A comparison of techniques for investigating groundwater-surface water interactions along the Brunswick River, Western Australia.

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Abstract

Traditionally groundwater and surface water have been managed as separate water resources. However, in many regions, they are hydraulically connected and the abstraction from one can influence the other. There is an increasing body of knowledge recognising the significant implications of groundwater-surface water interactions. Similarly, there are an increasing number of methods being developed to assess these interactions. Throughout Australia the methodology is still in the developmental stage and with a growing number of methods to choose from, selecting the most suitable one is a challenge.

Seven methods were compared for investigating groundwater-surface water interactions in the Brunswick River. These included hydrogeological mapping, hydrograph analysis, temperature studies, seepage measurements, a salinity survey, field observations and water budgeting. The suitability, advantages and disadvantages and the overall results of each method were compared. All the techniques, except a salinity survey, were found to be suited to the Brunswick River environment. The results produced from this project are among the first for groundwater-surface water assessment in Western Australia. The project was successful in determining the spatial variability and scale of connectivity along the Brunswick River, and produced a hydrogeological cross section displaying connected reaches along the river. The temporal variability in connectivity was not immediately assessed and should be considered in future work.
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Introduction

Nearly all surface water features interact with groundwater (Winter et al. 1998). These interactions can have significant implications for both water quantity and quality. However, in many regions groundwater and surface water are managed as separate resources. This can cause many water management issues. An example of this is the over-allocation of water, where the same parcel of water may be allocated twice, once to a groundwater user and then again to a surface water user. This overlap can become a serious issue where allocation is high relative to water availability, as is increasingly becoming the case throughout Australia and many parts of the world. Seepage of groundwater into a river can be important in maintaining flows during extended dry periods and many groundwater dependent ecosystems rely on contributions from groundwater as part of their survival. Therefore, analysis of groundwater inputs and interactions with streams becomes critical when dealing with issues such as water allocation and trading, ecosystem water requirements, reliability of water supply and design of water storages.

Groundwater-surface water interactions are difficult to observe and measure and have commonly been ignored in water management considerations and policies (Winter et. al., 1998). The National Water Initiative, a comprehensive strategy driven by the Australian Government to improve water management across the country, promotes the management of Australia’s water resources as a single resource, recognising the connection between surface water and groundwater systems. This has resulted in a large number of river research projects and method development focusing on assessing the connection between groundwater and surface water.

The Department of Water, like many water resource management agencies throughout Australia, is expanding its understanding of groundwater-surface water interactions to assist with sustainable decision making. Many rivers throughout Australia, particularly in the south west of Western Australia, are under increasing pressure to be developed for use as water resources. Damming the Brunswick River is among a list of potential options
for Western Australia’s future water supply sources (Water Corporation 2005). It is important to understand the functionality of a river system before any adjustments to its natural state can be made. However, while several studies have begun classifying groundwater dependent ecosystems in the area, very little is currently known about the connectivity between groundwater and surface water along the Brunswick River.

The objectives of this project were:

1) To identify reaches of hydraulic connection along the river and determine whether they are gaining (where groundwater discharges into surface water), losing (where surface water infiltrates into and recharges groundwater stores) or neutral (neither gaining nor losing) in character, and in doing so,

2) Compare several techniques for investigating groundwater-surface water interactions along the Brunswick River

Techniques are compared by evaluating their assumptions, limitations, advantages and disadvantages, suitability to the Brunswick River and other environmental conditions, their spatial scale of assessment and the overall implications of their results.
1.0 Catchment Description

The Brunswick River is located approximately 30 km north east of Bunbury and passes through the town of Brunswick Junction. Its catchment area is 286 km$^2$ and extends past the Darling Scarp into the State Forest (Figure 1). The Brunswick River joins with the Collie River approximately 6 km upstream of the Leschenault inlet. The main tributaries of the Brunswick River are the Wellesley, Lunenburgh and Augustus rivers.

The catchment can be divided into two areas, the upper catchment which is upstream of the Darling fault line including the scarp and its foothills; and the lower catchment, west of the Darling scarp, which lies on the Swan coastal plain. Approximately 75% of the lower catchment is cleared of native vegetation and approximately 25% of the upper catchment is cleared (Rose 2004).

Land use in the upper catchment is dominated by the Worsley Alumina refinery and the State Forest. Historically known for its large population of cattle and dairy farming within Brunswick Junction, the lower part of the catchment is now dominated by private horticultural and agricultural land users, mostly beef livestock. A recent water use survey along the river found there are eight licensed surface water users and ten unlicensed groundwater users extracting water from the Brunswick River system (DoW 2006). The majority of land owners in the lower catchment receive water for stock and irrigation purposes from the Wellington reservoir. Harvey Water control the distribution of irrigation water during the irrigation season, which typically runs from October to April (Harvey Water 2003). During the irrigation season, excess surface water runs off the properties and is discharged into the Brunswick River.

Two storage dams lie within the Brunswick River catchment, Beela Dam, which lies on the Brunswick River and has a storage capacity of 0.02 GL, and the Worsley Alumina refinery dam on the Augustus River, which creates a large fresh water reservoir with a storage capacity of 5.2 GL. Beela Dam was constructed in 1948 to supply the Brunswick...
Figure 1. Brunswick River Catchment and location (K. Annan 2006)
Junction Regional Water Supply Scheme, serving Brunswick Junction and the nearby towns of Burekup and Roelands (Water and Rivers Commission 2001). Beela Dam is no longer used for water supply to the scheme and the towns are now connected to the Western Australia’s integrated water supply scheme (IWSS) (Worsley Alumina 2005). Worsley are licensed to abstract 2.1 GL per year from the freshwater reservoir for their bauxite mining operations and are required by contract to maintain an output summer flow of approximately 35 ML per hour from the reservoir to maintain flows in the Brunswick River (Worsley Alumina 2005).

Several streamflow gauging sites exist along the Brunswick River and its main tributaries, operating at varying periods of time (Figure 2). Three sites along the Brunswick River, (612032, 612022 and 612047), and one along the Wellesley River (612024), remain operational while the other sites have been shut down and are no longer used to report flow data.

![Figure 2. Period of operation for streamflow gauging sites in the Brunswick River, referred to by their name and AWRC reference number.](image-url)
The Brunswick catchment lies in a high rainfall zone, crossing the 900 mm to 1200 mm isohyets, common for Darling Scarp jarrah forest. Mean annual catchment rainfall is 909 mm, recorded between 1975 and 2004, at Brunswick Junction Post Office. Mean monthly rainfall recorded at the Brunswick Junction Post Office from 1981 to 2005 (Figure 3), shows June as the peak rainfall month. Comparatively, this year (2006), was an unusually dry year, with well below average rainfall recordings during May to July (Figure 4) and a shift in peak monthly rainfall from June to August. The shift in peak rainfall caused a shift in peak flow during 2006 from the average peak stream flow month of June to August.

Figure 3. Mean monthly rainfall in the Brunswick River catchment (recorded at Brunswick Junction Post Office (009513))
The mean annual flow of the Brunswick River, recorded at Cross Farm streamflow gauging station (612032) from 1990 to 2005, is 130 GL (Figure 5). The Brunswick River may be classified as a perennial and unregulated stream, as it flows all year, and while natural summer flows are maintained by input from the Worsley Dam along the Augustus River, storage capacity of the dam (5.2 GL) is only a small proportion of the mean annual flow (130 GL). Therefore the river is not subject to major regulating effects (Pearcey pers. comm. 2006a).


2.0 Literature Review

Traditionally groundwater and surface water have been managed as isolated components of the hydrologic cycle, even though they interact in a variety of physiographic settings (Sophocleous 2002). Interactions between these systems have commonly been ignored in water management considerations and policies (Winter et al. 1998). Some believe this is due to the separation of the fields of hydrology and hydrogeology (Sophocleous 2002), while others believe it is because the interactions are difficult to assess (Winter et al. 1998). There is a growing consensus among Australian water managers that groundwater and surface water interactions have many significant implications for sensitive water issues including over-allocation, environmental water requirements, river restoration and overall water quantity and quality (Baskaran et al. 2005; Brodie et al. 2005; Evans et al. 2005). In the last decade recognition of the importance of groundwater-surface water interaction has flourished (Langhoff et al. 2006), and today it is widely recognised that to better manage these water issues there is a need to manage groundwater and surface water together as a connected resource.

Before any further discussion on groundwater-surface-water interactions and assessing connectivity can occur it is important to understand the underlying concepts of connectivity and how it is recognised in a river system.

2.1 Definitions of connectivity

A connected water resource is the combination of a surface water feature, such as a river, and the groundwater system that can directly interact in terms of movement of water. The hydrological cycle describes the constant movement of water above, on, and below the Earth's surface (Figure 6). The cycle operates across all scales, from the global to the smallest stream catchment (Smith 1998) and involves the movement of water through evapotranspiration, precipitation, surface runoff, subsurface flow and groundwater pathways. The water table is the expression of groundwater in the shallow aquifer. A
confined aquifer is created by the presence of an impermeable barrier, known as an aquitard at the base of the shallow aquifer.

Groundwater and surface water are not isolated components of the hydrological cycle and they may interact in a range of topographic, geologic and climatic landscapes (Winter et al. 1998). A variety of definitions for the terms surface water and groundwater have been presented in hydrology literature. This thesis will use the basic definition that all water above the surface of the land is considered surface water and all water below the surface of the land is groundwater. Also ambiguous is the name given to the interface between groundwater and surface water, some scholars have called it the groundwater-surface water transition zone (Ford 2005), groundwater-surface water interface (Sophocleous 2002), the stream-aquifer interface (BRS 2006) or the hyporheric zone (Kaleris 1998). This thesis will call it the groundwater-surface water interface.

While the definitions of these terms are ambiguous, the terms used to describe the processes of exchange among them (including fluxes, recharge, discharge, leakage and seepage), are even less clearly defined. The term seepage usually relates to the flow of
water through porous medium (such as sediments). The term flux relates to the flow rate of fluid through a given surface area. Hence, seepage flux refers to the direction and rate of water movement through the groundwater-surface water interface. This thesis will refer to the exchange across the groundwater-surface water interface as seepage flux, where downward (negative) seepage flux indicates flow from surface water to groundwater (recharge) and upward (positive) seepage flux indicates flow from groundwater to surface water (discharge). The term ‘high seepage’ will refer to relatively large fluxes of either discharging or recharging seepage and the term ‘low seepage’ will refer to relatively small exchange fluxes. These concepts are based on definitions used by Sebestyn and Schneider (2001) and have been diagrammatically interpreted for visual understanding below (Figure 7).

![Figure 7. Vertical directions of seepage flux (Sebestyen & Schneider 2001)](image-url)
In order for interaction between surface water and groundwater systems to occur, the systems need to be hydraulically connected. Hydraulic connection is believed to exist between surface water and groundwater systems when the water table is near or above the river bed. Interactions between rivers and groundwater may be classified in three ways:

1) Gaining system: gain water from inflow of groundwater through the stream bed.
2) Losing system: lose water to groundwater by outflow through the streambed.
3) Neutral system: neither gaining nor losing

In order for groundwater to discharge into a stream, the elevation of the water table adjacent to the stream must be higher than the elevation of the river bed. This setting creates an upward hydraulic gradient, which promotes groundwater inflow to the stream and thus a gaining system (Figure 8a). For surface water to seep into groundwater the elevation of the water table must be lower than the elevation of the river bed. This creates a downward hydraulic gradient between the stream and aquifer, promoting the outflow of surface water through the stream bed and thus a losing system (Figure 8b). In both cases it is assumed a permeable structure exists that allows the hydraulic head to move water across the stream bed (Braaten & Gates 2001).

![Figure 8. a) Gaining system and b) Losing system (Winter et al. 1998)](image-url)
A neutral system occurs where the water table is at the same elevation as the river bed and thus in hydraulic continuity with the stream (Figure 9).

![Figure 9. Hydraulically neutral system (Silliman & Booth 1993)](image)

A neutral system may also occur where the system is hydraulically disconnected, usually due to the presence of a thick impermeable barrier (Sophocleous 2002). Although this setting has been more commonly described as a disconnected losing system (Figure 10). In this setting the stream is disconnected from the groundwater system by an unsaturated zone, the water table may have a discernible mound below the stream (Figure 10) if the rate of recharge through the streambed and unsaturated zone is greater than the rate of lateral groundwater flow away from the water table mound (Winter et al. 1998).

![Figure 10. A disconnected system, where the stream is separated from the groundwater by an unsaturated zone. The overall system is losing to the aquifer (Winter et al. 1998).](image)

It is possible to have a variably gaining/losing situation where the stream may be gaining and losing in the same reach at different times of the year. Furthermore, a stream may be gaining in some reaches and losing in others. Therefore, it is important to consider spatial
and temporal variations in groundwater-surface water interaction before the connectivity along a stream can be classified.

Scale issues in time and space are a significant issue in the assessment and management of stream-aquifer connectivity (BRS 2006). Connectivity may vary temporally, due to changes in seasons or decreasing water stores over time. In a spatial context there are three main scales relating to connectivity:

1) *Regional/catchment*-scale, where the stream is placed in context with the overall setting of the catchment (typically >100 km$^2$).
2) *Intermediate/feature*-scale, at the level of individual surface water features, such as the stream reach (typically 1-100km); and the
3) *Local/site*-scale, where site-specific studies provide insights into processes particularly at the stream-aquifer interface (<100 m).

The concept of groundwater interacting with surface water is not new and has been studied since the 1960’s (Meyboom 1961, Toth 1962, 1963, Freeze and Witherspoon 1967). Early studies arose from interest in interactions between groundwater and lakes due to concerns related to eutrophication and acid rain (Sophocleous 2002). Over the past two decades interest in the relationship of groundwater to headwater streams, wetlands and coastal areas has increased (Sophocleous 2002). Recently, attention has been focused on exchanges between near-channel and in-channel water (Woessner 2000; Evans et al. 2005; Ivkovic et al. 2005). However, as described by Sophocleous (2002) the work done has mainly focused on the exchange of water, solutes and energy within the hyporheric zone and at the local scale. Studies of the interaction between groundwater and streams on the intermediate scale, including the flood plain (Brusch & Nilsson 1993; Hoffman et al. 2000), are fewer, yet they have shown that interaction between ground water and surface water can occur in a number of ways (Langhoff et al. 2006), including seepages that not only occur through the streambed, but also bank seepage and over bank flow.
2.2 Techniques used to investigate connectivity

Assessing groundwater-surface water interactions is often complex and difficult (Brodie et al. 2005a). Commonly, groundwater level measurements are used to define the hydraulic gradient and the direction of groundwater flow. Flow measurements at various points along the stream are used to estimate the magnitude of gains or losses with the underlying aquifer. Other tools used to investigate groundwater-surface water interaction include seepage meters (Lee & Hynes 1978; Cherkauer & McBride 1998), river bed piezometers (Baxter et al. 2003), time-series temperature measurements (Stonestrom & Constanz 2003) and environmental tracers (McCarthy et al. 1992; Crandall et al. 1999; Herczeg et al. 2001; Baskaran et al. 2004). In most cases the limited number of data collection points results in a lack of detailed understanding of groundwater-surface water interactions in the field (Brodie et al. 2005a).

The Bureau of Rural Sciences (BRS), a government agency at the interface between science and policy within the department of Agriculture, Fisheries and Forestry Australia, is leading the way for managing connected groundwater-surface water resources in Australia, and has produced a framework for doing so. This report (Brodie et al. 2006), discusses an array of investigation and assessment techniques for identifying groundwater-surface water interactions. Whilst this is a major leap forward in understanding groundwater-surface water interactions across Australia, the development of these techniques is still in the experimental stage and it is weakly understood which techniques are the most applicable in certain stream environments. With many trials using several techniques, often producing different results, it is hard to decide which techniques are the most appropriate. A lot of the experimentation has occurred in Australia’s eastern states, adding to a data base of connection characterisation for these streams. This extent of experimentation is lacking in Western Australia and although it is assumed the techniques can be used universally, it is not completely certain that the same techniques can be adapted to WA streams. This dissertation contributes to initial steps being taken to apply these techniques and gain understanding of connected waters in WA.
Connectivity mapping
Hydraulic connection refers to systems where there is an opportunity for groundwater and surface water to exchange, and occurs where river bed and groundwater elevations are in close proximity to each other. The main factor controlling connectivity is the difference between the surface water level and the groundwater level (BRS 2006). Connectivity mapping refers to methods used to determine the presence of hydraulic connection along a river reach or throughout a catchment. The simplest way to assess connectivity is to compare the elevation of the base of the river channel with the elevation of groundwater. Ivkovic et al. (2005) used this method as a first step in determining whether the major rivers in the Naomi catchment, NSW, were in hydraulic connection with the underlying aquifers. They used a GIS and groundwater database to achieve this. The potential for hydraulic connection was assumed to exist where groundwater levels were within 10 m from the surface. The 10 m measure is an estimated difference between the elevation of the floodplain, where groundwater levels were measured, and the base of the river within the Naomi catchment.

