN and DOC concentrations are similar.
APPENDIX 5. GROUNDWATER RESIDENCE TIME

One of the project objectives is to define the groundwater residence time within the Ellen Brook Catchment. It was suggested that Chlorofluorocarbons (CFC) analysis can be used to identify the groundwater age. Given the known variation in atmospheric CFC concentration with time the age of the groundwater (time since recharge) can be estimated by measuring CFC concentration in the groundwater and converting the concentration to an apparent age using known solubility relationships and the recharge temperature (Cook and Solomon, 1997). The CFC aging method is used for recently recharged groundwater, i.e. from 1965 to present (Cook and Solomon, 1997).

1. CFC analysis
The groundwater sampling methodology was recommended by the analysis laboratory (Leaney, personal communication). Two CFC compounds (CFC-11 and CFC-12) were measured in the gas stripped from the groundwater samples using high purity nitrogen gas and measurement via gas chromatography using the method described by Bussenberg and Plummer, 1992.

The groundwater CFC-11 and CFC-12 concentrations (pg/kg) were converted to an equivalent concentration in the atmosphere (pp by vol) using the salinity of the water, the recharge temperature of the water (mean annual temperature) and the surface elevation. This value was then matched to measured atmospheric CFC data to give a CFC-11 and CFC-12 age.

2. Bore selection for groundwater sampling
Within the constraints of the project timeline and the budget it was impossible to undertake a substantial drilling program to support groundwater sampling at various depths and within various geological strata along preferred transects. Accordingly, the agreed scope of work identified the opportunity to utilise the existing bores for the groundwater sampling program in the catchment.

For this reason available bore logs and details of bore construction were analysed. Only bores screened within the Superficial Formation were included in the analysis, because it is unlikely that the landuse practice would have any significant impact on the deeper groundwater systems, and thus investigation of those systems is outside of the project objectives.

According to the supplied WIN database there are 134 boreholes in the Ellen Brook catchment with the bore inlets positioned at different depths within various geological strata. In order to identify the suitability of the available bores for the groundwater sampling program the bores were classified based on the following criteria:

- The bore inlet was located within the Superficial Aquifer. The approximate depth of the Superficial Aquifer was defined based on the available bore log data.
- The bore inlet intervals were no greater than 5 m
- The bores were accessible for sampling

Only 15 bores met all the above criteria (Figure A5-1). The bores are predominantly located in the southern part of the catchment and the inlet depths varied from less than 5m to more than 40m.
Groundwater contribution to nutrient export from the Ellen Brook catchment

Figure A5-1 Groundwater sampling locations
3. Groundwater residence time

The results of the groundwater age analysis are given in Table A5-1. The CFC-11 results suggest potential contamination of groundwater as they fall outside the potential window for expected groundwater and atmospheric equivalent CFC concentration (Figure A5-2). CFC-11 contamination has previously been reported by Plummer et al. (2000) and Hohener et al. (2003) who attributed to various sources including agricultural pesticides, solvent spills, landfill, and infiltration of contaminated river water and sewage water. There appears to be a spatial pattern to higher CFC-11 values (Figure A5-3), however it is not known whether this is related to land use such as the Pearse RAAF base or other activities in the catchment.

Given the contamination of CFC-11, in these circumstances the CFC-12 analysis provides more reliable estimate of the groundwater age. From the calculation based on CFC-12 concentrations, groundwater residence time is likely to be 30 years or older. Shallower bores show younger ages however there was no spatial relationship observed (Figure A5-4). This suggests that the sampled groundwater is unlikely to be affected by recent land management.

Nutrient concentrations were also measured along with the CFCs (Table A5-2) however no relationship was observed between CFC concentration and the nutrient concentrations when all locations considered as a whole. Generally TN and TDP concentrations observed are low. However there appears to be a link between high ammonia observed in bore NR2C and the young CFC age. Given that this bore is shallow and situated on the Bassendean Sands the high ammonia concentrations are likely to be related to recent recharge.

