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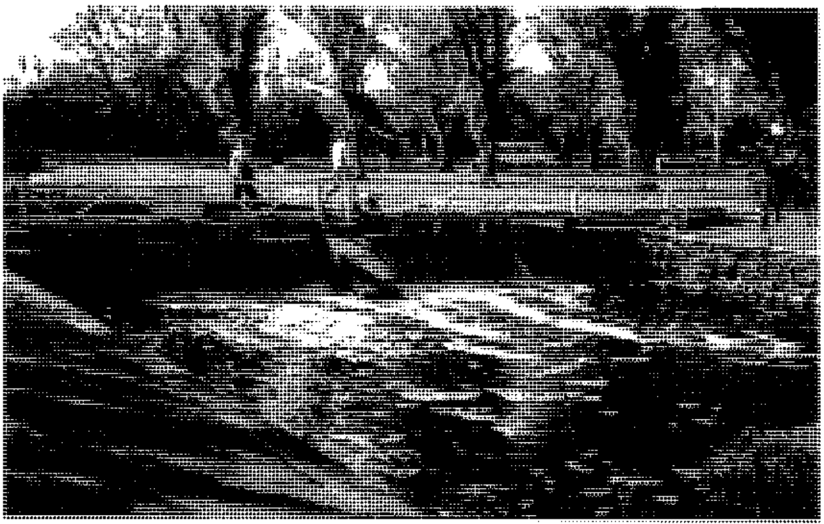
Preliminary Ecological Water Requirements for Gingin and Lennard Brooks.



Report prepared for

Water & Rivers Commission

by

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Frontispiece: Weir and waterwheel on Gingin Brook at Gingin Town site (photo. Andrew Storey)

EXECUTIVE SUMMARY

Ecological water requirements (EWRs) were assessed for the Gingin/Lennard brooks. Both systems are dominated by strong interaction with groundwater and are legislatively controlled under the *Rights in Water and Irrigation Act 1914*, amended 2000.

The climate of the region is described as Mediterranean with warm dry summers and cool wet winters. The average annual rainfall for Gingin is 732 mm. However, since 1975 there has been a significant reduction (11%) in annual rainfall which was most evident in winter months. Coefficients of variation showed extremely low variability, indicating predictable flows within the same month.

Flows are abstracted for local agricultural irrigation, particularly during summer, making water allocation for the environment an important issue. Currently, surface water allocations from Gingin and Lennard brooks are about 2.4 GL/a and 1.1 GL/a respectively. The Water and Rivers Commission (WRC) consider the current abstraction from Gingin Brook near sustainable limits, and since Westralia Fruits have switched to groundwater pumping, the current abstraction from Lennard Brook to be sustainable. The main concern for both brooks is a regional decline in groundwater levels, as these potentially will threaten the perennial nature of the brooks if flows during summer are reduced. The interaction with groundwater levels shows a fluctuating patterns with significant recharge of lower Gingin Brook in the winter to probably discharge during summer. This recharge results in substantial transmission loss from Gingin Townsite to Bookine Bookine during summer.

Gingin Brook arises on the Dandaragan Plateau, and flows southwesterly. To the east of Gingin town the tributaries of Moondah and Wowra brooks join the main channel at a main confluence which is low-lying and waterlogged. On the coastal plain, two tributaries, Mungala and Quin brooks, join Gingin Brook from the north and south respectively.

Lennard Brook is a relatively short system with headwaters on the Dandaragan Plateau flowing westwards as a single channel to the base of the Gingin Scarp. The riparian vegetation/foreshore condition on the Lennard and particularly Gingin Brook was considered in relatively good health (Pen and Scott 1995 code: A3 – C1) especially in headwaters where both clearing and stocking was reduced.

Recently, a decline in summer water flows in parts of Gingin Brook initiated studies on EWRs. EWRs are based on the premise that the environment has a right to water; that is it has to be regarded as a legitimate user. The terminology used in this report is based on that used in the *National Principles for the Provision of Water for Ecosystems* (ARMCANZ/ANZECC, 1996), and adapted by WRC (2000a) where:

Ecological water requirements (EWRs) are defined by the Water and Rivers Commission as: "the water regimes needed to maintain ecological values of water dependent ecosystems at a low level of risk." (WRC, 2000a). The determination of EWRs for water resources around Western Australia is a fundamental part of the water allocation decision-making process as an input into determining the sustainable yield of those resources

Environmental Water Provisions (EWPs) are defined by the Commission: as "the water regimes that are provided as a result of the water allocation decision-making process taking into account ecological, social and economic impacts. They may meet in part or in full the ecological water requirements." (WRC, 2000a) This

component of the process is outside the scope of this study.

EWRs in this region were scientifically determined using a "holistic" methodology; a building block protocol considered "best practice" for Australian systems. EWRs are determined in the context of the desired future state (DFS) of the system. For Gingin/Lennard brooks, the DFS is maintenance of the existing biodiversity and ecological processes, at a low level of risk.