Knowledge of the hydrogeological setting is critical in understanding groundwater-surface water interactions (BRS 2006). Specific information on hydrogeological parameters, such as those listed below, provide a useful context when evaluating the extent and direction of groundwater-surface water exchanges. However, hydrogeological mapping across Australia is by no means complete (Brodie et al. 2006). Useful hydrogeological parameters to evaluate groundwater-surface water exchange, include (BRS 2006):

- groundwater availability, in terms of bore yield
- groundwater quality, typically salinity
- potentials, in terms of depth to water table, elevation of groundwater surfaces, groundwater flow paths and head difference between aquifers
- aquifer hydraulic properties, typically transmissivity and storativity
- aquifer structure, typically aquifer boundaries, structural contours of the aquifer top and base, aquifer thickness, and specific features such as faults.
In the absence of specific hydrogeological mapping, more generic geological information is useful at the stream reach level as well as the catchment level (BRS 2006). Identification of geological structures such as faults or basement highs that control the geometry and hydraulic properties of aquifers is particularly important. Stratigraphic information such as the distribution of low-permeability clay layers or paleochannels that act as preferential pathways is used to map variability of stream-aquifer connectivity. For example, connectivity in the Cudgegong Valley NSW is controlled by geological features (Hamilton 2004). Bedrock constrictions or faulting restricts groundwater throughflow in the alluvial aquifer resulting in shallower water tables and gaining conditions in the river. Away from these geological features, the regulated Cudgegong River is largely a losing stream (Hamilton 2004).

Mapping of geomorphologic features has also been used to characterise connectivity. Analysis of the geomorphology of some North American alluvial aquifers inferred a relationship between dominant groundwater direction and parameters such as channel slope, sinuosity, incision and channel width-to-depth ratio (Larkin & Sharp 1992).

State wide connectivity mapping occurred in the major inland valleys of New South Wales (Braaten & Gates 2001), where the majority of the state’s water extraction occurs. Hydraulic connection was established by overlapping groundwater depths with locations of major rivers. Groundwater depths were determined from several digital groundwater maps and monitoring bores within 1 km of the rivers. Again, in this study, hydraulic connection was assumed to be present where river reaches overlay groundwater levels less than 10m from the surface. A map showing hydraulic connection of inland rivers and aquifers was produced which revealed a consistent geomorphologic pattern of groundwater extraction at various distances to connected river reaches (Braaten & Gates 2001). The map was useful in providing sufficient information for prioritisation of connected river-aquifer systems for further research and policy development.

Once hydraulic connection is established, it is important to establish the predominant direction of flux between the river and groundwater system. This is often done by installing a series of mini-piezometer transects crossing the river and coupled with river
stage information, to compare water table and river bed elevations (Cey et al. 1998). Direction of flux may also be assessed by examining groundwater contours, which represent lines of equal potentiometric head. Contours that curve in towards the upstream end of the stream indicate a gaining stream (Figure 11a) and contours that curve towards the downstream end indicate a losing stream (Figure 11b).

Figure 11: Groundwater contour patterns around streams (a) contours pointing upstream for gaining streams (b) contours pointing downstream for losing streams (Winter et al, 1998)

Groundwater modelling has also been used to determine the flow path and movement of water through the aquifer system. An array of predictive models has been developed and used throughout the literature to improve understanding of the key hydrological processes, to evaluate flow behaviour within groundwater-surface water systems and to quantify the water balance components in terms of storage and flux. Many existing numerical groundwater models omit or oversimplify surface-groundwater interaction processes (CDM 2001). The commonly used groundwater flow model, MODFLOW (Harbaugh et al. 2000), includes packages that represent interactions with various surface water features. The MODFLOW River package calculates seepage flux using Darcy's Law with estimates of a leakage coefficient and the head difference between the groundwater elevation in the model cell and the specified stream elevation. Holland et al. (2005) used this MODFLOW package to test the impacts of groundwater abstraction on stream flows in the Upper Ovens River, Victoria. The relationship between the commencement of groundwater abstraction and stream flow impacts has also been assessed in groundwater modelling by Braaten and Gates (2004) using numerical solutions and analytical approaches (Evans et al. 2005).
Hydrograph Analysis

A stream hydrograph is the time-series record of stream flow conditions. The hydrograph represents the aggregate of the different water sources that contribute to stream flow (Brodie & Hostetler 2005). Two main components that make up the stream flow hydrograph are:

(i.) *Quickflow* – the direct response to a rainfall event including overland flow (runoff), and direct rainfall onto the stream surface (direct precipitation), and;

(ii.) *Baseflow* – the longer-term discharge derived from natural storages and from lateral movement in the soil profile (interflow)

![Figure 12: Components of a typical streamflow hydrograph (Brodie & Hostetler 2005)](image)

The relative contributions of quickflow and baseflow changes through the stream hydrographic record, and the flood or storm hydrograph (Figure 12) is the classic response to a rainfall event and consists of three main stages (Brodie & Hostetler 2005). Initially low-flow conditions exist in the stream consisting entirely of baseflow at the end of a dry period. Then as rainfall begins, an increase in streamflow is observed by the quickflow response dominated by runoff. This initiates the rising limb towards the crest of the flood hydrograph. The rapid rise of the stream level relative to surrounding groundwater levels reduces the hydraulic gradient towards the stream and is expressed by
a reduction in the baseflow component at this stage. Eventually the quickflow component passes, expressed by the falling limb of the flood hydrograph (also called the recession curve). With declining stream levels timed with the delayed response of a rising water table from infiltrating rainfall, the hydraulic gradient towards the stream increases (Brodie & Hostetler 2005). At this time, the baseflow component starts to increase. At some point along the falling limb, quickflow ceases and streamflow is again entirely baseflow. Over time, baseflow declines as natural storages are gradually drained during the dry period up until the next significant rainfall event (Brodie & Hostetler 2005).

Hydrograph analysis involves analyzing the stream flow hydrograph to separate and interpret baseflow from quickflow. The technique has had a long history of development since the early theoretical and empirical work of Boussinesq (1904), Maillot (1905) and Horton (1930). A multitude of methods have since evolved, which can be categorised into three main approaches: baseflow separation, frequency analysis and recession analysis.

**Baseflow Separation**

Baseflow separation uses the time-series record of stream flow to derive the baseflow signature, either by graphical methods or more automated techniques, such as digital filters. Graphical separation methods focus on defining points along the hydrograph where baseflow intersects the rising and falling limbs of the quickflow response. Filtering methods process the entire stream hydrograph to derive a baseflow hydrograph and involve the use of digital filters. Early work with digital filters (O'Loughlin et al. 1982; Chapman 1987) was based on a filter commonly used for signal processing (Lyne and Hollick, 1979), which has been shown to yield similar results to conventional graphical methods (Nathan & McMahon 1990). Ivkovic et. al (2005) used baseflow filtering techniques to analyse daily stream data as part of their investigation into groundwater-surface interactions in the Naomi catchment, NSW. Comparisons of the baseflow component were made across ten gauging stations, spread out over two sub-catchments representing downstream and upstream environments. Results showed that baseflow contributions were greatest within the upland streams. However, the data used at each site was collected over different time intervals between 1957 and 2000, which would make it
difficult to compare the flow characteristics across stations and would produce misleading results. For an accurate comparison across stations, identical time intervals would need to be used. A recursive digital filter was used by Evans and Neal (2005) to separate the baseflow component of hydrographs from 178 gauging sites across the Murray-Darling Basin. The filter applied was developed by Lyne and Hollick (1979) and a consistent filter parameter value of 0.925 was adopted. Seasonal and annual baseflow indices were then calculated. The criteria for selecting sites for analysis in the study by Evans and Neal (2005) were more robust than Ivkovic et al. (2005) and included sites where flow was unregulated, the flow record covered the period 1990 to 1999 inclusive, and no more than 5% of the data record was missing.

**Frequency analysis**

Frequency analysis takes a statistical approach and involves evaluating the relationship between the magnitude and frequency of streamflow discharges. In its most common application, a flow duration curve (FDC) is generated showing the percentage of time that a given flow rate is equalled or exceeded (Brodie & Hostetler 2005). As well as the general shape of the FDC, various low-flow indices have been developed to characterise baseflow, but many of these are strongly intercorrelated (Smakhtin 2001) and limited work has been undertaken to link these indices to groundwater processes (Brodie & Hostetler 2005). To this end, some studies have combined low-flow frequency analysis with recession analysis (Loganathan et al. 1986; Gottschalk et al. 1997).

**Recession analysis**

Recession analysis focuses on the recession curve and involves selecting particular recession segments from the hydrographic record to be individually or collectively analysed to gain an understanding of the processes that influence baseflow (Brodie & Hostetler 2005). Hydrograph recession analysis is widely used in hydrological research and water resources planning and management (Tallaksen 1995; Smakhtin 2001). Graphical methods, such as correlation or matching strip techniques, involve plotting multiple recession curves to derive a master recession curve representing a composite of baseflow conditions. In analytical methods, equations are applied to fit the recession
segments. The applications of recession analysis since the early 1900’s have been numerous and include such areas as low-flow forecasting (Vogel & Kroll 1992), separation of baseflow from surface runoff and the assessment of evapotranspiration loss (Wittenberg & Sivapalan 1999). The rate at which a groundwater store discharges in the absence of recharge is one of the earliest fields of investigation in hydrology and has developed into a closed system of repetitive discovery and re-discovery (Nathan & McMahon 1990).

Overall, hydrograph analysis, is heavily based on the assumption that baseflow equates to groundwater discharge, which may not always be valid. Other storages can contribute to the baseflow regime of the stream as water can be released into streams over different timeframes from different storages such as connected lakes or wetlands, snow, glaciers, caverns in karst terrains, or bank storage (Griffiths & Clausen 1997). As the hydrographic record represents a net water balance, baseflow is also influenced by any water losses from the stream such as direct evaporation, transpiration from riparian vegetation, or seepage into aquifers along specific reaches (Brodie & Hostetler 2005). Studies have shown that water use or management activities such as stream regulation, direct water extraction, or nearby groundwater pumping can significantly alter the baseflow component (Evans & Neal 2005). Hence, careful consideration of the overall water budget and management regime for the stream is required when evaluating the significance of groundwater to the baseflow signal. For groundwater to be a significant contribution to baseflow, the unconfined aquifer needs to be adequately replenished (typically on a seasonal basis), have a shallow water table that is higher than the stream water level, and have adequate water storage and transmission properties to maintain flow to the stream (Smakhtin 2001). This means that other methods need to be used in conjunction with this technique to confirm groundwater discharge to the river. Methods such as hydrometric analysis and connectivity mapping have been used in conjunction with baseflow analysis (BRS 2006).
From the literature reviewed it is clear that hydrograph analysis is a well established strategy in understanding the magnitude and dynamics of groundwater discharge, and there is a strong consensus among practicing hydrologists that baseflow analysis provides a very useful tool for understanding groundwater discharge to streams (Evans & Neal 2005; Brodie & Hostetler 2005; Ivkovic et al. 2005). Specifically, Evans & Neal (2005) state ‘these underused techniques provide valuable insights to groundwater processes, especially the relative and absolute magnitude of surface water and groundwater interaction’. While much of the focus has been on developing and refining baseflow methods, very little published data exists on trends in baseflow over time. According to Evans and Neal (2005) the combination of baseflow separation, trend analysis and knowledge of catchment conditions provides a very powerful technique to identify and quantify groundwater impacts on stream flow.

**Environmental Tracers**

The quality and quantity of water can both be affected by the interaction of groundwater and surface water (Dixon-Jain et al. 2005). For example, contaminated aquifers that discharge into streams can result in long-term contamination of surface water or, conversely, streams can be a source of contamination to aquifers (Winter et al. 1998). Analysing and interpreting the chemistry of water can provide valuable insights into groundwater-surface water interactions. Dissolved constituents can be used as environmental tracers to track the movement of water (Brodie et al. 2005a).

Environmental tracers can be used to determine source areas of water and dissolved chemicals in catchments, to calculate hydrologic and chemical fluxes between groundwater and surface water, to calculate water ages indicating residence times, and to determine average rates of chemical reactions that take place during transport (Winter et al. 1998). Environmental tracers can occur naturally or may be introduced specifically to study groundwater-surface water interactions, the later referred to as artificial tracers. Some of the commonly used environmental tracers include field parameters such as electrical conductivity or pH, temperature, dissolved oxygen, major ions such as calcium, magnesium and sodium, stable isotopes, radioactive isotopes, and industrial chemicals such as chlorofluorocarbons (Brodie et al. 2005a). Several studies have used a
combination of these tracers to assess groundwater-surface water interactions (McCarthy et al. 1992; Crandall et al. 1999; Herczeg et al. 2001; Cook et al. 2003; Baskaran et al. 2004). Geochemical mass balance models have been used to estimate mixing ratios of river water and groundwater (Cook et al. 2003).

Temperature Survey

Heat has been widely used as a tracer of water movement to estimate areas of seepage flux (Silliman & Booth 1993; Barron 2003; Conant 2004). Heat is a useful tracer of water movement as it is conservative throughout the hydrological cycle and can be readily measured in the field. Stonestorm and Constanz (2003) have recognised that the use of heat as a tracer is a robust method for quantifying groundwater-surface water exchanges in a range of environments, from perennial to ephemeral channels. In a connected system, the exchange of water between the stream and shallow aquifer plays a key role in influencing temperature not only in streams, but also in their underlying sediments (Baskaran et al. 2005a). A comparison of stream and sediment temperatures can characterize the type of connection occurring at a reach (Silliman & Booth 1993). Comparing variations in the temperature of streams and their river bed sediments over a number of days is a well practiced technique in characterising connected reaches (Constantz 1998; Constantz et al. 2002; Baskaran et al. 2005b).

The key of temperature surveys is the varying temperature signals within the stream, stream sediment and groundwater systems. Stream temperature varies diurnally due to solar radiation, air temperature, rainfall and stream inflows, including groundwater discharge. In contrast, regional groundwater is constant at the daily time scale. Sediment temperature may be influenced by stream or groundwater temperature depending on the connection at that reach. In a losing system, the sediment temperature is influenced by stream temperature as the seepage flux is downwards. In a gaining stream, sediment temperature is influenced by groundwater temperature as the flux is upwards.

Silliman and Booth 1993 were among the first researchers to conduct an investigation into the potential for using time-series measurements of surface water and sediment
temperatures to identify gaining or losing portions of a stream. Their work was developed when it was realised ‘substantial studies had been performed on the variability of groundwater temperature over annual cycles, yet fewer studies had been performed in following temperature cycles near the ground water surface over periods of a few days to weeks’ (Silliman & Booth 1993). From this work temperature signals for three potential forms of stream-aquifer connectivity (gaining, losing and neutral) were hypothesized.

![Figure 13: Temperature signals (Fahrenheit versus time of day) as proposed by Silliman and Booth (1993) showing a) gaining, b) losing and c) neutral conditions (Silliman & Booth 1993)](image)

The first case (Figure 13a) shows signals for a stream that is strongly gaining groundwater. In this case, the temperature in the sediments is controlled by advection from the groundwater system. The sediment will reflect the temperature of the groundwater and would be expected to remain relatively constant over periods of days. In gaining conditions, shallow sediments show little variation as the influence of surface temperature is moderated by water flowing upward from depths where temperatures are constant (Baskaran et al. 2005a).

The second case (Figure 13b) represents a losing condition and a negative seepage flux from the stream to the aquifer, where the temperature in the sediments closely mimic the temperature of the surface water. In losing streams the downward flow of water transports heat from the stream into the sediments, which propagates diurnal temperature fluctuation into the sediment profile (Baskaran et al. 2005a).

The third case (Figure 13c) involves zero flux through the sediments. In this case, the temperature within the sediments will be driven by conduction (Silliman & Booth 1993). The temperature within the sediments will vary during the day as the temperature of the surface water varies (Silliman & Booth 1993). The average temperature of the sediments
will fall between that of the surface water and the temperature predicted at the depth of measurement through consideration of the subsurface geothermal gradient (Silliman & Booth 1993).

While hypothesis for the first two cases, gaining and losing conditions, are reasonable and have been widely agreed upon and applied in analysing temperature signals for many studies, it is the authors belief that the hypothesis of temperature signals for a neutral condition is too generalized, and the similarity between losing and neutral signals would make distinction between these two systems difficult. Temperature surveys are restricted in classifying neutral conditions, and a hypothesis for such a condition is unrealistic.

While used extensively overseas, the use of temperature analysis in Australia is relatively new. Baskaran et al. (2005) pioneered the use of time-series temperature monitoring for defining seepage flux in Australia and trialled temperature loggers in two contrasting catchments; the Borders Rivers Catchment, which is part of the Murray Darling basin crossing the Queensland/NSW border and the Lower Richmond catchment, a coastal catchment on the north coast of NSW. Temperature signals were examined during 2004 and 2005 to capture the high flow season (summer) and the low flow season (winter). At different sites in both catchments, submersible temperature recorders were installed within the stream as well as at various depths (0.25-1.2 m) within the stream bed (Baskaran et al. 2005a). At the same site mini-piezometers were constructed to measure the shallow water table and stilling wells were constructed to measure stream stage. The temperature profiles recorded at one site in the Border Rivers catchment are shown in Figure 14. The stream temperature during high flow (November-December) shows variation over a range of 26.1-35.9°C, whereas no diurnal variation is evident in the sediment temperature over the same time period (Figure 14a) and it was concluded this time-series temperature data provides evidence of shallow groundwater input to the stream (a gaining system). During the low flow season (July 2005) there is significantly less diurnal variation in stream temperature, in the order of 0.7-2.2°C (Figure 14b). Regardless, the sediment temperature record has slight fluctuations that relate to the
diurnal stream pattern, with a lag of about 3-4 hours (Baskaran et al. 2005a). This pattern indicates that the stream is losing water to the groundwater at this time.

Figure 14. Stream and sediment temperature signals showing a) gaining conditions and b) losing conditions along Dumersq River, Border Rivers catchment (Baskaran et al. 2005a)

Groundwater and stream level measurements complemented the results showing that in July groundwater levels were generally below the stream level, which confirms losing conditions. This study concluded that the river at this site can gain groundwater during high flow periods and lose water to the groundwater system during low flow periods (Baskaran et al. 2005a).