### Table A5-1 Groundwater age based on groundwater CFC concentrations

<table>
<thead>
<tr>
<th>WIN ID</th>
<th>Site Code</th>
<th>Inlet depth</th>
<th>CFC concentration in water</th>
<th>CFC Apparent age</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td>mBGL</td>
<td>CFC-11 pg/kg</td>
<td>CFC-12 pg/kg</td>
</tr>
<tr>
<td>20084481</td>
<td>RG3B</td>
<td>40-46</td>
<td>158</td>
<td>&lt;20</td>
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<td>5362</td>
<td>NR2C</td>
<td>11-15</td>
<td>&lt;25</td>
<td>99</td>
</tr>
<tr>
<td>5506</td>
<td>L300a</td>
<td>64-68</td>
<td>163</td>
<td>28</td>
</tr>
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<td>L260a</td>
<td>38-43</td>
<td>141</td>
<td>51</td>
</tr>
<tr>
<td>5407</td>
<td>L160a</td>
<td>39-43</td>
<td>153</td>
<td>38</td>
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<tr>
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<td>L170a</td>
<td>25-28</td>
<td>137</td>
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<tr>
<td>5422</td>
<td>L280a</td>
<td>19-22</td>
<td>255</td>
<td>63</td>
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<td>EBC9/99_a</td>
<td>18.25-18.75</td>
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<td>20083201</td>
<td>EBC2/99_c</td>
<td>5.5-6.0</td>
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<td>66</td>
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</tbody>
</table>
Figure A5-2 (a) Ellen Brook groundwater CFC concentration compared to the typical CFC in groundwater and (b) Ellen Brook groundwater CFC expressed as the atmospheric equivalent concentration compared to historical atmospheric CFC concentration.

Table A5-2 Groundwater nutrient concentrations observed in bores sampled for CFCs.

<table>
<thead>
<tr>
<th>WIN_ID</th>
<th>Site_Code</th>
<th>TN</th>
<th>TDN</th>
<th>DON</th>
<th>NH3-N</th>
<th>NO3-N</th>
<th>N_NO2</th>
<th>TP</th>
<th>TDP</th>
<th>SRP</th>
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<tr>
<td>20084481</td>
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<td>0.32</td>
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<td>&lt;0.02</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
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<tr>
<td>5362</td>
<td>NR2C</td>
<td>7.5</td>
<td>7.5</td>
<td>1</td>
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<td>&lt;0.01</td>
<td>&lt;0.02</td>
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<td>&lt;0.01</td>
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<td>0.36</td>
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<td>&lt;0.02</td>
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<td>0.18</td>
<td>0.15</td>
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Figure A5-3 Groundwater CFC-11 concentration for bores sampled April 2008. Note that the CFC-11 was contaminated compared to CFC-12. A plume of CFC-11 seems to be associated with groundwater movement south from Pearce Air Force base.
Figure A5-4 Groundwater age based on CFC-12. For the two bore nests groundwater age is shown according to increasing depth.
1. Introduction

The Ellen Brook catchment has been identified as one of the major contributors of nitrogen and phosphorus to the Swan-Canning Estuary. As part of the Water for a Healthy Country Flagship initiative, a project entitled “Groundwater contribution to nutrient export from the Ellen Brook Catchment” was set up to investigate groundwater fluxes and quality within the catchment. The collaborators that were involved in this work include CSIRO, Western Australia Department of Water and Coastal Catchment Initiatives. More details of this project can be found in a preliminary report by (Barron et al., 2008).

The project has used indirect indicators such as analysis of base flow, groundwater residence time and remotely sensed data to identify groundwater contribution to Ellen Brook. This report summarises the investigation of the potential of using available remote sensing image archive to detect locations of near-surface groundwater in the Ellen Brook catchment. The aim is not to map the locations of groundwater at this stage, rather it is an exploratory study to investigate the feasibility of using remote sensing technology to detect patterns related to or indicative of near-surface ground water. The focus of this report is on describing the satellite data processing methods, the analyses performed on the data, the results achieved and the conclusions.