Study sites were located in seven representative reaches:

Lennard Brook

- Immediately upstream of Westralia Farms at Ashby;
- Immediately to the west of Brand Highway

Gingin Brook

- On the headwaters of Gingin Brook at Whakea Road;
- On the headwaters of Moondah Brook;
- On Gingin Brook immediately downstream of Gingin township;
- On Gingin Brook at "Glencoe";
- On Gingin Brook downstream of Nolan Bridge on Gingin Brook Road.

These sites were classified into four "nodes" or sections of similar channel morphology:

Section 1 (Lennard Brook)
Section 2 (Moondah Brook, upper Gingin at Whakea)
Section 3 (mid Gingin; "Hotel")
Section 4 (lower Gingin; Glencoe, Nolans Bridge).

As a process of the building block methodology, key water-dependent components of the riverine ecosystem were first identified. These important ecological components to be maintained by the flow regime included; channel maintenance[1], riparian vegetation, aquatic macroinvertebrates, reproductive migration of fish and carbon/energy linkages (in three dimensions; upstream-downstream {including the estuary}, channel-associated wetlands and surface-groundwater). Total monthly flows needed to meet all EWRs for each section during each month (*i.e.* spatially and temporally) were then calculated in the context of the existing hydrology (comparing to existing percentiles flows).

The condition of flow at all sites was uniform (Froude Numbers ~0.08) and bed paving materials were in the sand/silt category. The resistance to flow (Manning's n) was low at baseflow conditions, rapidly increasing with stage height where flow interacts with large woody debris in the channels. The Manning's Equation (and a Strickler Approximation *sensu* Newbury and Gaboury 1993) was used to determine the volumes of water required to attain different stage heights for the pre-determined water-dependent ecosystems. The final flow models (Tables 10a-10d) show the recommended flow regimes for EWRs. These flows range from about 6GL/a in Node 1 (Lennard Brook) to over 23GL/a in Node 4 (lower Gingin Brook). These flows represent, in many sites, about 30% of current mean annual flows meaning there is little excess water capacity for further abstraction in the systems, particularly Gingin Brook. Summer and autumn are the critical periods where EWRs are close the median flows.

The flow regimes presented here are the initial "request" for water for the environment. The final Environmental Water Provision (EWP) will be determined

[1] **Channel maintenance flows are in-stream flows that maintain existing (or active) channel dimensions (*e.g.* through the physical process of erosion), and prevent the accumulation of sediment and organic debris.**

after social, economic and industrial users have been considered.

Monitoring Program

To determine if the determined EWRs are being met, the water levels should be monitored at each node by assessment of the nearest upstream gauging station (and assuming little transmission gain/loss between the station and the node). Whilst, current abstraction would probably have little impact on total flows over winter, during summer, abstraction may result in critically-low flows. It is therefore recommended that the monitoring program concentrate on the maintenance of summer/autumn flows.

In many reaches, land clearing and uncontrolled livestock access to river channels has exacerbated erosion. Therefore, EWRs of the Gingin/Lennard brooks should not be viewed in isolation from other river restoration issues, but should form part of an Integrated Catchment Management (ICM) plan.

The adequacy of EWRs should be monitored in an adaptive management context (*e.g.* AEAM) as outlined below. It must be emphasised that any recommended modified flow regime should be considered as a first estimate. A detailed monitoring program is recommended to assess adequacy of EWRs (see below) and should include hydrological, physical and biological parameters. This program should be assessed after three years' data have been collected.

RECOMMENDED MONITORING REGIME FOR GINGIN/LENNARD BROOKS.

Parameter	Methodology	Sites/ Frequency
Hydrology	Gauging station	Daily flows (especially during summer/autumn) at Molecap, Gingin Townsite, Bookine Bookine
Physical	Water quality sampling	Seasonally at the five sites surveyed in the current report
	Pool aggradation	Annually at the seven sites
	Channel morphology	Annually at the seven sites (both banks)
	Pool viability	Annually at focal pools in each region
Biological	Aquatic macroinvertebrates	Annually ("dry" season at the five sites)
	Fish recruitment	Annually at the five sites (coincide with breeding)
	Riparian assessment	Annually (summer) at the five sites

1. INTRODUCTION

This report documents an assessment of the Ecological Water Requirements (EWRs) for dependent ecosystems of Gingin and Lennard brooks. The assessment was undertaken for the Swan Goldfields Agricultural Region of the Water and Rivers Commission (WRC).

1.1 Background

Gingin and Lennard brooks are significant, perennial freshwater systems within the Shire of Gingin, approximately 80 km north of Perth, Western Australia. Both systems are dominated by interaction with groundwater aquifers and are fed by significant groundwater seepage through peaty banks at various points along each brook. Both brooks are controlled for water use and abstraction under the *Rights in Water and Irrigation Act 1914*, amended 2000, whereby all non-riparian users of the brooks are licensed.