The method is based on the assumption that the temperature in the sediments will be controlled (ignoring internal sources of thermal energy such as those which may be derived from biological activity) by advection of thermal energy via water flow and conduction of thermal energy owing to a temperature difference between the stream water and the ground (Silliman & Booth 1993; Baskaran et al. 2005a).

While a relatively new technique in Australia, temperature analysis shows promise for characterising the type of connection occurring along a river.
Salinity Survey

Salinity surveys measure the salinity of surface water at a number of locations along a river reach, determine if any noticeable pattern exists and whether this pattern can be related to local groundwater salinity. Salinity surveys have been used successfully in studies identifying contributions to the stream from groundwater discharges (Porter 2001; Stelfox 2004). The salinity survey is specifically applicable in areas where the shallow groundwater is relatively saline compared to the stream and is a significant contributor to the overall salt load of the stream. In this situation groundwater inflows can be located by a corresponding peak in the stream salinity plot. Salinity surveys have the potential to quantify the groundwater contribution to stream flow using a simple mass balance equation (Oxtobee & Novakowski 2002):

\[ Q_G = Q_S \left( EC_S - EC_{S+G} \right) / \left( EC_{S+G} - EC_G \right) \]

where \( Q_G \) is the relative contribution from the groundwater system
\( Q_S \) is the ambient stream discharge
\( EC_S \) is the measured ambient electrical conductivity of the stream
\( EC_G \) is the measured electrical conductivity of the discharging groundwater, and
\( EC_{S+G} \) is the electrical conductivity of the stream resulting from mixing with the groundwater input.

Differences in the salinity of the shallow and deeper groundwater systems were the basis for investigating groundwater discharge to streams on the Alstonville Plateau, northern NSW (Brodie et al. 2006). A field chemistry survey of the plateau streams was undertaken, involving the measurement of electrical conductivity. The mass balance equation described by Oxtobee & Novakowski (2002) was used to determine the relative contribution of the deeper groundwater, estimated as being in the order of 10% of stream flow under these low-flow conditions (Brodie et al. 2006).
Seepage measurements

Seepage measurements involve the use of seepage meters to measure the flux across the groundwater-surface water interface. This technique differs from the other techniques described so far, in that it provides a direct indication of seepage flux, rather than being inferred from other parameters such as temperature, salinity, head differences or unaccounted water budgets. Seepage meters are the most commonly used devices for the direct measurement of seepage flux (Brodie et al. 2006).

Seepage meters were initially developed in the 1940’s in response to the need to measure loss of water from irrigation channels (Israelson & Reeve 1944) and their application was extended in the 1970’s for use in small lakes and estuaries (McBride & Pfannkuch 1975; Lee 1977; John & Lock 1977; Lee & Cherry 1978). Since the meters were popularised by Lee (1977) and Lee & Cherry (1978) they have been used in numerous studies of seepage fluxes in rivers (Lee & Hynes 1978; Libelo & McIntyre 1994; Cey et al. 1998; Landon et al. 2001; Langhoff et al. 2006), the near-shore marine zone (Bokunieicz & Pavlik 1990; Valiela et al. 1990; Simmons 1992; Cable et al. 1997; Taniguchi et al. 2003), tidal zones (Belanger & Walker 1990; Robinson et al. 1998; Byrne & Meeder 1999), coral reefs (Simmons & Love 1986; Simmons 1986; Lewis 1987), large lakes (Cherkauer & McBride 1998) and water-supply reservoirs (Woessner & Sullivan 1984). Seepage meters have been used to determine water budgets and quantify contaminant flux (Fellows & Brezonik 1980) and have the potential to determine the quality of the water being discharged to surface water (U.S. EPA 2006), although few studies have achieved this.

The basic concept of the seepage meter is to cover and isolate part of the sediment-water interface with a chamber open at the base and to measure the change in the volume of, water contained in a bag attached to the chamber, over a measured time interval (Brodie et al. 2005b). Additional water in the bag represents an upward (gaining) flux. A decrease in bag volume represents downward (losing) flux. Potential sources of installation and measurement error that can influence the amount of water exchanged to the bag have been identified. These include: upward advection of interstitial water (the Bernoulli effect), venturi effects of stream flow on the collection bag, anomalous short term influx
due to bag properties, gas accumulation in the chamber, frictional resistance causing head losses, ineffective seals, and the capture of shallow through flow rather than groundwater (Brodie et al. 2005b). The success of seepage meter depends on the environment they are being used in and the control of installation and measurement errors.

Seepage meters can be successfully applied in a variety of settings due to their flexible design. The components of the seepage meter (Figure 15) can be adjusted to suit particular environmental settings, a feature which has allowed the meters to be widely applied in numerous studies. The conventional seepage meter design by Lee (1977) uses one third of a 200 L steel oil drum with an outlet for a tube attached to the drum and a collection bag attached to the tube with rubber bands.

Over the years, various modifications have been made to the basic seepage meter to address potential sources of installation and measurement error and to accommodate designs to environmental settings. Whilst the inverted open drum described by Lee (1977) is still the basis of the chamber, a wide range of materials have been used for the drum including capped PVC casing (Schincariol & McNeil 2002), plastic buckets (Cey et al. 1998; Alexander & Caissie 2003), a purpose built rectangular stainless-steel funnel (Paulsen et al. 2001), fibreglass domes (Shinn et al. 2002) or a cut-down galvanised water tank (Rosenberry & Morin 2004). The choice of material depends on environmental settings and requirements. For example, Cherkauer and McBride (1988) carried out seepage studies in Lake Michigan, USA, where meter designs needed to be robust and stable for use in dynamic flow conditions. In this case the chamber was modified by

Figure 15. Components of a typical seepage meter; (1) inverted chamber open at base, (2) collection bag, (3) connection tube, (4) protective cover and (5) gas venting tube (Brodei et al. 2005a)
adding a 50-70 kg layer of concrete to the inside of the chamber, with the lower surface of the concrete conically shaped to direct upward flow of water and gas to the chamber outlets (Brodie et al. 2006).

Gas accumulation in the chamber during operation may be avoided by placing the tube for the collection bag on the side of the chamber and inserting another tube at the top of the chamber which is extended above the water surface and open to the atmosphere (Brodie et al. 2006). Another way of achieving gas release was trialled by Cherkauer and McBride (1988) and involved adding a small pipe with a ball valve to the top of the chamber to vent any trapped air when the chamber is initially placed into the water body. After the air is released the valve is closed and the bag is attached, and so this design does not allow for gas accumulation release during the operation of the meter.

Collection bag composition has also been recognised as a factor affecting the accuracy of results. A lot of focus in seepage meter design has been on the type of collection bag used varying from plastic glad bags (Lee & Cherry 1978), wine cask bladders (Brodie et al. 2005b), bladders from hydration systems (Brodie et al. 2005b) and oven basting bags (Shinn et al. 2002). Small volume elastic bags such as balloons and condoms have been trialled and found to give useful results (Isiorho & Meyer 1999). However, comment by Harvey and Lee (2000) on these trials suggests the results to be questionable and misleading. Harvey and Lee (2000), while pleased that researchers were working to improve the conventional seepage meter, were particularly concerned that the paper by Isiorho and Meyer (1999) would lead others to believe that small-volume, elastic measurement bags are desirable for seepage measurement. They believed the variability in results collected, a seepage flux variation between 0.18 – 1.27 m/d, did not support the use of any type of small volume elastic bag for seepage measurement.

Seepage meters have been applied successfully in many environments. However, their failure is also common. Despite a series of trials, seepage measurements failed to provide any measurement of water flux into or out of the river system in a study conducted by Cey et al. (1998) quantifying groundwater discharge to a small perennial stream in southern Ontario, Canada. Seepage measurements were conducted with time intervals
ranging from one hour to over 24 hours, yet no appreciable seepage was detected at any location or at any time (Cey et al. 1998). At some installation locations, the failure of the seepage meters was attributed to an improper seal between the seepage meter and the coarse streambed sediments. At other locations the seepage flux through low conductivity sediments may have been too small to detect (Cey et al. 1998). Similarly, after many unsuccessful attempts Langevin (2000) determined that seepage meters could not be used within the tidal environment of Biscayne Bay, Florida because flow rates measured at seepage meters were not in agreement with tidal phases, or were not proportional to vertical head differences at nested offshore monitoring wells (Langevin 2000).

Several logistical problems were encountered by Brodie et al. (2005a) during trials of various seepage meter configurations in the Borders and Richmond River catchments, NSW, including; the inability to adequately embed the meter into the clay profile and the accumulation of biogenic gas and kinking or submerging of the venting tube, which was brought about by relatively high stream flows (Baskaran et al. 2005a). In the Borders River catchment, some of the seepage meters measured positive (gaining) seepage, contrary to other assessment methods (such as mini-piezometers or hydrochemistry) which suggested negative (losing) seepage. This was attributed to anomalous input of water to the bag due to capture of shallow throughflow and upwards advection, which was due to the inability to install the meter to sufficient depth.

Overall measurements of the exchange rate by means of seepage meters are problematic because it is difficult to evaluate their reliability (Kaleris 1998). High spatial and temporal variability in seepage characteristics can result in poor repeatability of measurements. Such variability can be attributed to variations in water levels through time, spatial variations in aquifer hydraulic conductivity, the presence of a thin clogging layer and changes in its hydraulic resistance, or variable seepage velocities across the stream profile, with velocity decreasing with increasing distance from the bank (Kaleris 1998). While questionable in their ability to provide accurate quantitative details of seepage flux, such as its magnitude at a particular location, they are a successful in their ability to provide directional analysis of seepage flux, and can indicate gaining or losing.
Water budgeting

Water budgeting involves determining a component of the hydrologic cycle, by measuring or having knowledge of all other components. Water budgeting is a common approach for investigating seepage flux between a stream and underlying aquifer (Brassington 1998). Measuring stream flow at specific sites along the stream subdivides the stream into reaches. A water budget can be determined for each reach, by measuring flow into and out of the reach and accounting for all inputs and outputs.

Flow measurements can be taken from gauging stations, by relating the river stage to the historic rating curve to determine a flow rate. Flow measurements may also be conducted directly in the field by measuring stream flow at particular points in the river, often referred to as discharge measurements. Common methods for conducting discharge measurements are: volumetric analysis, velocity-area method, slope-area method, dilution gauging and thin plate weirs (Brassington 1998; Hauer & Lamberti 1996). These methods differ in their approach but the end product of each is a measurement of stream flow discharge.

The difference between inflows and outflows along a reach may then be attributed to the interaction between the stream and the underlying aquifer. When applied to a defined reach, the groundwater flux \((Q_{gw})\) is estimated from:

\[
Q_{gw} = Q_{dn} - Q_{up} + \sum Q_{out} - \sum Q_{in}
\]

where \(Q_{dn}\) is the flow at the downstream end of the reach

\(Q_{up}\) is the flow at the upstream end

\(Q_{out}\) are outputs from the reach (evaporation, extraction), and

\(Q_{in}\) are inputs to the reach (rainfall, runoff, tributaries and irrigation drainage).

This follows the convention that a positive \(Q_{gw}\) indicates a net input of groundwater to the reach. A negative \(Q_{gw}\) indicates a net loss of surface water to the groundwater system (BRS 2006)
2.0 Literature Review

Geophysics and remote sensing

Geophysical or remote sensing imagery can assist in the interpretation of groundwater-surface water interactions. Geophysical surveys provide mapping of the spatial and temporal variations in properties such as groundwater chemistry (particularly salinity), soil moisture content and soil/sediment texture. Mapping of these parameters can be useful in identifying hotspots in terms of saline groundwater discharges into streams or leakage of fresh water into alluvial aquifers (Brodie et al. 2005a). Such surveys can map the geological and geomorphological features that control stream-aquifer connectivity. They can also be used to map indicators of groundwater discharge (such as vegetation types, waterlogged or saline areas) in the landscape. Geophysical data collection can be undertaken at different scales using different platforms, including satellite, aircraft, vehicles or boats (BRS 2006). There are three main types of geophysical and remote sensing surveys:

1) Remote Sensing, including airborne and satellite imagery, such as Landsat TM multispectral imagery, airborne electromagnetics, magnetics, radiometrics and radar.
2) Ground surveys; electromagnetics, electrical conductivity and seismic studies.
3) Borehole logging; involves running either one or a combination of different geophysical tools down boreholes drilled into the ground.

Borehole logging involves running either one or a combination of different geophysical tools down boreholes drilled into the ground. It is the most invasive of the three main geophysical methods, but it is capable of giving a far more detailed picture of the hydrogeology. Geophysics and remote sensing provide opportunities for rapid, non-invasive mapping of landscape parameters that either indicate or control groundwater-surface water interactions. Surveys can provide good spatial resolution in the vicinity of surface water features, while multiple surveys can provide information in terms of changes through time. However, undertaking and interpreting these surveys can be complex, requiring specific technical expertise and extensive calibration with other datasets, such as borehole logs and chemical analyses.
Field Observations

Visual indications of the interaction of groundwater and surface water systems can be observed in certain catchments and settings (Brodie et al. 2006). A case study highlighting the use of field indicators occurred in the Tuckean Swamp, a large estuarine swamp within the Lower Richmond catchment, NSW. This swamp has been highly modified with construction of drains and a tidal barrage to manage frequent flooding. Seepage of shallow acid groundwater into the Tuckean Swamp drains is believed to be occurring and can be indicated in the field by these observations (Hagley 1996):

- Unusually clear water, due to the presence of aluminum in the acidic water
- Extensive deposition of yellow-brown iron precipitates on the drain bed and on vegetation
- The establishment of acid tolerant plants such as lilies

Common visual indicators of groundwater discharge into streams have been defined by (Brodie et al. 2006) and include:

- The direct observation of water flow from seepages and springs at the margins or within the bed of the surface water feature. Springs may occur on banks or hill slopes and in some locations subaqueous springs can result from preferred paths of ground water flow through highly permeable sediments (Figure 16).

![Figure 16. Discharge of groundwater into surface water through a subaqueous spring (Winter 1999)]
- In colder times of the year, water vapour above discharge zones may be observed due to the contrast between the warmer groundwater and cooler air temperatures. In alpine areas during winter, seepage areas can remain continually ice or snow-free in contrast with their surroundings.

- Changes in the groundwater chemistry due to mixing with surface water can result in mineral precipitates such as iron and manganese oxides.

- Water colour and odour can be an indicator, particularly if the groundwater is contaminated. This may be the case in catchments with urban, industrial, mining or intensive agricultural development. Discharge of highly acidic groundwater can be indicated by a dramatic increase in the clarity of the surface water, due to the flocculating of clay particles by elevated levels of dissolved aluminum.

Identifying and mapping field indicators of groundwater discharge can be readily incorporated into a fieldwork program with little additional costs. However, there is a high dependence on the observer’s knowledge of visual indicators. Field indicators can show where groundwater seepage occurs but are limited in quantifying seepage flux.

**Ecological Indicators**

Certain plants and animals can be used to identify the nature and extent of groundwater-surface water interaction. The most common ecological indicators are aquatic plants, phreatophytes and hyporheic biota.

Aquatic plants can be indicators of groundwater discharge. For example, cattail plants have been used as indicators of fresh groundwater input to saline prairie lakes in North Dakota (Swanson et al. 1984). Lodge et al (1989) indicated that submerged aquatic plant biomass was enhanced where groundwater inflow velocity was greater. In a desert stream setting, algae abundances in streambed sediments recovered more rapidly from flash flooding in areas with upward movement of groundwater (Valett et al 1994). This was attributed to the groundwater providing a source of nutrients to the algae (Brodie et al. 2006). Groundwater discharge may favour the growth of particular aquatic plants. The predominance of acid-tolerant species such as water lilies can indicate significant discharge of acidic groundwater (Brodie et al. 2006).
While monitoring of ecological indicators is a method that can be readily incorporated into a field work program and is useful as a reconnaissance tool to target sites of groundwater discharge, it is dependent on observer's expertise in biological identification and limited in providing quantitative information on seepage flux.

2.3 Literature summary and study motivation

Interactions between groundwater and surface water are complex (Sophecelous 2002) and difficult to observe and measure (Winter et al 1998). An array of techniques has been developed throughout history to investigate these interactions. Some techniques are well established and have a strong historical backing, while others are relatively new and still developing. A common challenge with assessing groundwater-surface water interactions is selecting the most appropriate techniques for the river environment. Whilst combinations of these techniques have been applied in numerous studies investigating groundwater-surface water interaction along eastern Australian rivers and overseas, at the commencement of this project, no such study had occurred along a Western Australian river.

Seven techniques were selected to investigate groundwater-surface water interaction along the Brunswick River, including: connectivity mapping, baseflow separation, temperature survey, salinity survey, water budgeting, seepage meters and field observations. These particular methods were selected from those discussed in the Literature Review based on particular aspects which made them suitable for the Brunswick River environment:

- Connectivity mapping was used to determine seepage flux direction, because the flow of water between a surface water feature and the underlying aquifer is largely controlled by the difference between the surface water level and the groundwater level. This was used instead of groundwater contour or flow system methods, because detailed groundwater contour information along the Brunswick River did not exist, therefore limiting the use of groundwater contours to indicate flow direction.
• Baseflow separation was selected due to the extensive record of historical flow data for several gauging stations spread spatially along the river.

• Temperature survey showed promise because it had been used successfully in similar environments, as discussed above, and temperature loggers were obtainable.

• Salinity survey was selected because it had been applied successfully in a similar study along the Moore River (Stelfox 2004), and a database of salinity data already existed at several sites along the river.

• Water budgeting is a well established and highly used technique, and equipment for conducting flow measurements and resources for determining other water budget parameters were available.

• Seepage meters were selected because a lot of research regarding their design and operation was available to aid seepage trials, and they hadn’t yet been trialled successfully along rivers in Western Australia yet.