2. Study Area

The Ellen Brook catchment is located about 35km north-east of Perth in Western Australia. The main land-uses within the Ellen Brook catchment are agricultural, with an expanding region of urban and rural residential development in the south. It includes sections of the Gnangara Mound, RAAF Base Pearce several national parks. The picture below shows the study area.
3. Data and Pre-processing Methods

The study has processed a series of images to characterise ground cover spectral and thermal responses through the drying period after winter rainfall. It is hypothesized that, at least in some vegetation systems, the drying patterns of near-surface groundwater systems will differ in some consistent manner from those in other areas. Landsat 7 ETM+ imagery was the only suitable source of available thermal data at appropriate spatial resolution to test this hypothesis.

The Landsat 7 sensor has been operational since August 1999. However in July 2003 problems developed with the scan line corrector and all subsequent images (SLC-off) have narrow wedges of missing data comprising approximately 20% of the image area. Although there are now methods for compensating for this missing data, in this study we chose to use only complete data and hence were limited to the 1999-2003 date range.

A sequence of as many cloud-free images as possible was sought from September in late spring through to April in the following autumn within the available date range. The 2000-2001 spring/summer period provided the most suitable imagery. Seven dates of imagery were acquired – all available cloud-free imagery that was not immediately after rainfall. Rainfall records from the Bureau of Meteorology were used to make the assessment. The image dates are

- 24 September 2000
- 10 October 2000
- 13 December 2000
- 15 February 2001
- 3 March 2001
- 4 April 2001
- 20 April 2001

Both the multi-spectral and thermal data were processed and analysed. The panchromatic image data was processed, but not used in the analyses stages. The panchromatic image is a single band formed from integration over a broad visible wavelength range. It has finer
spatial resolution (15m instead of 30m for the multi-spectral and 60m for the thermal image bands) and the extra detail can often provide more information on the ground cover type. However the bulk of the information on vegetation condition is contained in the infrared and thermal wavelengths.

The multi-spectral and panchromatic data were ortho-rectified and calibrated to the 2000 rectification and calibration base from the Department of Climate Change Land Cover Change Program using methods described in Furby 2002. The merged AUSLIG 9 second and 3 second digital elevation models were used with a satellite orbital model in the ortho-rectification. The images were registered to the base with sub-pixel accuracy (RMS errors of 7.5-10.5m over 56 independent check points). Standard viewing geometry (earth-sun distance) and BRDF corrections were applied to the ortho-rectified images. The 3 March 2001 image was selected as the calibration base as it was cloud-free had had a large dynamic range. The other images were calibrated to this base using invariant target calculations.

The thermal images were ortho-rectified using the same process as applied to the panchromatic imagery. That is, the image coordinates of ground control points used with the multi-spectral imagery were adjusted for the new pixel size (doubled for panchromatic, halved for thermal) and the same models fitted. Calibration of thermal imagery was not possible as in situ temperature data was not available. In this study, we used the thermal response as a relative indicator of variations within cover types. Recovery of actual ground temperatures from the thermal imagery is a complicated process and is an area of active research (see for e.g Wukelic et al 1989 and Schott et al. 2001) which is beyond the scope of this study.

3. Analysis of multi-spectral data

This section describes the analyses that were performed on the multi-spectral image data, and the results achieved. The purpose of this analysis was to study the changes in reflectance of vegetation over the seven dates to see if patterns emerged that could be associated with the presence / absence of near-surface ground water.

3.1 Method

- Calculate a greenness index (TM band 4 - TM band 3).
- Calculate temporal summaries of the index over time – linear and quadratic coefficients from orthogonal polynomials (Wallace et al, 2006 and Wallace and Furby, 1994).

The hypothesis behind these analyses was that rainfall-dependent vegetation systems would dry out (become less green) faster than vegetation systems that had access to ground water. The Normalized Difference Vegetation Index (NDVI, (TM band 4 - TM band 3) / (TM band 4 + TM band 3)) is the most commonly used greenness index, however in this instance the calculations were simplified by omitting the normalization step as the data was already calibrated. This index is most sensitive to changes in grassy vegetation types (such as crops and pasture) rather than woody vegetation types or bare soil.