Over the last five to eight years there has been a gradual decline in summer water flows in parts of Gingin Brook (WRC, 1998), which concerns local landholders. Ecological Water Requirements of each brook had not been determined. Therefore, with regard to environmental considerations as well as the need to establish a long term sustainable allocation plan, a moratorium on the issuing of new licences was set until Ecological Water Requirements for the brooks were determined.

As part of this process, the Swan Goldfields Agricultural Region commissioned the current study to determine EWRs for Gingin and Lennard brooks.

1.1.1 Statutory Framework

Ecological Water Requirements (EWRs) are critical for the maintenance of riverine ecosystems downstream from impoundments (see Davies *et al.* 1998) or in regions where there are high rates of abstraction. EWRs are based on the premise that the environment has a right to water; that is it has to be regarded as a legitimate user. The terminology used in this report is based on that used in the *National Principles for the Provision of Water for Ecosystems* (ARMCANZ / ANZECC, 1996) and adapted by WRC (2000a) where:

Ecological Water Requirements (EWRs) are defined by the Water and Rivers Commission as: "the water regimes needed to maintain ecological values of water dependent ecosystems at a low level of risk." (WRC 2000a). The determination of EWRs for water resources around Western Australia is a fundamental part of the water allocation decision-making process as an input into determining the sustainable yield of those resources.

Environmental Water Provisions (EWPs) are defined by the Commission: as "the water regimes that are provided as a result of the water allocation decision-making process taking into account ecological, social and economic impacts. They may meet in part or in full the ecological water requirements." (WRC, 2000a) This component of the process is outside the scope of this study.

EWPs that maintain the ecological integrity of river systems are also consistent with the objectives of the Environmental Protection Authority of Western Australia (EPA) to "maintain or improve the quality of surface water to ensure that existing and potential uses, including ecosystem maintenance are protected" (EPA 1993).

Both State and Federal Governments have endorsed the National Strategy for

Conservation of Australia's Biological Diversity and the National Strategy for Ecologically Sustainable Development which are designed to "protect biological diversity and maintain essential ecological processes and life support systems".

In order to minimise the environmental impact of altering river flow, it is necessary to consider the EWRs of the river environment, compare this to the actual flows and ecosystem response, and adjust management practices accordingly.

1.2 Legislative Basis

The *Rights in Water and Irrigation Act 1914* was amended during 2000 to bring water resource management in line with COAG Water Resource Policy and is currently the major water legislation in Western Australia.

1.3 Specific Aims of the Report

The current study presents the determination of EWRs for Gingin and Lennard brooks using the "Holistic Approach" for in-stream flow assessments. Further details can be found in Arthington (1998), Davies *et al.* (1998), Davies & Creagh (2000). One of the main principals of this approach is that any modified flow regime should mimic (as closely as possible) the natural flow regime. This approach was proposed, partly to overcome the limitations of existing in-stream flow methods, but also to redirect the emphasis of in-stream flow management away from species assessments towards the level of the ecosystem, and to the maintenance of flow-dependent ecosystem processes (Arthington *et al.* 1993, Davies *et al.* 1998).

As a conspicuous part of the biota, macroinvertebrates and fish were targeted as key components of the in-stream flow assessment technique. Elsewhere, the commercial and recreational value of many species has lead to a greater understanding of flow requirements of fish compared to flows needed to protect other key river features.

Specific aims of the current study were to:

(i) Determine the Ecological Water Requirements (EWRs) for Gingin Brook (from its source to its confluence with Moore River) and Lennard Brook (from its source to the wetlands west of Brand Highway);
(ii) Develop appropriate monitoring strategies for dependent riverine and wetland ecosystems.

Methods employed to meet these aims included:

- Analysis of historical data on hydrology to further elucidate the impacts of the altered water regime;

- A survey of existing channel morphology and flow regimes to determine flows to maintain the channel and associated river pools and riparian zone. Water levels in pools are important for the maintenance of ecological processes and fringing vegetation;

- Review of existing literature detailing foreshore assessments of riparian vegetation, surveys of fish and aquatic macroinvertebrate fauna and hydrogeological assessments of the brooks. Key flow requirements of aquatic fauna, known to be present, were considered to ensure that EWRs were sufficient to (a) generate high flow conditions for fish species that spawn in flooded riparian vegetation and (b) to enable movement of adult fish and juveniles and (c) maintain adequate and diverse in-stream habitat to support macro-invertebrate communities;

2. GINGIN AND LENNARD BROOK CATCHMENTS

2.1 Rainfall

The climate of the region is Mediterranean with warm dry summers and cool wet winters. The average annual rainfall for Gingin (Gingin Post Office; 009018) for the length of record (1907 to 2000) is 732 mm and average pan evaporation is 2200mm, with evaporation exceeding rainfall for the eight months, between September and April.