• Field observations could readily be carried out in conjunction with all other methods, and many field trips and on site visits occurred

This combination of techniques was selected because they cover a range of scales, assessing connectivity at the catchment scale (connectivity mapping), the river feature scale (baseflow separation, salinity survey, water budgeting), and the local/site specific scale (temperature survey, seepage measurements, field observations). They also involved a balance between field work and desktop analysis.
3.0 Methodology

This section outlines the techniques used to investigate groundwater-surface interactions in the Brunswick River and the methodology involved. Some techniques involved desktop studies, some field studies and some a combination of both (Figure 17). Two reaches along the river, one near the Cross Farm streamflow gauging station and the other near Sandalwood streamflow gauging station, were selected for focused field investigation involving the installation of seepage meters, temperature loggers and water budget analysis. The location of the study reaches are displayed in Figure 18 and the reasons for selecting these sites are discussed in Section 3.1.1.

Figure 17 Conceptual model of techniques used in groundwater-surface water interaction assessment along the Brunswick River.
3.1 Field Studies

Field work was carried out on several occasions to gain information and data necessary to analyse groundwater-surface water connectivity along the Brunswick River. The date and purpose of each field trip has been summarised in Table 1.

Table 1. Date and purpose of field work carried out during 2006

<table>
<thead>
<tr>
<th>Date</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>27/2/06-1/3/06</td>
<td>Initial field reconnaissance and water quality testing</td>
</tr>
<tr>
<td>14/3/06-15/3/06</td>
<td>Flow measurements representing summer conditions</td>
</tr>
<tr>
<td>20/4/06-21/4/06</td>
<td>Refined flow measurements</td>
</tr>
<tr>
<td>15/5/06</td>
<td>Searching for groundwater bores</td>
</tr>
<tr>
<td>26/6/06-30/6/06</td>
<td>Major field investigation with techniques (1)</td>
</tr>
<tr>
<td>20/9/06-26/9/06</td>
<td>Major field investigation with techniques (2)</td>
</tr>
</tbody>
</table>

In late February, 2006, a field reconnaissance was conducted to gain understanding and orientation along the river and its surrounding environment. Two major field investigations occurred in June and September 2006. The original objective of these investigations was to apply all of the techniques on both occasions, at both study reaches, and compare their outcomes, as seen through different seasons; Winter (June) and Spring (September). Ideally, more contrasting seasons, such as summer and winter, would have been selected. In general summer is the best time to conduct groundwater-surface interaction studies, as it represents baseflow conditions (Bureau of Rural Sciences (BRS) 2006). However, due to timing of the project, this was not possible.

Figure 18 displays the location and sites involved in field work methodology, including the study reaches, bores measured, gauging stations used to collect daily and historical records of flow data. This figure will be referred to frequently in subsequent sections.
Figure 18. Location and components of field work (K. Annan 2006)
3.1.1 Study Reach Selection

Selection of reaches for more focused field investigation was based on the following parameters:

- Quantity and quality of available on-site data resources,
- Minimal effect by irrigation inflow and extraction outflow, and
- Ease of access

The site required 4WD access to the river so that heavy equipment could be brought to the study sites. Public access along the river is relatively restricted, with over 60% of the river running through private property. In the upper catchment the river is enclosed in thick State Forest and pine plantations, with access possible only at bridges and crossings. Some equipment, such as temperature loggers and seepage meters, were required to be left on site for many days. For this reason, sites with high public usage were avoided due to vandalism or theft risk. Study sites also required nearby bores to measure lateral groundwater trends in the area, and a currently operating gauging station so that baseflow analysis could be conducted, and flow rates calculated. For purposes of accurate water budgets, sites were selected so there was minimal impact from land users, either contributing to water balance outflows via groundwater pumping or direct streamflow extraction; or contributing to inflows from run off during the irrigation season.

From a choice of four possible sites that matched these criteria, two study reaches; Cross Farm (study reach 1) and Sandalwood (study reach 2) were selected. Cross Farm has easy access under the Australind By-pass, with a current streamflow gauging station and at least three bores within a one km radius. Access to Sandalwood, whilst much more restricted, is possible through a private property where access was organised through communication with the land owner. Due to the relatively high elevation at Sandalwood (up to 90m above sea level (AHD)) and underlying geology (dolerite and granite), bores and thus bore data in the vicinity of Sandalwood were very limited, apart from five Water Corporation bores located 4 km upstream of the study reach. However, upon further field investigation these bores were found to be decommissioned and could not assist with current groundwater level data. However, records kept from the time of their construction
and operation (1982-1983) contained useful information such as bore logs and historic water levels.

3.2 Techniques

The seven techniques employed in this study and related to the conceptual methodology diagram presented in Figure 15 are:

- Connectivity mapping
- Baseflow separation
- Temperature survey
- Salinity survey
- Water budgeting
- Seepage meters
- Field observations

3.2.1 Connectivity Mapping

Mapping river bed and water table elevation was carried out to indicate the presence and character of connected reaches by comparing their elevations. River base elevation was determined from a series of topographic contour data sets analysed using the Geographical Information System (GIS) software ArcGIS. Water table elevation was determined from a combination of data sets including bore logs, groundwater contours and water levels measured from bore dipping. Underlying geological structure was investigated from a combination of geological maps and bore logs. More details on assessing river base elevation, groundwater level elevation and underlying geology are described in the following sections.

3.2.1.1 Assessing river base elevation

A digital elevation model (DEM) of the Brunswick River area was not readily available. River base elevation was determined using ArcGIS software to create a triangular irregular network (TIN), a data structure used to model continuous surfaces (Burrough & McDonnell 1998). A TIN is built from joining known point values into a series of triangles based on a Delaunay triangulation. The triangulation allows a variable density and distribution of points to be used which reflects the changes in altitude values within
3.0 Methodology

an area. Delaunay triangulation method is a proximal method that satisfies the requirement that a circle drawn through the three nodes of a triangle will contact no other point. Restated, this means that all sample points are connected with their two nearest neighbours to form triangles. Elevation data points and values from topographical contour maps within a 2 km radius of the river were used as input data for TIN creation. Varying scales of contour mapping were available along the river, ranging from 1 m interval contours in the lower catchment, 2 m contours in the middle of the catchment and 5 m intervals in the upper catchment. As a result three contour maps were used and their data combined to create the TIN surface model. Details of the contour maps used and a map showing their extent may be found in Appendix A.

A supporting ArcGIS programme, 3D Analyst, was used to intersect the line of the river with the TIN. The values at points where the river intersected the TIN were recorded. At each intersection point two values were given, one value giving the elevation (in metres AHD) and another showing the distance along the river. From this process a data set of point values, with x (distance)/y (elevation) coordinates was established.

3.2.1.2 Assessing groundwater elevation
Overall, limited groundwater information was available directly along the river. As shown in Figure 18 the closest monitoring bores owned by the Department of Water (DoW) and readily available for analysis did not lie on the river itself but were within 2km. Using only the DoW bore data it was difficult to assess groundwater levels across the catchment, and private bore data was also used to improve spatial resolution. A letter was sent to private land owners asking of the existence of any bore or wells on their property and for their assistance with obtaining groundwater information and current water level measurements. A copy of the letter sent out to all private land owners within a 2km radius of the Brunswick River is shown in Appendix A.

Replies were quick and, by June, permission to assess bores had been granted from all private land owners and a groundwater level investigation plan was established. The plan involved assessing 19 bores along the river (named B1 to B19), displayed in Figure 18.
The objective of the investigation was to measure the depth to resting water level at each bore, determine the total drilled depth of the bore and other construction details, such as distance from top of casing to ground level and the length of the screened interval. The bores varied in their construction type, between those that were built for suburban residential purposes to those that were built on farms for agricultural use. Based on their level of construction and ability to provide data the 19 bores were classified into four groups; private residential bores, private farm land bores, DoW monitoring bores and decommissioned Water Corporation bores (as shown in Figure 18).

Bore analysis began on 26th of June 2006. Information regarding the total drilled depth of each bore and their construction details were sourced from conversations with bore owners and records kept from bore construction. The method of groundwater level assessment varied for each group of bores. Residential style bores did not allow the current/direct measurement of water levels as they had sealed and bolted protective casings, and therefore information for bore analysis was restricted to historic records of data collected at the time of their construction. Whereas, farm style bores, allowed the insertion of a water level meter for direct, on site and current water level measurement. At these bores water levels were recorded using a Solinst water level meter displayed in Figure 19.

![Solinst water level meter](image)

Figure 19. The Solinst water level meter used in groundwater level assessment

Water levels in the DoW monitoring bores were also directly measurable during the bore analysis period with the water level meter. The decommissioned Water Corporation bores included two of the five bores that were once in operation but had since been destroyed,
and therefore water level information for these bores was also restricted to records from the time of their construction. Several springs in the vicinity of the river were also included in groundwater level analysis (Figure 18), as were a set of groundwater contours sourced from a study done on the hydrogeology of the Collie River basin (Rutherford 2000). Details on the bores used for groundwater level analysis are provided in Appendix A.

On arrival some ‘bores’ turned out to be wells. Open wells such as those shown in Figure 20 were excluded from analysis because it was suspected that water levels in the wells were influenced by outside atmospheric effects such as rainfall and evaporation, especially as 16mm of rainfall had been recorded the day before analysis begun, and water levels measured at the wells were higher than expected.

3.2.1.3 Assessing underlying geological structures

As stated by Brodie et al. (2006) knowledge of the hydrogeological setting is critical in understanding groundwater-surface water interactions. Therefore, an assessment of underlying geology along the river was carried out to complement groundwater analysis. Bore logs from DoW monitoring bores and some privately owned bores were used to assess the vertical extent and character of superficial formations. Several geological maps were used to assess the horizontal extent of underlying geological formations. Most of the maps were sourced from the DoW internal GIS database, IntraGIS, and from a study assessing the geology of the Collie River basin (Rutherford 2000).
3.2.1.4 Data compilation

River bed and groundwater elevation data was combined with underlying geological information by creating a hydrogeological cross section of the river. The process of producing the cross section involved the use of a computer aided drawing programme, Corel Draw, to draw in geological boundaries. GIS software was then used to add in lines representing accurate river bed and water table elevations and to accurately mark the locations of any bores, gauging stations, springs, major river and road crossings, the darling fault line and Brunswick Junction.

The major assumption associated with this technique is that river bed elevation as derived from ArcGIS and groundwater levels projected onto the stream show a true comparison between river bed and groundwater elevation.

3.2.2 Baseflow Separation

A baseflow separation technique was applied in this study to determine and compare the baseflow index (BFI), the ratio of baseflow to total stream flow, at three locations along the river. The Lyne and Hollick (1979) recursive digital filter, a common tool used in signal analysis and processing, was used to separate the quickflow from the baseflow by removing the high-frequency quickflow signal to derive the low-frequency baseflow signal. It uses the time series record of stream flow as input, and was applied to daily stream flow data sourced from 612032 (Cross Farm), 612047 (Beela) and 612022 (Sandalwood) (Figure 18). The stations record river level and output flow discharge based on a rating table developed from the historic record of flow data. For accurate comparisons of baseflow separation across locations, observations within the same time interval were analysed. The time when all three stations were operating and recording daily flow data simultaneously was from 10/5/2000 to 6/4/2006.

The Lyne and Hollick (1979) recursive digital filter was selected because it is commonly applied to daily flow data (Grayson et al.). The Lyne and Hollick algorithm is of the form;
3.0 Methodology

\[ q_{f(i)} = \alpha q_{f(i-1)} + \frac{(q_{(i)} - q_{(i-1)})}{1+\alpha} \]

Where; \( q_{f(i)} \) is the filtered quick flow response at the ith sampling instant (flow units)

\( q_{(i)} \) is the original stream flow (flow units)

\( \alpha \) is the filter parameter

The filtered baseflow = \( q - q_f \) and, the baseflow index (BFI) is calculated as;

\[ BFI = \frac{q - q_f}{q} \]

The filter was run through a visual basic macro in Microsoft Excel, developed in 2000 by Dr. Aditya Jha for the Surface Water Hydrology branch of the Department of Water. The model takes the date and volume of daily streamflow data as its input, and runs it through three passes. The first and third passes are forward passes using Equation 1 directly, whereas the second pass is a backwards pass using \((i+1)\) instead of \((i-1)\) in Equation 1. In the first pass, \( q_{(i)} \) is the measured streamflow, in the second pass it is the computed baseflow from the first pass, and in the third pass it is the computed baseflow from the second pass. These passes smooth the data (Evans & Neal 2005). The model estimates the contribution from baseflow at each daily observation, which can combine to get the total contribution from baseflow over a given time period.

The estimated baseflow is sensitive to the value of the filter parameter (Evans & Neal 2005). A filter parameter of 0.925 was selected for use in this study, as it is recommended for daily data and has been found to provide the best match to graphical baseflow estimates (Nathan & McMahon 1990).

According to Evans and Neal (2005) very little published data exists on trends in baseflow over time. Due to the underlying assumptions of baseflow contribution, and the structure of the stream hydrograph, it was perceived that there should be a relationship between the BFI and minimum stream flows. In this study, annual trends in the BFI over the entire record of stream flow at each station were determined and compared with
annual trends in the minimum flow recorded at each year. The two series were displayed together through graphical techniques in Microsoft Excel, and compared to determine if there is any relationship between the two series. Linear regression was applied to determine the correlation coefficient, which is an indicator of how well the data sets are correlated. Linear regression involves fitting a trend line to the two data set series and determining the equation of the trend line, which ultimately produces the coefficient of determination ($r^2$). The correlation coefficient ($r$) may be calculated by taking the square root of the coefficient of determination.

### 3.2.3 Temperature Survey

Monitoring of temperature within the stream as well as underlying river bed sediments was used to investigate groundwater-surface water interaction at Cross Farm and Sandalwood. Odyssey submersible temperature recorders (Figure 21) were employed to collect temperature signals at 15 minute intervals. The Odyssey logger was chosen due to its low cost, compact waterproof design and memory capacity, and was highly recommended by other field researchers (Baskaran pers. comm. 2006). The loggers are submersible up to 10 m and record temperature in the range of $-10^\circ$C to $50^\circ$C (ODRS 1995).

![Figure 21. Features of the Odyssey submersible temperature loggers](image)

Installation processes differed for each logger, depending if they were being deployed into the stream or stream bed and at which location. At Sandalwood one logger was
inserted 0.5m into the stream bed by pushing a 50mm diameter galvanised pipe, into the river and removing sediment from its core. The logger, attached to the end of a 40mm PVC pipe, was slipped into the sediment through the galvanised pipe (Figure 22a). The galvanised pipe was removed leaving the logger imbedded in sediment with the PVC pipe protruding above the stream (Figure 23). Wiring was attached to the end of the logger and fed through the PVC pipe so that the logger could be retrieved successfully at the end of monitoring. The installation process for the stream temperature logger was different, and involved securing it onto a metal picket with a cable tie. The free end of the picket was pushed into the sediment until the sensor tip was in the desired position, approximately 5cm below the current river stage (Figure 22b). This position was selected because it assured the tip would remain among the flowing stream at all times during the monitoring period, taking into account any anticipated changes in river stage.

![Figure 22. Inserting temperature loggers at Sandalwood into a) the stream bed and b) the stream](image-url)
Installation at Cross Farm followed the same process, but due to the potentially high public access at the site it was desirable to make the loggers less noticeable to passers-by. Vandalism was an issue which was given serious consideration in the design of temperature logger installation. To make them more secure and less noticeable to passers-by PVC piping from the stream bed logger was cut at river bed level so that it did not protrude above the stream surface, as it did at Sandalwood. Positioning of the stream temperature logger also varied from the Sandalwood design, and involved turning the logger upside down so that the body of the logger did not stick above river level, whilst keeping the sensor tip at the desired position. At Cross Farm, it was obvious that the south bank of the river had a much higher public access potential than the north side. Another precaution taken to avoid vandalism was to place the loggers as far away from the south bank as possible, as it was anticipated that passers-by would not risk getting wet.

Figure 23. Temperature survey set up at Sandalwood
to destroy the equipment. The loggers were therefore inserted by wading out into the river closer to the north bank. Once the loggers were satisfactorily secured, GPS coordinates, photos and detailed notes and sketches outlining the loggers’ positions were taken to record the exact location of the loggers so they could be retrieved after the monitoring period.

![Stream logger](image1.png) ![Stream bed logger](image2.png)

**Figure 24. Temperature survey set up at Cross Farm**

To allow temperature loggers time to settle into equilibrium at least the first day should not be included in analysis (Baskaran pers. comm. 2006). Installation and collection of temperature loggers was carried out on the following dates and times listed in Table 2. The effective monitoring period (EMP) has been determined to allow for the desired settling time and has been determined by subtracting the first day from the start date at Cross Farm and the first two days at Sandalwood. A two day settling period was selected for Sandalwood because field work, trialling other techniques, was conducted in the vicinity of the temperature survey set up for the first two days. It is considered that the activities on these two days could have disrupted temperature signals and these days were not included in analysis.
Table 2. Dates and times of installation, collected and effective monitoring period of the temperature surveys

<table>
<thead>
<tr>
<th></th>
<th>Cross Farm</th>
<th>Sandalwood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date of installation and start time</td>
<td>26/6/06 @ 1200</td>
<td>20/9/06 @ 1130</td>
</tr>
<tr>
<td>Date of collection and end time</td>
<td>30/6/06 @ 1230</td>
<td>26/9/06 @ 900</td>
</tr>
<tr>
<td>Total period of monitoring</td>
<td>96.5 hours</td>
<td>141.5 hours</td>
</tr>
<tr>
<td>Date and start time of EMP</td>
<td>27/6/06 @ 1200</td>
<td>22/9/06 @ 1130</td>
</tr>
<tr>
<td>Total period of effective monitoring</td>
<td>72.5 hours</td>
<td>117.5 hours</td>
</tr>
</tbody>
</table>

The two major assumptions made with this method are that groundwater is constant at the daily timescale and sediment temperature is influenced by positive seepage from groundwater to surface water or by negative seepage from surface water into groundwater.
3.0 Methodology

3.2.4 Salinity Survey
An assessment of surface water salinity along the river was used in an attempt to determine groundwater seepage into the river. Electrical conductivity (EC) is a typical measure of salinity, based on the theory that solutions with a higher salinity concentration are better conductors of electricity and therefore produce higher EC values. EC was measured on site at 13 locations along the stream (shown in Figure 26) and compared with local groundwater salinity. Groundwater salinity was determined from records of groundwater analysis from DoW monitoring bores contained on the Departments’ water information network (WIN) system, and by taking in field measurements from the same private farm land bores used in groundwater level assessment (displayed in Figure 18).