A brightness index (TM band 3 + TM band 5) was also briefly investigated. This index is known to respond to changes in condition, primarily density, in woody vegetation (Wallace and Furby, 1994, Furby and Wallace, 1999). The trends shown in the remnant vegetation in and fringing the Ellen Brook catchment all corresponded to fires. Given that water stress would have to be quite extreme to provide measurable changes in woody vegetation density
and also since these are deeper rooted vegetation types that have easier access to groundwater, studies of this index were not pursued.

One of the simplest ways to track greenness is to plot the greenness for a site against time, as illustrated in Figure 2. Sites can be compared by plotting multiple trends together. However, when the input data is from images, it is appealing to create an image display that summarises this information spatially.

One way of summarising the information in the index plots is to describe the shape of the greenness trend through time. If a site does not change, or has small fluctuations around a constant greenness, the trend will be a horizontal line, as shown in Figure 2. As vegetation dries out, the greenness will decrease over time. The rate of change may be constant (linear) or be faster in different time periods (curved) as shown in Figure 2. Rainfall or irrigation may cause a site to become greener over time. The trend will still be linear or curved, but the slope or direction of curvature will be in the opposite direction. If the trigger event for the change occurs part way through the time interval, for example irrigation or loss of water source in mid-summer, the greenness trend will also appear curved. By calculating shape parameters, namely mean, slope and quadratic curvature, the greenness trend can be displayed in image form, as illustrated in Figure 3.

We hypothesise that greenness decline in areas where there is no or little access to water will be more sudden and likely to be characterized by a ‘quadratic’ response of this kind, while areas with access to water (ground or irrigated) will exhibit slower, more ‘linear’ rates of greenness decline or in the case of irrigation, a possible increase instead of a decline.

![Figure 2. Schematic plot of different greenness responses over time which may be associated with different vegetation and water status conditions. The constant line represents no change, linear slope represents slow decline, and the quadratic line represents rapid decline of vegetation.](image)

### 3.2 Results

An example trend image display which highlights these different responses over the seven dates is shown in Figure 2 below. The linear and quadratic slopes for each pixel are displayed in the image on the left. The areas that appear in green are areas of generally
linear greenness decline, which under the hypothesis above would be associated with available water (ground or irrigated) in the scheme above. Areas in yellow that show a quadratic trend indicate more rapid decline in greenness in the early dates. Dark areas show little change in greenness and are mostly perennial vegetation and some continuously irrigated paddocks. The multi-spectral image on the right is from March. Green annual vegetation appears in bright green in the combination of image bands chosen for display to evaluate the observed trends.

The trend image highlights areas that persist in greenness longer than the surrounding vegetation. Field verification work is necessary to establish the water source. A site visit in late summer 2008 to one of the streams highlighted in the trend image did show water flow and was added to the water monitoring sites used in other aspects of the study of the Ellen Brook catchment, suggesting that the trends image is a useful investigative tool.

Figure 3. Left: Greenness trend image where black indicates no change, green indicates linear decline and yellow indicates quadratic decline in greenness over the 7 dates. Right: Multi-spectral image (03/03/01) with bands 5, 4, and 2 represented in red, green and blue respectively.

4. Analysis of thermal image data

The response observed in thermal image data is highly dependent on the land cover types. Some examples are shown in the following pictures in Figure 4. The pictures on the left are example areas of multi-spectral images taken at different dates while the corresponding thermal images are on the right. The different colours in the thermal images represent the different temperatures reflected by the different land cover types. In cooler areas such as the bush, we see shades of blue and green while warmer areas (dry vegetation or bare ground) are represented by shades of yellow and red. As the images are not calibrated, we cannot directly compare values (colours) between images, but we can compare values within images.
The thermal response varies according to ground cover type and condition. Transpiring vegetation usually appears cooler than dry vegetation or bare ground. Within a vegetation type, e.g. within a paddock, variations in the thermal response can indicate variations in plant water usage.