A WTW conductivity probe meter (Figure 25) was used to measure EC in the stream and groundwater samples. It was calibrated to standard conditions in the Bunbury DoW laboratory on the morning of salinity assessment. Details on the calibration process are included in Appendix A.

In stream salinity measurements were conducted by placing the probe in a flowing section of the stream and waiting for the digital reading on the meter to equilibrate. Three samples were taken at each location and the average of these was used. For salinity measurements at private bores, water samples were pumped from the bore. In the case of wells or bores without operational pumps, a bailer was used to purge samples for analysis.

Figure 25. WTW conductivity measuring probe
Figure 26. Sites where salinity samples were taken (K. Annan 2006)
Figure 26 shows the location of sites selected for salinity assessment, numbered 1 - 13. Site selection for salinity survey points was based on accessibility and even distribution along the river.

The aim of this method is to detect any significant changes in stream salinity and, from analysis of groundwater salinity data, assess whether these changes are a result of groundwater discharge.

The major assumption behind the application of this method is that there is a significant difference between groundwater and surface water salinities. For instance, it can be readily applied, in the case where shallow groundwater is relatively saline, compared to stream flow, and is a significant contributor to the salt load of the stream (Brodie et al. 2006).

### 3.2.5 Water Budgeting

Stream flow inputs (rainfall, stream inflow including tributary inflow and runoff) were compared with stream flow outputs (stream outflow, evaporation and abstraction) through a water budgeting process, which assumes the unaccounted difference reflects the water exchanged between groundwater and surface water (Langhoff et al. 2006). Rainfall was recorded at the rain gauge at Brunswick Office (station 009513). Evaporation was estimated from daily pan measurements at the closest Bureau of Meteorology (BOM) site, at Harvey (station 009812). Abstraction from surface water users was estimated from a user survey, and involved contacting owners along the river to determine the quantity of water they had abstracted during the water budgeting period. Inflow into the stream from irrigation return water, rainfall and runoff from rainfall events was difficult to measure and water budgeting was conducted in periods where these components would be avoided, (ie. after several days of fine conditions and outside of the irrigation season). Stream inflows and outflows at the beginning and end of the study reaches were determined from discharge measurements, either inferred from gauging station records or measured directly in the field using the area/velocity method.
Field discharge measurements used the area velocity method to calculate flow through the river. It is based on the measurement of velocity, depth and distances at a number of vertical slices along a transect perpendicular to the stream (Figure 27).

![Diagram](image)

**Figure 27. Stream transect along the river used to determine flow discharge in the area/velocity method (WRC 1998).**

The combination of distance and depth is used to calculate the cross sectional area. The stream width was measured using a measuring tape, and depth along the verticals was measured from a graduated pole. An OTT C31 fan type current meter, with a horizontally aligned vane that rotates in proportion to stream velocity, was used to measure velocity in the stream, by calculating the revolutions per second. Figure 28 shows an image of a discharge measurement being conducted in the field.

![Image](image)

**Figure 28. Conducting discharge measurement at site 1.1**
Flow is typically measured at 0.6 D (0.6 of the stream depth measured downward from the surface), a depth considered to reflect average velocity conditions. Where necessary, up to three depths can be used to measure velocity at a vertical; usually at 0.2D, 0.6D and 0.8D. The number of vertical slices across the river width necessary to get an accurate flow measurement depends upon the width of the stream itself (Table 3).

<table>
<thead>
<tr>
<th>Width</th>
<th>Number of Verticals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 2m</td>
<td>10-12</td>
</tr>
<tr>
<td>2m-3m</td>
<td>12-15</td>
</tr>
<tr>
<td>3m-6m</td>
<td>15-20</td>
</tr>
<tr>
<td>6m-30+m</td>
<td>20-25</td>
</tr>
</tbody>
</table>

Total discharge ($Q$) is calculated by integrating the stream velocities with the cross sectional area of the stream profile, and can be calculated using the mid-section method;

\[
Q = \frac{1}{2} \sum_{i=1}^{n} (X_{i+1} - X_i)(U_iY_i + U_{i+1}Y_{i+1})
\]

where $i$ is the number of verticals (1 indicates the initial point on the starting bank),

$n$ is the total number of verticals,

$X_i$ are the distances to successive measurement points along the transect,

$U_i$ is stream velocity, and

$Y_i$ is the water depth.

An initial discharge measurement run was conducted in March at 15 sites to gain an understanding of flow distribution along the river and indicate any sites for further investigation. From this assessment two reaches were selected for detailed water budgeting analysis (Figure 29). These particular reaches were selected because they contain the two study sites, Cross Farm and Sandalwood, and results from the initial discharge measurement run in March (Appendix B) identified a significant change in flow volume between the start and end of each reach. Detailed flow budgeting at Cross
Farm occurred on 29th June 2006 and at Sandalwood on 25th of September 2006. Water budgeting reaches and points where discharge measurements were taken are shown in Figure 29. The method of streamflow measurement at each point has been summarised in Table 4. Figures showing the cross sectional transects, including distance, depths and number of vertical slices, for discharge measurements are in Appendix B.

Table 4. Methods used at each site to determine streamflow inputs and outputs for water budgeting

<table>
<thead>
<tr>
<th>Site</th>
<th>Streamflow measurement method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Discharge measurement with velocity-area method</td>
</tr>
<tr>
<td>1.2</td>
<td>Reading river stage level from 612039 gauging station and determining flow from rating curve from gauging station</td>
</tr>
<tr>
<td>1.3</td>
<td>Reading river stage level from 612032 gauging station and determining flow from rating curve from gauging station Rating curve from gauging station</td>
</tr>
<tr>
<td>2.1</td>
<td>Reading river stage level from gauging station 612047 and determining flow from rating curve from gauging station</td>
</tr>
<tr>
<td>2.2</td>
<td>Discharge measurement with velocity-area method</td>
</tr>
<tr>
<td>2.3</td>
<td>Reading river stage level from gauging station and determining flow from rating curve from gauging station</td>
</tr>
</tbody>
</table>
Figure 29. Reaches where water budgeting occurred and points where discharge measurements were taken (K. Annan 2006)
There is a portion of error associated with discharge measurement taken at gauging stations and in the field. A standard 4% measurement error is expected for all discharge measurements, but will vary at each site, depending on river bed, gauging station set up and flow conditions (Williams pers. comm. 2006). Field discharge measurements were given a standard error of 4%, due to standard river bed and flow conditions, while measurements from gauging stations 612022 and 612047 were given an 8% error interval and 612032 a 10% error interval, due to the run down nature of the gauging stations. 612032 has a specifically higher error interval because the station was not originally built to record daily flow levels, it was initially built as a flood warning site and is not adequately set up to record accurate changes in daily river levels (Williams pers. comm. 2006).

The major assumption of this technique is that it assumes the unaccounted difference between inputs and outputs indicates the amount of water exchanged between groundwater and surface water systems.
3.2.6 Seepage Meters

The methods described so far have been indirect ways of measuring seepage flux, where the nature and magnitude of groundwater flow is inferred from other parameters such as hydraulic head, temperature, salinity or baseflow analysis. Conversely, direct methods use instruments that directly measure the flow of water at the interface between the surface water feature and the aquifer. Seepage meters are the most commonly used devices for the direct measurement of seepage flux (Brodie et al. 2005b).

3.2.6.1 Seepage meter design

As discussed in the Literature Review (Section 2.0), various seepage meter designs and modifications have been used in river studies. In this study three seepage meter designs were trialled. The third and final design, was most suitable for the Brunswick River (Figure 30).

![Figure 30. Seepage meter design three: chamber made from one third of a 200 L steel oil drum (a), with an outlet (b) for 12.5 mm ID tubing (c) attached to the collection bag (d) by a 13 mm male defender fitting (e) and through a tap valve (f). Bag was housed in an open length of PVC (g). A second outlet (h) for a 7mm piece of tubing (i) allowed gas ventilation and was held in place by a metal picket (j).](image)

The meter was based on the classic design by Lee (1977) and used the top third of a 200 L steel oil drum converted into an open chamber. Diameter of the drum was 56.5 cm, which is considered relatively large and is recommended as laboratory tests indicate that
variability in seepage measurements decrease with increasing diameter of the chamber (Isiorho & Meyer 1999). Typical seepage meters are 30-60 cm in diameter (ANCID 2000). The chamber had an outlet on the side wide enough to attach 12.5mm diameter clear flexible plastic tubing. Laboratory tests recommended that the tubing diameter should exceed 7.9mm to reduce the hydraulic resistance that can cause measurement error (Rosenberry & Morin 2004). The tubing was attached to a 4L wine bladder, chosen as the collection bag due to its flexible, smooth, compliant and thin walled structure (Brodie et al. 2005b). Connection between the tubing and the wine bladders was achieved by removing the original tap of the bladder and inserting a 13mm male defender in its place. The tubing was pushed over the male defender and an air tight seal was created (Figure 31). A valve was placed between the chamber and the collection bag, located three quarters along the tubing length. The idea of the valve was to incorporate a control for the commencement and end of the test. Another outlet on top of the chamber was used for a tube to be extended above the water surface, open to the atmosphere to allow venting of any accumulated gas. The outlet tube was made of 7mm rigid plastic tubing and held in an upright position by a metal picket. The bag was housed in an open length of PVC pipe to protect it from being pierced, or detached or from drifting upwards.

![Figure 31. Close up of the tap valve and seal between the chamber and collection bag](image-url)
3.2.6.2 Seepage meter operation

The following procedures and practices were carried out during seepage meter operation, and were largely inspired by those detailed in Brodie et al. (2005).

1) The chamber was inserted into the river sediment open end down until it was 2 cm above the sediment surface, by filling it with water and then pushing it slowly into the sediment. It is not desirable for the chamber to protrude out of the river bed too much because of upward advection of interstitial water (Bernoulli effect) caused by such positive relief in river environments with currents (Brodie et al. 2005b). The chamber also needs to be inserted significantly deeply into the sediment to limit the ingress of shallow throughflow or re-circulated surface water (Brodie et al. 2005b). The chamber was tilted slightly so that the vent hole was relatively elevated, to allow trapped gas to escape.

2) Sufficient time was allowed between installation of the chamber and operation so that hydraulic pressures inside the chamber could equilibrate with those of the surface water body. Laboratory tests suggest that 80% of this equilibrium occurs in the first 10 minutes (Cherkauer & McBride 1998; Cable et al. 1997), and investigators have used stabilisation times ranging from 10-15 minutes to 2-5 days (Brodie et al. 2005b).

3) The wine bladder was prefilled with a known volume of water, 500 mL, before attachment. Pre-filling reduces bag flexing, preventing unwanted head loss, and can be used as a measure of reverse flow into the sediment (Shinn et al. 2002).

4) To make sure the water in the bag is in hydraulic equilibrium with the surface water body, the bag is slowly lowered into the water with the valve open and the chamber end of the tubing above the water surface (Brodie et al. 2005b). Any air within the bag was expelled through the tubing, and then the valve was closed. Care was taken not to lose any water from the bag during this process. The tube was then attached to the chamber, by submerging the bag and valve end of tubing first, to allow air bubbles in the tubing between the valve and the chamber end to escape.

5) The bag was placed inside its protective cover to complete the meter design.

6) Seepage measurements begun by opening the valve and recording the time.
7) After a period of time the seepage measurement was ended by returning to the meter, turning the valve closed and recording the time. The total duration of the test is based on local seepage regime and can vary from less than an hour to several days (Brodie et al. 2005b).

8) The bag was removed from the chamber via the tubing and the volume of water in the bag was measured on site with a 5L measuring bucket.

Seepage flux (Q) can then be calculated by:

\[ Q = \frac{(V_f - V_o)}{tA} \]

where

- \( V_o \) is the initial volume of water in the bag,
- \( V_f \) is the final volume of water in the bag,
- \( t \) is the time elapsed between when the bag was connected and disconnected, and
- \( A \) is the plan area of the chamber

Seepage meters were employed in study reach one (Cross Farm) during June and in study reach two (Sandalwood) during June and September. The original seepage meter design trialled in June (design 1) differed from the one described above (design 3). While based on the same foundation by Lee (1977), only one outlet from the drum, the top outlet, was present in design 1. The single outlet was used for tubing attached directly to a GLAD-lock plastic freezer bag, the collection bag in this design, selected originally for its flexible design and recommendation by Lee and Cherry (1979). Connection between the bag and tubing was made with duct tape, and did not involve the use of tap values or fittings to ensure an air tight seal (Figure 32b). An open length of PVC piping was again used to house the collection bag. The preliminary design is shown in Figure 30a. Meters borrowed from CSIRO were also trialed (design 2), which were similar in design to design 1 yet lighter as the drum was made of plastic (Figure 33).
3.0 Methodology

Figure 32. Seepage meter design 1 (a) and its collection bag attachment to the tubing (b)

Figure 33. Seepage meter design 2 (CSIRO)

Table 5 shows the dates and design type of seepage measurement trials conducted. Original seepage meters placed at Cross Farm during the June trial were vandalised, producing no results. To avoid further damage seepage measurements were not carried out at this site again.

**Table 5. Dates and design type used in seepage meter trials**

<table>
<thead>
<tr>
<th>Dates of seepage measurements</th>
<th>Cross Farm</th>
<th>Sandalwood</th>
</tr>
</thead>
<tbody>
<tr>
<td>28/6/06-29/6/06</td>
<td>Design 1 VANDALISED</td>
<td>Design 1</td>
</tr>
<tr>
<td>20/9/06-25/9/06</td>
<td>n/a</td>
<td>Design 2 and Design 3</td>
</tr>
<tr>
<td>25/9/06-26/9/06</td>
<td>n/a</td>
<td>Design 2 and Design 3</td>
</tr>
<tr>
<td>26/9/06-9/10/06</td>
<td>n/a</td>
<td>Design 3</td>
</tr>
</tbody>
</table>
3.2.7 Field Observations

A field reconnaissance survey was carried out in late February 2006 to identify locations showing signs of groundwater discharge. Visual indicators of groundwater discharge that were searched for in the field included:

- Seepages and springs
- River pools in baseflow conditions
- Reaches were flow has ceased
- Reaches were flow is continuous, and
- Changes in water composition, colour and odour

There are tell tale signs to look for when locating springs (Brassington 1998). Springs can be noted on a landscape by a change in colour at their location compared to the rest of the field. Rushes and sedges which grow in wet places are often a darker green than the grass covering the rest of the field (Brassington 1998). Clumps of sedges and rushes seen at intervals can indicate the spring line (Figure 34).

Figure 34. Detecting a spring line in the field (Brassington 1998)

Formation of river pools and maintenance of pool levels outside the wet season are an indication of areas where the stream is groundwater fed, with potentially gaining conditions. Reaches where flow is continuous throughout the year also suggests gaining
conditions, as the stream does not dry up with the season. Conversely, reaches where flow has ceased may indicate losing conditions.

Water colour and odour can be an indicator of groundwater discharge, particularly if the groundwater is contaminated, which may be the case in catchments with urban, industrial, mining or intensive agricultural development (Brodie et al. 2006). For example, discharge of highly acidic groundwater can be indicated by a dramatic increase in the clarity of the surface water, due to the flocculating of clay particles by elevated levels of dissolved aluminum (Brodie et al. 2006).

Field observations were not restricted to the original reconnaissance survey and were continued in conjunction with other field work and site visits. A Garmin III global positioning system (GPS) was used to record the location of any field observations for later identification on digital maps.
4.0 Results and Findings

This section displays the major results of each technique and includes a comparison of their spatial scale, results, and suitability to the Brunswick River environment.

4.1 Results of each technique

4.1.1 Connectivity Mapping
Information from groundwater level analysis during the groundwater level assessment in June 2006, as well as levels collected in September have been tabulated in Appendix C. The results from hydrogeological investigations to determine connection along the river, including river bed and groundwater level assessment, and the interpretation of underlying geology have been combined into a hydrogeological cross section of the river.

River bed and groundwater elevations

The cross section shows the elevation of the water table compared to elevation of the river bed along the river from its confluence with the Collie River to its most upstream point in the State Forest. Based on the difference between these elevations the cross section can indicate the presence of gaining and losing reaches, which will be further discussed in section 5.3 (Significance of results for connectivity along the Brunswick River). From the difference in these elevations a map showing connectivity along the river has been developed (Figure 34).
Figure 34. Gaining and losing reaches of the Brunswick River (K. Annan 2006)
Underlying geological structure

The geological structure underlying the Brunswick River in the lower catchment (east of the Darling fault line) is vastly different from that underlying the river in the upper catchment. Quaternary deposits and superficial formations consisting of Tamala Limestone, clay and sand members of the Guildford formation and Bassendean sands make up the underlying structure in the lower catchment. Older, Archaean age, formations underlie the river in the upper catchment, with the variable presence of colluvium valley fill deposits, containing varying amounts of laterite. Outcrops of Cainozoic laterite were also indicated in the upper catchment by geological map sheets.

Consultation with other geological investigations revealed this pattern of geology is common for the Darling Scarp, which is the name given to the surface expression of the Darling Fault lying on the western edge of the Yilgarn Block, a plateau of stable, Archaean crystalline rocks where linear belts of metamorphosed sedimentary and volcanic rocks are invaded by large areas of granite (Briggs et al. 1980). Cainozoic laterite covers the majority of the Darling Range and consists of a ferruginous or aluminous layer generally 2 m thick overlying a pallid, kaolinitic zone (Briggs et al. 1980). The soils of the region are largely of granitic origin with laterites dominating those of the ridges and slopes on the Darling Range (Churchward & McArthur 1980).
(Please see the cross section attached on separate .pdf ‘Brunswick River hydrogeological cross section’)

Figure 35. Hydrogeological cross section of the Brunswick River (K. Annan 2006)
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4.1.2 Baseflow Analysis

Results from base flow analysis and determination of the baseflow index (BFI) have been summarised in Table 6. There is a decreasing trend in BFI downstream, from Sandalwood (612022) with a BFI of 44% to Beela (612047) with a BFI of 39% to Cross Farm (612032) with a BFI of 32%. For comparison across stations, analysis was conducted over the coinciding periods of flow records for each station (10/5/2000 – 6/4/2006), and a separate BFI was generated for each year. The BFI’s produced in 2006 were significantly larger than any other year, because the flow record for 2006 only included data for the first four months of the year (1/1/2006 to 6/4/2006), which represent baseflow conditions and the stage where baseflow dominates the hydrograph. Since the following quickflow period was not included in the BFI calculation for 2006 the results were biased towards higher BFI’s. Therefore streamflow data for 2006 was not included in the overall comparative calculation of BFI across each station. Consistent with this rationale of not including partial yearly flow data, data from the year 2000 was also disregarded when comparing the BFI at each station.

<table>
<thead>
<tr>
<th>Year</th>
<th>612022</th>
<th>612047</th>
<th>612032</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>48%</td>
<td>64%</td>
<td>39%</td>
</tr>
<tr>
<td>2001</td>
<td>57%</td>
<td>53%</td>
<td>38%</td>
</tr>
<tr>
<td>2002</td>
<td>45%</td>
<td>36%</td>
<td>35%</td>
</tr>
<tr>
<td>2003</td>
<td>42%</td>
<td>33%</td>
<td>31%</td>
</tr>
<tr>
<td>2004</td>
<td>41%</td>
<td>37%</td>
<td>30%</td>
</tr>
<tr>
<td>2005</td>
<td>45%</td>
<td>43%</td>
<td>31%</td>
</tr>
<tr>
<td>2006</td>
<td>72%</td>
<td>72%</td>
<td>66%</td>
</tr>
</tbody>
</table>

The results show that baseflow contributions were greatest within the upper catchment, with baseflow contribution to streamflow decreasing downstream. Trend analysis comparing the fluctuation in annual BFI over the entire record of streamflow with annual fluctuations in the minimum stream flow record at each site, showed there is a clear correlation between the two series (Figure 36 - 38).
4.0 Results and Findings

Figure 36. Annual BFI versus minimum annual streamflow at Sandalwood (612022)

Figure 37. Annual BFI versus minimum annual streamflow at Beela station (612047)
Linear regression analysis quantified a strong correlation ($r > 0.5$) between BFI and annual minimum flow at each station, as shown in Figure 39-41. Equations of linear regression trend lines and the coefficient of determination are displayed in Appendix C.
4.0 Results and Findings

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Figure 39. Linear regression showing the relationship between annual BFI and minimum stream flow data, line of best fit and correlation coefficient at stream gauging site 612022

Figure 40. Linear regression showing the relationship between annual BFI and minimum stream flow data, line of best fit and correlation coefficient at stream gauging site 612047
The highest correlation occurred at Beela (612047) station. This is an interesting result because Beela station is the most accurate of the three stations in recording daily streamflow data.
4.1.3 Temperature Survey

Stream bed and river bed temperature variations over the effective monitoring period were plotted against one another to analyse the temperature signal patterns at study reach one; Cross Farm (Figure 42) and study reach two; Sandalwood (Figure 43). Stream surface temperature signals at Cross Farm during June 2006 show a typical diurnal variation in temperature, in the range 11.6°C to 14.2°C. The sediment temperature signal is not constant and varies over the range 13.9 °C to 14.1 °C over the monitoring period. When compared to the pattern of variation in stream temperature, sediment temperature has an approximate lag time of 3-5 hours. Average shallow groundwater temperature measured in this region was 17.5 °C. The pattern shown here suggests sediment temperature is not influenced by groundwater temperature, because it is not constant over the monitoring period and rather it is influenced by surface temperature, as it shows a slight fluctuation over time and sediment temperature values are within the range of surface temperature values. This pattern suggests a downward rather than upward seepage of water across the stream bed and thus represents a losing condition.

Figure 42. Losing temperature signal at study reach one: Cross Farm
Temperature monitoring during September 2006 at Sandalwood showed the characteristic diurnal surface variation signal, with values ranging between 12.1 °C and 14.8 °C. However, unlike Cross Farm, no variation at all was recorded in the sediment profile, and it remained at a constant value of 14.7°C during the monitoring period. Local groundwater temperature in this upstream reach is assumed the same as near Cross Farm, due to constant temporal and spatial properties of groundwater temperature. The fact that no variation in the sediment temperature profile occurred during the period, suggests that sediment temperatures are not influenced by stream water and are rather controlled by groundwater influences. Therefore, gaining conditions are experienced at this reach.

![Temperature graph](image)

Figure 43. Gaining temperature signal at study reach two: Sandalwood
4.1.4 Salinity Survey

All salinity measurements taken at each study site are shown in Appendix B. The average of the three measurements at each site is displayed in the graph below.

![Graph showing salinity readings along the Brunswick River](image)

Figure 44. Salinity readings measured at sites along the Brunswick River during February and June

Groundwater salinities measured at 8 locations, including 7 bores and 1 spring, throughout the catchment during June 2006 showed a large variation in conductivity, ranging from 250µS/cm to 1735µS/cm (Table 7). Four of these 8 sites were measured in September 2006 and the range in salinities was still variable from 321µS/cm to 890µS/m. Some sites gave similar readings to their June recordings, such as B8 from 884µS/cm in June to 890µS/cm in September, while others changed considerably over the three months; B16 decreased in salinity by more than half from June (1735µS/cm) to September (627µS/cm). Due to the inconsistent readings of groundwater salinity throughout the catchment it was difficult to determine an overall value for local groundwater salinity. Therefore any changes in stream salinity could not be matched with groundwater seepage.
Table 7. Variations in groundwater salinities measured at bore sites and a spring in the Brunswick catchment during June and September 2006

<table>
<thead>
<tr>
<th>Site for groundwater salinity measurement</th>
<th>June 2006</th>
<th>September 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>B11</td>
<td>349 µS/cm</td>
<td>-</td>
</tr>
<tr>
<td>B14</td>
<td>534 µS/cm</td>
<td>-</td>
</tr>
<tr>
<td>B15</td>
<td>250 µS/cm</td>
<td>321 µS/cm</td>
</tr>
<tr>
<td>B16</td>
<td>1735 µS/cm</td>
<td>627 µS/cm</td>
</tr>
<tr>
<td>B9</td>
<td>508 µS/cm</td>
<td>-</td>
</tr>
<tr>
<td>B10</td>
<td>537 µS/cm</td>
<td>-</td>
</tr>
<tr>
<td>B8</td>
<td>884 µS/cm</td>
<td>890 µS/cm</td>
</tr>
<tr>
<td>S1</td>
<td>585 µS/cm</td>
<td>385 µS/cm</td>
</tr>
</tbody>
</table>

### 4.1.5 Water Budgets

Results from water budgeting based on measurements of inputs and outputs in the study reaches are tabulated below (Table 8). For location of study reaches and discharge measurement sites please refer back to Figure 29 in Section 3.2.5 (Water Budget Methodology).

Table 8. Water budgeting results for study reach one (Cross Farm) on the 29th of June

<table>
<thead>
<tr>
<th>Component</th>
<th>Measured at</th>
<th>Discharge (L/s)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow at the start of the reach:</td>
<td>Site 1.1</td>
<td>322</td>
<td>(+/- 4%)</td>
</tr>
<tr>
<td>Inputs:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tributary inflow from Wellesley river</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rainfall</td>
<td>Site 1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Runoff</td>
<td>Brunswick Post Office</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>43</td>
<td>(+/- 8%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Brunswick Post Office n/a</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>Outputs:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaporation</td>
<td>Harvey BOM site</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abstraction from water users</td>
<td>water user survey</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>Balance of inputs and outputs</td>
<td></td>
<td>+ 43</td>
<td></td>
</tr>
<tr>
<td>Estimated flow at end of the reach</td>
<td></td>
<td>365</td>
<td></td>
</tr>
<tr>
<td>Measured flow at end of reach</td>
<td>Site 1.3</td>
<td>450</td>
<td>(+-10%)</td>
</tr>
<tr>
<td>Unaccounted difference</td>
<td></td>
<td>85</td>
<td></td>
</tr>
</tbody>
</table>

At study reach one (Cross Farm) no rainfall, negligible evaporation and no abstraction from water users occurred during the period of water budgeting. Initial budgeting suggests there is an additional 85 L/s entering stream flow along the reach. When considering the errors involved with gauging station and discharge measurements, the difference could reduce to 25 L/s (calculated by taking the upper error bound of discharge
for inflows and flow at the start of the reach, and subtracting the lower error bound of discharge for flow at the end of the reach). Conversely, by taking the lower error bound of discharge for inflows and the upper error bound of discharge for flow at the end of the reach, the unaccounted difference could be as much as 147L/s. Overall, this balance suggests the study area is gaining water along its reach.

At study reach two (Sandalwood) no rainfall, negligible evaporation and no abstraction from water users occurred during the period of water budgeting. Initial budgeting suggests there is an additional 415L/s entering stream flow along the reach. When considering the errors involved with gauging station and discharge measurements, in a similar fashion to that at study reach one, the unaccounted difference could reduce to 290L/s or could be as much as 540 L/s. This balance suggests there is a strong positive flux of seepage occurring in this area, and thus a gaining reach.

Table 9. Water budgeting results for study reach two (Sandalwood) on the 26th September 2006

<table>
<thead>
<tr>
<th>Component</th>
<th>Measured at</th>
<th>Discharge (L/s)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow at the start of the reach</td>
<td>Site 2.1</td>
<td>433</td>
<td>(+/- 8%)</td>
</tr>
<tr>
<td>Inputs:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tributary inflow from Lunenburgh river</td>
<td>Site 2.2</td>
<td>209</td>
<td>(+/- 4%)</td>
</tr>
<tr>
<td>Rainfall</td>
<td>Brunswick post office</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Runoff</td>
<td>-</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Outputs:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaporation</td>
<td>Harvey BOM site</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Abstraction from water users</td>
<td>Water user survey</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Balance of inputs and outputs</td>
<td>+209</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimated flow at end of reach</td>
<td></td>
<td>642</td>
<td></td>
</tr>
<tr>
<td>Measured flow at end of reach</td>
<td>Site 2.3</td>
<td>1060</td>
<td>(+/- 8%)</td>
</tr>
<tr>
<td>Unaccounted difference</td>
<td></td>
<td>418</td>
<td></td>
</tr>
</tbody>
</table>
4.0 Results and Findings

4.1.6 Seepage Meters
Results from all seepage meter trials at study reach two have been tabulated below (Table 10). As discussed earlier, no results were produced for study reach one (Cross Farm) due to vandalism. Calculations of seepage flux have been included in Appendix C.

<table>
<thead>
<tr>
<th>Date and time of measurement period</th>
<th>Trial</th>
<th>Design Type</th>
<th>Diameter (m)</th>
<th>Plan Area ( (m^2) ) ( (A = \pi r^2) )</th>
<th>Test duration (days)</th>
<th>Difference (mL)</th>
<th>Seepage flux (L/d/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28/6/06 12.30pm-29/6/06 11.30am</td>
<td>A</td>
<td>1</td>
<td>0.56</td>
<td>0.2463</td>
<td>0.958</td>
<td>270</td>
<td>1.14</td>
</tr>
<tr>
<td>20/9/06 11.30am-25/9/06 4.45pm</td>
<td>B</td>
<td>2</td>
<td>0.57</td>
<td>0.255</td>
<td>5.22</td>
<td>No change</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>0.56</td>
<td>0.2463</td>
<td>5.22</td>
<td>1365</td>
<td>1.06</td>
</tr>
<tr>
<td>25/9/06 5.15pm-26/10/06 9.15am</td>
<td>D</td>
<td>2</td>
<td>0.57</td>
<td>0.2463</td>
<td>0.67</td>
<td>No change</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E</td>
<td>0.56</td>
<td>0.2463</td>
<td>0.67</td>
<td>160</td>
<td>0.97</td>
</tr>
<tr>
<td>26/9/06 9.30am-9/10/06 12.30pm</td>
<td>F</td>
<td>3</td>
<td>0.56</td>
<td>0.2463</td>
<td>13.125</td>
<td>2850</td>
<td>0.87</td>
</tr>
</tbody>
</table>

No results were collected with design two, due to a restrictive hydraulic gradient that the design presents, where water needs to flow upwards against gravity before it can reach the bag. A great proportion of the 270mL collected during trial 6, is thought to be influenced more by installation errors than actual seepage flux. While the bag was already intact, the chamber was shifted further into the river bed and this is thought to have created a pressure within the chamber strong enough to exert water into the collection bag. Due to different design set ups, it is good practice to compare results from the same design only. All trials from design three (C, E and F) show that the reach is receiving a low positive gaining flux ranging between 0.88 – 1.06 L/d/m².

Investigators have incorporated a meter correction factor to the calculation of seepage rates, taking account of the measurement error due to frictional resistance and head losses.
within the meter. Laboratory testing indicated a ratio of measured to actual seepage of 0.77 (Belanger & Montgomery 1992). However, such correction factors would be unique to a particular seepage meter and would require calibration in a laboratory flume (Brodie et al. 2005b). Such calibration did not occur in this study and thus the results can not be used to give a quantified indication of seepage flux. Instead, results are limited to a qualitative assessment, showing an overall positive seepage flux occurring in the reach. Successive trials with seepage meter design 3 produced results in a similar range, which suggests the meter is suitable for the Brunswick River environment and has the potential to produce more quantitative data.

4.1.7 Field Observations

Several visual indicators suggesting groundwater-surface water interaction were located in the field. The exact location of these indicators can be viewed in Figure 45 and a corresponding table of the observations and a description of what they imply, in terms of groundwater-surface water interaction, have been tabulated (Table 11). Supporting photographs for several of the observations are also displayed (Figure 46 to Figure 52).
Table 11. Visual indicates of groundwater-surface water interaction located in the field

<table>
<thead>
<tr>
<th>Visual Indicator</th>
<th>Observation</th>
<th>Implication</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Inundation: river looks swampy and is heavily inundated</td>
<td>Indicating completely saturated underlying aquifer and a high water table</td>
</tr>
<tr>
<td>2</td>
<td>Very murky water immediately after a rainfall event</td>
<td>Contribution from overland run off</td>
</tr>
<tr>
<td>3</td>
<td>Spring and spring line (Figure 46)</td>
<td>Upwelling of groundwater to the surface through preferential flow paths.</td>
</tr>
<tr>
<td>4</td>
<td>Spring (Figure 47)</td>
<td>Upwelling of groundwater to the surface through preferential flow paths.</td>
</tr>
<tr>
<td>5</td>
<td>Dolerite outcrop (Figure 48)</td>
<td>Presence of dolerite formations in the catchment</td>
</tr>
<tr>
<td>6</td>
<td>Natural fill dam (Figure 49)</td>
<td>Natural fill dam above the elevation of the river. Indicates strong contribution from water stored in banks and a high potentiometric head of groundwater in the area, relative to the river bed</td>
</tr>
<tr>
<td>7</td>
<td>Seepage running down the hillside (Figure 52)</td>
<td>Contribution from groundwater to the stream via over hill side seepage</td>
</tr>
<tr>
<td>8</td>
<td>Iron flocculation (Figure 51)</td>
<td>Groundwater discharge from underlying geological structure brings water to the stream that has leached through laterite containing iron stone</td>
</tr>
<tr>
<td>9</td>
<td>Seepage coming directly out of the bank and into the river (Figure 50)</td>
<td>Contribution from groundwater to the stream via over bank flow</td>
</tr>
</tbody>
</table>
Figure 46. Following a spring line along the hillslope (a), start of the spring noted by clumps of rushes and green patches of land, and by a small outcrop of rocks (b), continuation of the spring line (c) to a well which utilises water from the spring. Note the location of the river in the background at the bottom of the hillslope noted by cluster of trees.