Accordingly, our analysis of thermal imagery has been conducted within stratified cover types with a method that can highlight local temperature variations. In this project, we used the “z-score” (Larsen and Marx, 2001, pp. 282) as a means to study the local variations in the thermal response.

The z-score, also known as the standard score in statistics is a dimensionless quantity calculated by subtracting the mean from individual observed value and then dividing the difference by the standard deviation. The resulting z-score value then indicates how many standard deviations an observation is above or below the mean and in what direction (positive or negative). This is useful when seeking to compare datasets with different magnitudes in data range. In our case, negative z-score values indicates lower than average temperature within the cover type, positive z-score indicates warmer than average temperature within the cover type and zero z-score means average temperature.

4.1 Method
The following describes the steps carried out to analyse the thermal images.

• Stratify image into 3 broad classes of cover types namely, bush, continuously bare and green (annuals).

• Mask areas with surface water (lakes, dams etc).

• For each date, study the variation (deviation from the mean in a local window) within each cover type by calculating a z-score given by

\[ Z = \frac{x - \mu}{\sigma} \], where \( x \) is the pixel value, \( \mu \) is the mean of the class and \( \sigma \) is the standard deviation of the class in the local window.
• Merge the 3 different land cover z-score surfaces so that we have a single z-score surface for each date.

The stratification into land cover types was performed using the September imagery. A perennial vegetation (bush) extent map from the Land Monitor project (Land Monitor, 2008) was applied to separate bush from the remaining cover types. A brightness index (TM band3 + TM band5 > 170) was used to separate bare ground. A water mask was used to exclude surface water. The remaining area was assumed to have some proportion of green (annual) vegetation cover. The thresholds used with the indices were targeted to produce an optimal classification for the Ellen Brook catchment rather than for the whole image area.

The land cover type classification produced from the September image was applied to each image date in the sequence for the calculations to provide a consistent stratification for comparison of thermal patterns over time.

Note that using z-score to identify thermal anomalies has been proposed in a recent work by (Barron and Van Niel, 2007) where the mean and standard deviation for each class was calculated using the whole image. Here we have calculated these statistics within a local window surrounding each pixel to adjust for the external factors that affect thermal response in the area such as climate patterns, geology, terrain and land management. Hence more subtle variations may be detected by the z-score.

The size of the local window was varied by cover type. For green cover (annuals) the window was set to be the size of two typical paddocks. A smaller window was used for continuously bare areas. For the bush (perennials) a bigger window of the order of 2km was set. Only other pixels of the same cover type within each window were considered in the calculations.

Having formed the sequence of z-score images, the temporal variations were investigated in the following ways:
• review of regions that show large deviations (high positive or negative z-scores) in the late summer imagery;
• extracting regions whose patterns of deviation size and direction correspond to those that we hypothesize correspond to near-surface ground water expression; and
• trend analyses as described for the greenness index derived from the multi-spectral data.

4.2 Results

4.2.1 Review of late summer z-score images
An example of the z-score image for March together with its corresponding thermal and multi-spectral image of a local area in the catchment area is shown in Figure 5(a) below.

Green areas, both annuals and perennials, appear coolest (blue) in the thermal image. The areas indicated by the arrows in the lower left of the multi-spectral image are perennial vegetation along a creek line. The area indicated by the arrow in the top right of the multi-spectral image is annual vegetation associated with a wetland. Such areas still show as below the average of the surrounding regions of the same vegetation type (also blue) in the z-score image.

The bare paddocks appear warmer (red) than all the other cover in the thermal image. Only those areas that are different to their surrounds appear as blue (below average) or red (above average) in the z-score image. The z-score highlights local variations within paddocks and vegetation communities. Patterns can be seen within the bush in the top left
of the sample area and between paddocks in the top right (indicated by black arrows in the z-scores image). Within paddock variations can be seen more clearly as shown in Figure 5 (b).