Figure 47. Spring line, indicated by clumps of rushes and also the presence of water troughs used to store water as it passes over the landscape
4.0 Results and Findings

Figure 48. Geological indicator of dolerite outcrop

Figure 49. Natural fill dam at an elevation higher than the river base

Figure 50. Bank seepage: flow coming directly from the river bank into the river
Figure 51. Iron flocculation, occurring at the edge of the river bank
Figure 52. Seepage occurring along the hillslope (a), seepage streaming over exposed clay material (b), seepage running onto the road (c) and further down its path seepage following lower elevations to the river (d). Note the blue arrow indicating the location of the river.
4.2 Comparison of results at each study reach

Table 12. Comparison of techniques based on scale, results and suitability to the Brunswick River

<table>
<thead>
<tr>
<th>Technique</th>
<th>Spatial Scale</th>
<th>Results at Study Reach</th>
<th>Suitable for Brunswick River environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connectivity mapping</td>
<td>Intermediate to regional</td>
<td>Gaining and losing</td>
<td>Gaining</td>
</tr>
<tr>
<td>Baseflow analysis</td>
<td>Intermediate</td>
<td>Gaining</td>
<td>Gaining</td>
</tr>
<tr>
<td>Temperature survey</td>
<td>Local</td>
<td>Losing</td>
<td>Gaining</td>
</tr>
<tr>
<td>Salinity survey</td>
<td>Intermediate</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Water budgeting</td>
<td>Local</td>
<td>Gaining</td>
<td>Gaining</td>
</tr>
<tr>
<td>Seepage measurements</td>
<td>Local</td>
<td>n/a</td>
<td>Gaining</td>
</tr>
<tr>
<td>Field observations</td>
<td>Intermediate to regional</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>
5.0 Discussion

5.1 Significance of results at each study reach

Study Reach One (Cross Farm)

The area shows signs of gaining (in the part of the river overlying Bassendean sands) and losing (in the part of the river overlying Tamala Limestone). Overall water budgeting indicated the reach was gaining up to 85L/s along its reach. Temperature surveys and connectivity mapping suggest the reach is losing in its lower boundary. Baseflow analysis showed that this section of the river has a BFI of 32%, which shows a fair contribution from baseflow (Brodie pers. comm. 2006). However, in comparison across sites baseflow analysis shows that Cross Farm receives a decreasing amount of baseflow contribution than sites further upstream. This is in agreement with connectivity mapping which shows a gaining to losing trend from Sandalwood to Cross Farm.

Study Reach Two (Sandalwood)

All the techniques utilised within this reach, apart from the inconclusive results from the salinity survey, show signs of gaining. Water budgeting suggests the reach is gaining up to 540L/s within the reach. Temperature survey, seepage meters, connectivity mapping and baseflow analysis also suggest gaining conditions at this reach. This is a reasonable result because it is common for upper catchments to act as a collection source for water from their surrounding environment and gain stream flow volume for discharge further downstream.
5.2 Significance of results for connectivity along the Brunswick River

Overall results show that the Brunswick River is strongly connected with the underlying aquifer along its entire length. A discussion of connectivity along the river will follow (from upstream to downstream) and should be read in conjunction with Figure 35, the Hydrogeological Cross Section presented in Section 4.1.1 (from right to left).

Start of the river to Sandalwood:
This section can be classified as slowly gaining, which is common for upper catchment reaches in the Darling Scarp (Commander 1988). It receives a gaining contribution from groundwater as indicated by the higher piezometric pressure head compared to river bed elevation in the area and large amount of hillside and bank side seepage, as visually indicated through field observations. The underlying geological structure has the potential to create preferential flow paths and outward expressions of groundwater, which can explain the path of seepages along the hillside and points where direct bankside seepage occurs.

Sandalwood to Beela:
This reach continues to show a gaining system. The reach is specifically classified as strongly gaining, due to results from baseflow separation, water balance and seepage meters. Whilst temperature loggers showed gaining within this reach, and defined the direction of seepage flux, they were not able to quantify the magnitude of flux.

Beela station to the Tamala Limstone/Guildford Formation geological boundary
Overall this reach is gaining steadily down stream, as shown by the higher elevation of groundwater piezometric head compared to river bed elevation. The presence of a gaining system within this reach was also noted by field observations showing visual indications of seepages and springs flowing towards the river. Piezometric head values were interpreted from current bore measurements and the bores used for analysis along this
section were the closest to the river available. There is more certainty in piezometric head levels within this reach, with less error in projection expected and therefore a higher level of confidence in results for this reach can be assumed.

**Tamala limestone/Guildford formation geological boundary to approximately 1.3km upstream of Paris Road crossing**

At the start of this reach the river becomes a losing system, caused by a drop in groundwater elevation at the geological boundary between the Guildford sands and Tamala limestone. This drop in water table is common and can always be expected when these two geological formations meet (Commander 1988). The temperature surveys within this reach also showed losing conditions.

**1.3km upstream from Paris Road crossing to the Confluence with the Collie**

This reach is gaining, as shown by the higher elevation of groundwater (piezometric head) in the area compared to river bed elevation. Gaining within this section of the river has also been indicated by field observations such as heavy inundation in the area. Gaining conditions are common at the intersection of two major rivers. The Brunswick River meets another major river, the Collie River, within this section. It is also expected that within this section of the river, groundwater levels and ultimately surface water levels would be impacted by tidal fluctuations from the Leschenault Inlet (Pearcey pers. comm. 2006b).
5.3 Limitations of methodology

This sub-section will outline the major limitations associated with the application of each technique to the Brunswick River environment, in terms of the results they produced. It will also discuss the major limitations of the Brunswick River environment for the application of techniques.

5.3.1 Limitations of Techniques

**Connectivity mapping:** Relies on the projection of groundwater levels onto the stream, assuming that the elevation where the bore is measured and the elevation of the point on the stream where the data is projected are the same. This is not always true, especially further upstream. However this technique can be useful for comparison along the river reach, when the assumptions are kept constant.

**Baseflow analysis:** BFI’s recorded during some years showed a clear jump in BFI from Sandalwood (612022) to Beela (612047), which is likely to be due to the presence of a storage reservoir, Beela Dam, between the two sites. Inflow into the reservoir is often less than outflow, which may influence the low flow signal subsequently recorded at 612047.

**Salinity survey:** Variability in groundwater salinities restricted the use of this method to the Brunswick River environment. Variability in groundwater salinity is higher during the irrigation season, which is considered to be due to irrigation run off seeping through the ground and infiltrating to groundwater stores.

**Temperature survey:** Restricted in showing the direction of seepage flux, and can not be used to quantify the magnitude of seepage flux. Temperature surveys could show gaining or losing conditions, but not the presence of neutral conditions.

**Water budgeting:** The method relies on the accurate measurement of surface water flow, as well as appropriately accounting for all other gains and losses evident for the reach. The uncertainties associated with the flow measurements and estimates for water balance
components such as unmetered extraction, evaporation, ungauged tributary flows, overbank flooding losses and flood return flows can often exceed the magnitude of the seepage flux being estimated. This project used different techniques, associated with different error bounds, to measure streamflows, which influence the effectiveness of comparing measurements across sites.

**Seepage measurements:** During the project seepage meter designs kept evolving, so that accurate comparisons between sites and across time using the same seepage meter design were not made. When the same designs were comparable (ie. between trials C, E and F), they were employed at different duration times, and so again could not effectively be compared.

**Field observations:** no limitation of this technique occurred during this project.

**5.3.2 Timescale limitations of techniques characterising connectivity**
It is recognised that there are many configurations of exchange flow between surface water and groundwater. A reach can not simply be defined as gaining because it could lose during another season. Direct observation and measurement of groundwater processes is hindered by the differing timescales associated with the movement of water in the landscape. The movement of water above ground can be quite rapid in response to rainfall events. However, the movement of water beneath the land surface can be sluggish and more difficult to predict. (BRS 2006).

**5.3.3 Site Specific limitations**
The main factors affect the application of these techniques to the Brunswick River environment:
1) Brunswick River is heavily irrigated in the lower catchment during the irrigation season, typically October to April. Therefore flows volumes and water quality are seasonally affected by irrigation run off and,
2) Public access at important field study sites, for example Cross Farm, is very high, which promotes the likely hood and in the case of this research, the occurrence of vandalism.
5.4 Comparison of Techniques

This sub-section will include a discussion on the comparison between techniques, their spatial scale, results, suitability to the Brunswick River, universally suitable conditions, and best use practices and recommendations for their use. The advantages and disadvantages of each technique, based on findings and experience from this study and others, will also be addressed.

A note on costs: This study did not consider the specific costs of each technique, as they will vary between regions. However, it is recognised that costs are a major consideration of the suitability of a technique. Despite capital costs incurred when purchasing equipment, such as the temperature loggers, costs for all techniques were relatively minimal and therefore can be widely applied in a lot of regions.

5.4.1 Overall suitable conditions and recommended application of each technique

Suitable environmental conditions and best use practice recommendations for each technique have been summarised in Table 13.
Table 13. Suitability and application of techniques in the broader context

<table>
<thead>
<tr>
<th>Technique</th>
<th>Suitable environmental conditions</th>
<th>Best-use practice recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connectivity mapping</td>
<td>Where there is a measurable difference between groundwater and river bed elevation, and a knowledge of underlying geological structure is available.</td>
<td>Important to have a good understanding of the underlying geological structure, which may influence the direction of groundwater flow paths</td>
</tr>
<tr>
<td>Baseflow analysis</td>
<td>In rivers which are perennial and are not regulated, and where the historical record of streamflow is available.</td>
<td>Coinciding periods of streamflow data should be used when comparing baseflow contributions between different sites.</td>
</tr>
<tr>
<td>Temperature survey</td>
<td>In conditions where there is a significant difference in surface water and groundwater temperatures.</td>
<td>To be used in conjunction with a knowledge of nearby piezometric pressure head information. This can be achieved by setting up a transect of mini-piezometers along the stream if bores directly adjacent to the stream do not exist.</td>
</tr>
<tr>
<td>Salinity survey</td>
<td>Where there is a significant difference between groundwater and stream salinities, such that the input of groundwater into the stream can be detected.</td>
<td>Take salinity measurements in a section of the river which is flowing to give an accurate reading and take the average of three or more samples as the final reading. Conduct measurements in the direction from the most upstream point to the most downstream point.</td>
</tr>
<tr>
<td>Technique</td>
<td>Suitable environmental conditions</td>
<td>Best-use practice recommendations</td>
</tr>
<tr>
<td>--------------------</td>
<td>-----------------------------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Water budgeting</td>
<td>Suitable in any river environment, as long as it is possible to measure all of the input and output components of the water balance (either remotely or on site). It is best applied in low flow conditions (which is summer for south west WA, but differs for northern parts of the state and country).</td>
<td>It is widely recognised that runoff and baseflow contributions are the most difficult to measure components of the water balance over a given time interval (Wittenberg &amp; Sivapalan 1999). Therefore best use practices involve avoiding water budgeting periods when rainfall is forecasted and to wait for a sufficient amount of time to pass after a rainfall event (at least 3 days) before water budgeting begins. This is to allow time for runoff or delayed baseflow response from a rainfall event to pass into the stream before measurements. Flow measurements are best taken upstream to downstream in a ‘snap shot’ fashion, where the path of streamflow is followed downstream. It is very important to take into account measurement errors associated with each of the water balance components when calculating final budgets.</td>
</tr>
<tr>
<td>Technique</td>
<td>Suitable environmental conditions</td>
<td>Best-use practice recommendations</td>
</tr>
<tr>
<td>-------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Seepage meters</td>
<td>Most suitable in environments with slow moving water (less than 6m/s is recommended (ANCID 2000)) and limited surface water fluctuations from waves, currents or fast moving streamflow which can cause a reduction in hydraulic head in the collection bag and induce a false upward groundwater seepage under gaining conditions. Found to be more suitable in sandy geological profiles, rather than basement rock or clay areas, in terms of ability to push the chamber into the river bed.</td>
<td>Best practice involves giving the meter time to settle and adjust to equilibrium after installation. Settling times ranging between 1 hour to 6 days were used for in this study. An overnight settling period is recommended by this study. However, it has been shown that 80% of equilibrium can occur in the first 10 minutes (Cherkauer &amp; McBride 1998). It is recommended that an air ventilation tube is always used in seepage meter design, regardless of underlying soil conditions.</td>
</tr>
<tr>
<td>Field observations</td>
<td>Useful in all conditions and environmental settings. However, this is only the case if the observer is familiar with visual indicators of groundwater-surface water interaction and their implications.</td>
<td>It is recommended that detailed notes of the observation be made (including GPS location coordinates, photos and an in field). Where possible, the observation should be repeated during any successive field work to see whether there is any variation over time.</td>
</tr>
</tbody>
</table>
### 5.4.2 Advantages and Disadvantages

Table 14. Advantages and disadvantages associated with each technique

<table>
<thead>
<tr>
<th>Technique</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connectivity</td>
<td>Provides an understanding of the overall hydrogeology of the river system, which is critical in defining connectivity between streams and aquifers (BRS 2006). Hydrogeological mapping is an important part of developing a conceptual model showing the broader perspective of the nature and configuration of groundwater systems, the scale and direction of groundwater flow, geomorphological features and the hydraulic properties of aquifers.</td>
<td>Compiling and interpreting hydrogeological data was time consuming and complex. It involved interpolation of limited data from a sparse network of bores, and therefore is subject to misinterpretation (BRS 2006).</td>
</tr>
<tr>
<td>Baseflow analysis</td>
<td>Readily available input data, as it relies on stream flow data that is commonly collected and publicly available.</td>
<td>Only applicable to gaining stream conditions. Baseflow is assumed to be entirely groundwater discharge which may not always be valid. The method cannot be applied in rivers that are regulated or have significant diversions or extractions, or have large natural.</td>
</tr>
<tr>
<td>Technique</td>
<td>Advantages</td>
<td>Disadvantages</td>
</tr>
<tr>
<td>--------------------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Temperature survey</td>
<td>Temperature is a natural environmental tracer, therefore the signals arrive easily and are immediately available for interpretation. Submersible temperature logging devices are robust, simple, relatively inexpensive and available for various scales of measurement.</td>
<td>Interpretation of the temperature data can be ambiguous when viewed in isolation. Several potential operational issues that could effect temperature signals have been highlighted (BRS 2006); including timing the monitoring to coincide with reasonable diurnal variations of stream temperature, the requirement of understanding the shallow stratigraphy of the stream bed, and separating out localised effects (such as from weirs).</td>
</tr>
<tr>
<td>Salinity survey</td>
<td>An environmental tracer that is readily measured in the field and does not require sample collection for laboratory analysis. Has been shown to be a valuable tool in developing a conceptual understanding of groundwater flow near a stream and useful in providing information on groundwater evolution, residence times or mixing ratios that would otherwise be difficult to determine.</td>
<td>Relies on a significant difference between groundwater and stream salinities. And also relies that there is no spatial variability in groundwater salinities throughout the catchment, in order to guarantee a single local groundwater salinity value. Limitation only good for identifying gaining conditions, trying to interpret the loss of groundwater from the system with this method is rather ambiguous (BRS 2006).</td>
</tr>
</tbody>
</table>
### 5.0 Discussion

<table>
<thead>
<tr>
<th>Technique</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water budgeting</td>
<td>Simple and based on data that is commonly collected and publicly available. Temporal and spatial changes in seepage flux can be estimated.</td>
<td>The method relies on the accurate measurement of surface water flows, rainfall, evaporation and other gains and losses evident for the reach. A lot of measurement error is associated with flow measurements and estimates of the water budget components. Measurement errors can exceed the magnitude of the seepage flux, particularly for relatively short reaches. Therefore seepage estimates can be misleading.</td>
</tr>
<tr>
<td>Seepage meters</td>
<td>Simple and cheap design, which can be adjusted to suit particular environmental conditions.</td>
<td>Only measures flux at a single point in space, and require that many measurements occur to derive meaningful interpolations, which is labour intensive and time consuming. High spatial and temporal variability in seepage characteristics can result in poor repeatability of measurements.</td>
</tr>
<tr>
<td>Field observations</td>
<td>Readily incorporated into field work</td>
<td>Relies on the observers knowledge of groundwater-surface water visual indications and their implications</td>
</tr>
</tbody>
</table>
5.5 Consideration of connectivity for water management and implications of Dam construction

The major difference between a hydraulically connected and disconnected system in terms of water management, is that changes in water table influence the rate at which surface water gains water from or loses water to the aquifer in a connected system. Whereas activities causing water table adjustments, such as pumping shallow groundwater near the stream or reservoir development, do not affect the flow of the stream in a disconnected system (Winter et al. 1998). The Brunswick River is a highly connected system, and therefore any alterations to its storage regime upstream will be felt downstream, effecting downstream flows and the presence of any groundwater dependent ecosystems.

A new dam on the Brunswick River, with the capacity to supply up to 30 GL a year to the Western Australia’s integrated water supply scheme (IWSS), is being considered (Water Corporation 2005). Although the slightly gaining conditions of the upper reach may be considered ideal for reservoir development, due to the natural fill of the reservoir, it will still act as a storage barrier and restrict flows downstream.

The construction and operation of a reservoir can have a substantial effect on the stability of the river or stream channel downstream from a dam (Juracek 2000). Primary changes introduced by a dam include a reduction in the river's sediment load and an alteration of the flow regime (Juracek 2000). Typical changes in the flow regime include a reduction in the magnitude of peak flows and a possible increase in the magnitude of low flows (Williams & Wolman 1984). Such artificially introduced changes may trigger an adjustment by the river as it attempts to re-establish equilibrium (Leopold & Maddock 1953). Channel adjustments through width, depth and gradient changes, may be achieved in several ways, including channel degradation, aggradation or changes in channel pattern and shape.

In general, rivers downstream from dams initially adjust by channel degradation, enhancing river scouring and lowering the river bed levels. Typically, channel
degradation begins near the dam and eventually migrates a considerable distance downstream (Juracek 2000). Although Williams and Wolman (1984) stated that most channel changes occur during the first 5 or 10 years after dam construction, others have speculated that the complete adjustment of a channel may require 100 years or more (Andrews 1986; Knighton 1984).