Further investigation is needed to determine if the patterns visible in these images relate to water usage/source in the area.
Groundwater contribution to nutrient export from the Ellen Brook catchment

Figure 5(a). March 2001 images: Top: Multi-spectral image; middle: Thermal image; bottom: Z-score image.
4.2.2 Extracting hypothesized z-score patterns

We can use the time series of z-score images to highlight regions that meet certain assumptions about the response of regions with access to ground water. The first hypothesis is that vegetation with continuous access to ground water will continue to transpire more than the surrounding vegetation and so will always be cooler than its surrounds (column 1 in Table 1 below). The second possibility is that ground water has a constant temperature throughout the year. Areas with ground water access may then be warmer than their surrounds in winter and spring and become cooler than their surrounds in summer. This pattern is represented in the second and third columns of the Table 1 below.

<table>
<thead>
<tr>
<th>Dates</th>
<th>Deviation of z-score from average</th>
</tr>
</thead>
<tbody>
<tr>
<td>September</td>
<td>below above above</td>
</tr>
<tr>
<td>December</td>
<td>below below above</td>
</tr>
<tr>
<td>March</td>
<td>below below below</td>
</tr>
</tbody>
</table>

Table 1. Summary of scenarios which may identify areas with access to ground water.

We use some examples to discuss the results obtained based on the above assumptions.

**Example 1**

The areas with responses as in the first column of Table 1 are mostly bush and wetlands. This is expected since bush and wetlands are areas that have continuous access to water. An example is shown in the pictures below.

The picture on the left is the composite z-score image in grey background where the red areas are those that are consistently lower in temperature as compared to its surroundings (column 1 of Table 1). These areas correspond to wetland and dense or well-watered bush areas as shown in the multi-spectral image on the right.
Example 2

Figure 7 below shows an example of the type of areas that satisfy the thermal conditions of second and third columns in Table 1. The picture on the left is the composite z-score image in grey background with red and yellow colours representing areas that are satisfied by the second and third columns respectively, while the picture on the right is the corresponding multi-spectral image.

The highlighted areas are those where thermal response may indicate access to groundwater. However, the red areas seem to have also captured the irrigated areas (bottom left hand corner). Further field investigation is needed to establish the water source in these areas.

4.2.3: Trend analyses

Mean, linear and quadratic trends were calculated from the sequence of z-score images in the same way as described for the sequence of greenness index images. Figure 8 shows a display of the calculated trends together with the September and March multi-spectral images and z-score images. The different colours in the trend image identify areas with different thermal (z-score) response patterns over time. The patterns show detail within cover type but are quite complex and are difficult to interpret. We did not observe patterns that seemed to be directly associated with the presence groundwater as obviously as in the previous examples presented in section 3.
Figure 8: Multi-spectral, z-score and z-score trends images for a sample area.
The mix of colours in the trend image in Figure 8 is more complex than that for the greenness index in figure 3. The March z-score image (d) is a subarea of that presented in figure 5(a). The regions of below average z-score (blue) corresponding to the wet / green areas in March have many different starting points as shown in the September z-score image (c). Some are equally below average with a ‘no change’ trend (black) and some are average with a decreasing z-score trend (blue) in trend image (e). Decreasing trends are also found in areas that were above average in September and average or below in March which seem mostly associated with management actions in this example. ‘No change’ trends are also associated with a range of regions of annual and perennial cover that have an average thermal response throughout the sequence.

The Great Northern Highway bisects the sample area shown in Figure 8. To the east of the highway is the Ellen Brook. In the September z-score image the brook and surrounding regions have a below average thermal response compared to other nearby regions of annuals. By March, most of this region shows as average with some above average areas. The overall z-score trend is quadratic (shades of green or green mixing with red to form yellow if there is an overall increase in z-score), most likely associated with decreasing run-off into the brook and hence decreasing soil moisture. To the west of the highway the trends are very different. There are distinct regions of increasing z-score, some linear (red) and some quadratic (yellow). Once again the shape is determined by the starting point in September and reflects the greenest areas becoming simply averagely bare by March. How green such regions are in September is determined not only by water availability but by land use, crop or pasture, and the associated management inputs. Hence the trend is a response to a range of factors, not simply water availability.

Discussion and Conclusions

The analyses of both the multi-spectral and thermal image data have shown that appropriate processing of remote sensing imagery can identify areas indicative of the presence of near-surface ground water, consistent with the hypotheses provided in this report. Obvious areas such as summer flowing streams and wetlands are highlighted suggesting that further investigation of areas with similar responses is warranted. Targeted fieldwork is essential to validate the products and to evaluate the hypotheses proposed in this report. This field validation would determine areas correctly identified, and to identify and understand areas of “error”. Such a field program was outside the scope of this study and would ideally be carried out on the basis of products derived from imagery acquired and processed close to the validation date.

The thermal patterns are complex and an investigation of seasonal, geological and geographic effects on the response has not been considered in these exploratory analyses. Other datasets, including calibrations with in situ measurements, would be required to separate such effects from water driven responses.

It should be noted that the temporal drying responses and the thermal patterns indicative of groundwater are dependent on the seasonal conditions and the dates of imagery processed.

References


Greenness trend image

Dark areas represent no change, green represents slow decline in greenness and yellow represents quadratic decline in greenness.
Thermal Image (2000-2001)

Thermal image 24/09/00
Thermal image 13/12/00
Thermal image of 3/3/01
Z-score analysis

Image 3/3/01. Shades of blue: below average. Shades of green: average
Shades of yellow/red: above average.
Composite Z-score highlighting areas that satisfy conditions in Table 1. Background image: band5 of multi-spectral image 3/301 in greyscale. Red – warmer than average temperature in September and cooler than average temperature in December and March. Yellow – Warmer than average temperature in September and December but cooler than average temperature in March. Blue – Cooler than average temperature in all 3 dates
Areas that is warmer than average temperature in September and cooler than average temperature in December and March.
Areas that is cooler than average temperature in all 3 dates
APPENDIX 7. METEOROLOGICAL CONDITIONS WITHIN ELLEN BROOK CATCHMENT

The analysis was undertaken based on records at RAAF meteorological station, which is located approximately in the middle of the catchment. Rainfall, effective rainfall (as a difference between daily rainfall and daily potential evaporation when positive) and potential evaporation data are given in this section as daily, monthly and annual values for a period 1970-2006 and shown in Figures A7-1 - A7-4.

On annual basis potential evaporation exceeds rainfall (Table A7-1); however monthly potential evaporation is lower than rainfall during June-August. Annual average effective rainfall represents 70% total rainfall.

Considering residual mass analysis, based on monthly effective rainfall data (Fig. A7-5) it appears that there is a consistent reduction in available water resources since 1986. Daily rainfall events occur on average during 106 days per year, while effective daily rainfall is only recorded on average during 56 days per year.

Table A7-1 Annual average meteorological parameters

<table>
<thead>
<tr>
<th></th>
<th>Rainfall, mm</th>
<th>Effective rainfall, mm</th>
<th>Potential evaporation, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAAF station</td>
<td>662</td>
<td>462</td>
<td>1988</td>
</tr>
</tbody>
</table>
Figure A7-1 Daily rainfall, potential evaporation and effective rainfall data
Figure A7-2 Annual rainfall (a); variation from average annual rainfall (b), Number of days with rainfall per year (c) and monthly average, minimum and maximum rainfall (d)
Figure A7-3 Annual effective rainfall (a); variation from average annual effective rainfall (b), number of days with effective rainfall per year (c) and monthly average, minimum and maximum effective rainfall (d)
Figure A7-4: Annual potential evaporation (a); variation from average annual potential evaporation (b) and monthly average, minimum and maximum effective rainfall (c)
Figure A7-5 Residual mass graph for monthly effective rainfall