From this discussion it is clear that reservoir construction will effect the current state of the river, and has the potential to influence connectivity at reaches along the river. In addition to reservoirs, several other natural or human influenced factors may cause changes in channel-bed elevation over time, including regional climate change (Juracek 2000).

5.6 Implications of future climate change for connectivity

Climate change and decreasing trends in rainfall throughout the southwest of Western Australia over the next decade may influence connectivity along the Brunswick River. Predicted climate changes will result in shortened hydrographs, with flow occurring only at certain periods of the year and changing river classification from perennial to ephemeral.

The overall contribution from baseflow will be less. Connected reaches may start to become disconnected reaches, and gaining systems could turn into losing or neutral systems. A loss in connectivity along the river will not only see a loss in stream flow in the river, but the loss of groundwater dependent ecosystems can also be expected.
6.0 Conclusion

Effective management of water requires an understanding of the components of the hydrological cycle as well as the linkages between these components. One important connection that has been traditionally overlooked in water resource management in Australia is the interaction between surface water and groundwater resources.

This study discussed a broad range of techniques used currently and throughout history to assess groundwater-surface water interactions between streams and aquifers. Seven of these techniques were selected and used to investigate groundwater-surface water interactions along the Brunswick River, including: connectivity mapping, baseflow separation, temperature and salinity surveys, water budgeting, seepage meters and field observations. These methods were originally selected for the spatial and temporal variation they provide and because they offered a mix of field work and desktop studies.

Six of the seven techniques, excluding salinity surveys, were found to be suitable to the Brunswick River environment. Connectivity mapping proved to be a successful technique in mapping groundwater versus river bed elevations along the river to indicate gaining and losing reaches, despite associated errors in projecting groundwater levels onto the stream. Baseflow separation and the comparison of baseflow indices across different sites in the river indicated a decreasing contribution from groundwater to streamflow downstream. Temperature surveys, involved monitoring of stream and sediment temperature patterns, and revealed a losing seepage flux at study site one (Cross Farm) and a gaining seepage flux at study site two (Sandalwood). Water budgeting successfully quantified the unaccounted difference along each study reach and seepage meters showed study reach two was receiving a positive seepage flux. Field observations were helpful in confirming results from other techniques, including the location of seepage and springs in a connected and gaining reach. Salinity surveys proved inconclusive and unsuitable for the Brunswick River environment.
However, all techniques may be successfully applied in other river environments. Several recommendations for best use practices and ideal conditions for their application were outlined for each technique.

In general, the combined results of each technique show the Brunswick River is a highly connected system. Unlike many other connected streams throughout Australia, the Brunswick River is not over-allocated or highly regulated. Therefore, managers in this region can take lessons learned from eastern Australian examples and begin managing the system as a connected resource, before serious water issues such as over-allocation of the water resource emerge.
7.0 Recommendations and Future Work

It is anticipated that future work along the Brunswick River will occur in two areas including:

1) Studies involving environmental water requirements and determination of groundwater dependent ecosystems; and,

2) Assessment of the upper catchment for reservoir development.

Information contained and results found within this study will be useful for both areas of research as they require a detailed understanding of groundwater-surface water interactions along the river. However, subsequent interaction assessment studies should follow, because, whilst this study was successful in determining the spatial scale along the Brunswick River, it was unable to determine the temporal scale of the river. Assessment in this study occurred during high flow (winter) conditions. Therefore, it is recommended that the techniques used in this study be applied during low flow (summer) conditions to gain an understanding of the spatial extent of interactions along the river. It is recommended that the same techniques, not including the salinity survey, be applied. Best use recommendations, previously outlined in Section 5.4.1, should be taken into account when applying these techniques.

While a dam on the Brunswick River has been labelled as a highly prospective water source (Water Corporation 2005), it is anticipated that up to five years will be required to complete regulatory approval processes. It is highly recommended that this approval process involves an assessment of the temporal scale of groundwater-surface water interactions. Before a decision can be made on the effect of reservoir development it is recommended that a more detailed temporal assessment of connectivity occurs. It is recommended that the techniques outlined and used in this survey be considered, particularly water budgeting, temperature survey, connectivity mapping, baseflow analysis and field observations because these are suitably applied in conjunction. A salinity assessment in this upper reach is not recommended, as results have shown it to be
inconclusive. However the use of other environmental tracers, such as dissolved oxygen and stable isotopes could work in this situation.

Several extensions to the techniques used within this study and the adoption of other techniques, not specifically used in this study but introduced in the Literature Review, are recommended for future studies, including:

- Establishing a network of mini-piezometers to be used in conjunction with other techniques (namely temperature surveys and seepage meters). A network of mini-piezometers will also assist the knowledge of groundwater levels within the area, and can be monitored periodically to assess the temporal variation of connection.
- Temperature loggers could be placed in the stream for longer monitoring periods (up to months) to provide information in seasonal changes in seepage flux.
- Extend seepage meters to more quantitative results, involving calculating the total seepage flux across a section of the river by using a transect of seepage meters. Also, in gaining conditions, water collected in the collection bag could be used for chemical and physical analysis to assess the quality of incoming groundwater.
- Apply a groundwater flow model to help predict the movement of groundwater in areas where there is little recorded groundwater information, particularly in the upper catchment. The choice of model would be based upon available inputs for data sources. Specific groundwater-surface water interaction models are currently being designed to address these issues, and help assess connectivity (BRS 2006).
- Ecological indicator studies are recommended for any environmental water requirement work, including the identification of groundwater dependent ecosystems. The presence of unique aquatic habitats and fringing vegetation can help indicate groundwater dependent ecosystems, particular during low flow periods.

The Brunswick River is connected and should be managed accordingly. Finally, it is recommended that the results from this research be added to the growing database of connected water resources throughout Australia, and be included on the managing connected surface water and groundwater resources website as a case study.
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Appendices
APPENDIX A: METHODOLOGY

Appendix A1: Contours used in TIN creation
Appendix A2:

Letter sent to Private land owners requesting assistance with bore information

24 March 2006
TO:
(Owner of   )

Dear Sir/Madam
I am a student at the University of Western Australia, doing an honours project on the Brunswick River. My aim is to identify areas of surface water/groundwater interaction along the river and determine the direction of interchange. I also hope to quantify the amount of water exchanging over these interacting areas. I am particularly interested in any data you may have relating to your groundwater bore (eg. depth, rest water level, elevation of ground level at the bore, geology, bore logs, water quality information, yield). I am also interested to gain local knowledge of the river and its surrounding area (such as when the river usually stops flowing or slows down, locating areas where pools often form and any sites known for seeps). I would appreciate any data or information you can share and will gladly provide you with the results of my study upon its conclusion.

I would be grateful for your response in the enclosed reply paid envelope by 7 April 2006. My study is sponsored by the Department of Water (DoW). If you would like any further information on my research project please contact me at the DoW on (08) 6364 6930.

Thanking you in anticipation
Yours Sincerely

Katrina Annan
Environmental Engineering and Geographical Sciences Student
School of Environmental Systems Engineering
The University of Western Australia

Email: annank01@sees.uwa.edu.au
Phone: (08) 6364 6930
Appendix A3: Summary of bore details and data collected from groundwater level analysis

<table>
<thead>
<tr>
<th>Bore</th>
<th>In field reference</th>
<th>Type</th>
<th>Owner/Authorisation</th>
<th>Easting</th>
<th>Northing</th>
</tr>
</thead>
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<tr>
<td>B1</td>
<td>Bunbury Shallow BY3</td>
<td>DoW monitoring bore</td>
<td>Department of Water</td>
<td>382808</td>
<td>6317982</td>
</tr>
<tr>
<td>B2</td>
<td>Spence</td>
<td>Private residential bore</td>
<td>Spence</td>
<td>382245</td>
<td>6318001</td>
</tr>
<tr>
<td>B3</td>
<td>Howsen</td>
<td>Private residential bore</td>
<td>Howsen</td>
<td>382025</td>
<td>6318183</td>
</tr>
<tr>
<td>B4</td>
<td>Harvey Shallow HS74A</td>
<td>DoW monitoring bore</td>
<td>Department of Water</td>
<td>381095</td>
<td>6318454</td>
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<tr>
<td>B5</td>
<td>Symington</td>
<td>Private residential bore</td>
<td>Symington</td>
<td>382192</td>
<td>6319946</td>
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<tr>
<td>B6</td>
<td>English</td>
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<td>B7</td>
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<td>Christy</td>
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<td>Ridley 1</td>
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<td>Bernard Ridley</td>
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<td>6319975</td>
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<td>6319144</td>
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<td>Department of Water</td>
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<td>Private farm land bore</td>
<td>Clifton</td>
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<td>Treasure</td>
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<td>6319745</td>
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<td>B15</td>
<td>Davies</td>
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<td>Kim Davies</td>
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<td>6319104</td>
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<td>B16</td>
<td>Galati</td>
<td>Private farm land bore</td>
<td>Rodney Galati</td>
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<td>6319507</td>
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<td>Harvey Shallow HS72A</td>
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<td>B18</td>
<td>Brunswick Dam site 6</td>
<td>Decommissioned Water Corporation bore</td>
<td>Water Corporation</td>
<td>401889</td>
<td>6323648</td>
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<tr>
<td>B19</td>
<td>Brunswick Dam site 5</td>
<td>Decommissioned Water Corporation bore</td>
<td>Water Corporation</td>
<td>402739</td>
<td>6323798</td>
</tr>
</tbody>
</table>
Appendix A4 Calibration Process for WTW conductivity meter (Davies 1999)

A calibration check for the WTW conductivity meter is completed by taking observations using 1413, 6670, and 12880 µS/cm standard solutions at a temperature at, or close to, 25°C. The following details are noted:
- Date;
- Observer;
- Cell constant;
- Solution temperature(°C);
- Observed values for 1413, 6670, and 12880 µS/cm;
- Observed value adjusted to 25°C for the three solutions; and
- Appropriate comments.

Calibration checks (adjusted to 25°C) outside the following tolerances should be investigated.

<table>
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<tr>
<th>Solution</th>
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<td>1413</td>
<td>&lt; 1399</td>
</tr>
<tr>
<td>6670</td>
<td>&lt; 6603</td>
</tr>
<tr>
<td>12880</td>
<td>&lt; 12751</td>
</tr>
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</table>
APPENDIX B: Results

Appendix B1: Flow measurement results from initial discharge measurement (13th March – 14th March 2006)
Appendix B2: Area transects of discharge measurements, displaying depths, distance and vertical slices

Flow Transect from discharge measurement at site 1.1

Flow Transect from discharge measurement at site 2.2
## Appendix B3: Results collected from groundwater level analysis

<table>
<thead>
<tr>
<th>Bore</th>
<th>Elevation of bore at ground level (m AHD)</th>
<th>Measured water level from ground level</th>
<th>Water Level (m) AHD</th>
<th>Drilled depth</th>
<th>Equivalent distance along river (km)</th>
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<tr>
<td>B1</td>
<td>14</td>
<td>8.73m on 6/9/06</td>
<td>5.27</td>
<td>? (up to -307.56)</td>
<td>2.5</td>
</tr>
<tr>
<td>B2</td>
<td>11.00</td>
<td>11.200 m on 2/6/1998</td>
<td>-0.22</td>
<td>-34</td>
<td>2.83</td>
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<tr>
<td>B3</td>
<td>2.02</td>
<td>2m on 24/7/2001</td>
<td>0</td>
<td>-3</td>
<td>2.9</td>
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<tr>
<td>B4</td>
<td>7</td>
<td>5.36m on 5/9/06</td>
<td>1.64</td>
<td>-33</td>
<td>3.25</td>
</tr>
<tr>
<td>B5</td>
<td>5.58</td>
<td>5.500 m on 23/12/1998</td>
<td>0.08</td>
<td>-21</td>
<td>4.77</td>
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<tr>
<td>B6</td>
<td>6.01</td>
<td>5.800 m on 09/01/1996</td>
<td>0.21</td>
<td>-13</td>
<td>5.25</td>
</tr>
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<td>B7</td>
<td>4.47</td>
<td>3.600 m on 26/09/1989</td>
<td>0.87</td>
<td>-14</td>
<td>5.66</td>
</tr>
<tr>
<td>B8</td>
<td>6.00</td>
<td>1.75m on 26/7/061</td>
<td>4.25</td>
<td>?</td>
<td>7.09</td>
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<tr>
<td>B9</td>
<td>14.00</td>
<td>8.10m on 27/6/06</td>
<td>5.9</td>
<td>15.85</td>
<td>7.9</td>
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<tr>
<td>B10</td>
<td>14.00</td>
<td>7.34m on 27/6/06</td>
<td>6.66</td>
<td>-21.95</td>
<td>8.5</td>
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<tr>
<td>B11</td>
<td>11.00</td>
<td>3.71m on 27/6/06</td>
<td>0.29</td>
<td>4.60</td>
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<tr>
<td>B12</td>
<td>15.40</td>
<td>2.4 on 6/9/06</td>
<td>12.6</td>
<td>6.6</td>
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<tr>
<td>B13</td>
<td>10.00</td>
<td>0.760 m on 30/06/1947</td>
<td>9.24</td>
<td>-4</td>
<td>10.04</td>
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<tr>
<td>B14</td>
<td>14</td>
<td>2.56m on 28/6/06</td>
<td>11.33</td>
<td>4.2</td>
<td>10.78</td>
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<tr>
<td>B15</td>
<td>13</td>
<td>1.17m on 29/6/06</td>
<td>11.83</td>
<td>-3.66</td>
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<tr>
<td>B16</td>
<td>17.00</td>
<td>0.65m on 27/6/06</td>
<td>16.35</td>
<td>-5</td>
<td>13.7</td>
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<tr>
<td>B17</td>
<td>34</td>
<td>8.03m on 6/9/06</td>
<td>25.97</td>
<td>27</td>
<td>18.4</td>
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<tr>
<td>B18</td>
<td>145.00</td>
<td>2.25m on 27/1/83</td>
<td>142.75</td>
<td>?</td>
<td>38.30</td>
</tr>
<tr>
<td>B19</td>
<td>152.00</td>
<td>7.57m on 27/1/83</td>
<td>144.43</td>
<td>?</td>
<td>39.52</td>
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<td>Spring number</td>
<td>Elevation of water level at Spring (m AHD)</td>
<td>Equivalent distance along river (km)</td>
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<td></td>
<td></td>
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<tr>
<td>S1</td>
<td>27.5</td>
<td>18.576</td>
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<tr>
<td>S2</td>
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<td>22.94435</td>
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<tr>
<td>S4</td>
<td>96.6</td>
<td>23.10228</td>
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<tr>
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<td>84.9</td>
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<td>S7</td>
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<td>S9</td>
<td>245.7</td>
<td>52.21</td>
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</table>
### Appendix B4: Raw salinity measurement results at each site

<table>
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<tr>
<th>Site</th>
<th>In field reference</th>
<th>Easting</th>
<th>Northing</th>
<th>Distance along the river (km)</th>
<th>Salinity in February: 28/2/06 (µS/cm) Readings</th>
<th>AVERAGE</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Paris Road</td>
<td>381962</td>
<td>6317500</td>
<td>2</td>
<td>1529, 1530, 1530</td>
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<td>2</td>
<td>Cross Farm</td>
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<td>6310915</td>
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<td>1942, 1938, 1940</td>
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<tr>
<td>3</td>
<td>Salom</td>
<td>384700</td>
<td>6320265</td>
<td>9.08</td>
<td>2015, 2016, 2015</td>
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<tr>
<td>5</td>
<td>Arthurs Bridge</td>
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<td>6121130</td>
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<td>2041, 2040, 2040</td>
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<td>6</td>
<td>Caravan Park River</td>
<td>392040</td>
<td>6320321</td>
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<td>Beela Dam</td>
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<td>399540</td>
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<td>33.5</td>
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APPENDIX C: Calculations and equations

Appendix C1: Calculations of seepage flux

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<tr>
<th>Date and time of measurement period</th>
<th>Trial</th>
<th>Design Type</th>
<th>Diameter (m)</th>
<th>Plan Area (m²)</th>
<th>Test duration (days)</th>
<th>Difference (mL)</th>
<th>Difference (L)</th>
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<td>A</td>
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<td>0.958</td>
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DESIGN 1
Diameter = 0.56
Plan Area = 0.2463

DESIGN 2
Diameter = 0.57cm
Plan Area = 0.255

DESIGN 3
Diameter = 0.56
Plan Area = 0.2463

Seepage flux (Q) can then be calculated by:

\[ Q = \frac{(V_f - V_o)}{tA} \]

where \( V_o \) is the initial volume of water in the bag,

\( V_f \) is the final volume of water in the bag,

\( t \) is the time elapsed between when the bag was connected and disconnected, and

\( A \) is the plan area of the chamber

Seepage meter trial A:

\[ Q = \frac{0.270}{(0.958 \times 0.2463)} = 1.14L/d \]
Seepage meter trial B: n/a

Seepage meter trial C:
\[
Q = \frac{1.365}{(5.22 \times 0.2463)} = 1.06 \, L / d
\]

Seepage meter trial D: n/a

Seepage meter trial E:
\[
Q = \frac{.160}{(.67 \times 0.2463)} = 0.97 \, L / d
\]

Seepage meter trial F:
\[
Q = \frac{2.85}{(13.25 \times 0.2463)} = 0.87 \, L / d
\]
Appendix C2:
Linear regression equations and coefficient of determination ($R^2$) for baseflow trend analysis

Sandalwood (612022):
y = 0.4523x - 0.1599
$R^2 = 0.2887$

Beela (612047):
y = 0.484x - 0.1762
$R^2 = 0.9129$

Cross Farm (612032):
y = 5.274x - 1.6241
$R^2 = 0.7086$