2.2 Landforms & Vegetation

Gingin Brook arises on the Dandaragan Plateau, and flows southwesterly through a steep-sided broad valley, which cuts through limestone and ferruginous sandstones. To the east of Gingin town the tributaries of Moondah and Wowra brooks join the main channel at a main confluence which is low-lying and waterlogged. The river then meanders around the Gingin town site, before resuming a westerly direction. Upstream of the Brand Highway, the channel bifurcates and flows for some distance across the Pinjarra Plain as two separate shallower and smaller channels. Further to the west the channels rejoin and the brook resumes as a sinuous form flowing westwards across the Pinjarra Plain to its' confluence with the Moore River, approx 15 kms from the coast (Figure 1). On the coastal plain, two tributaries, Mungala and Quin brooks, join Gingin Brook from the north and south respectively.

Lennard Brook is a relatively short system. Its headwaters arise on the Dandaragan Plateau and consist of a north and south branch which meet and then flow westwards as a single channel to the base of the Gingin Scarp. To the east of the Brand Highway, the channel changes to a south-south westerly direction, and flows for several kilometres before discharging into a series of wetlands comprising the Bampanup Nature Reserve to the west of the Brand Highway.

Melaleuca rhaphiophylla and *Eucalyptus rudis* dominate the overstorey vegetation of the riparian zones of both Gingin and Lennard brooks. The former is in higher densities closer to the waters' edge, with the latter being more dominant with increasing distance from the water. Some *Casuarina obesa* are also present on Lennard Brook (WRC, 1998).

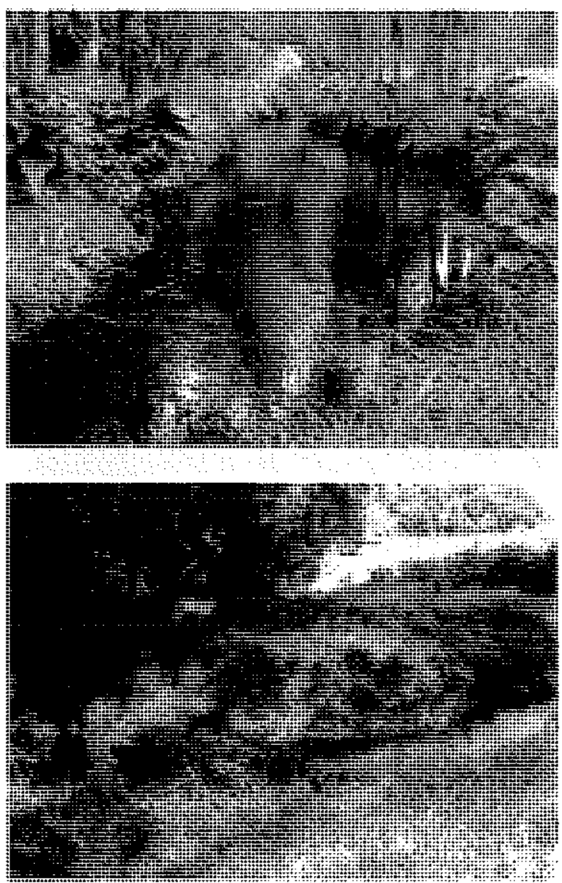

Plate 1. Riparian vegetation on Lennard Brook at Ashby (top), with dominant overstorey of *M. rhaphiophylla* and invasive weeds in understorey, and below Brand Highway (bottom) with invasive grasses.

Other native species on the Gingin and Lennard brooks consist of *Triglochin procerum* (Water Ribbon) within the main channel, and the sedges *Carex appressa* (Tall Sedge), *Carex fascicularis* (Tassle Sedge), *Baumea articulata* (Jointed

Twigrush) and *Baumea riparia* (River Twigrush). Other species also present in the riparian understorey includes *Centella cordifolia* (a perennial herb), *Lepidosperma longitudinale* (Pithy Sward-sedge), *Juncus pallidus* (Pale Rush), *Typha domingensis* (Native Cumbungi) and *Pteridium escultentum* (Bracken) (WRC, 1998). Additional species observed on Gingin Brook include *Agonis linearifolia* (Swamp Peppermint) and *Cyclosaurus interruptus* (Native Fern), with specimens of *Viminaria juncea* (Swishbush), *Jacksonia furcellata* and *Acacia saligna* (Coojong) recorded from relatively undisturbed reaches where the riparian vegetation shifted towards a Banksia-Marri woodland with species such as *Corymbia callophylla* (Marri), *Zamia* sp and *Xanthorrhoea preissii* (Grasstree). *Typha orientalis* was also present on Gingin Brook (WRC, 1998).

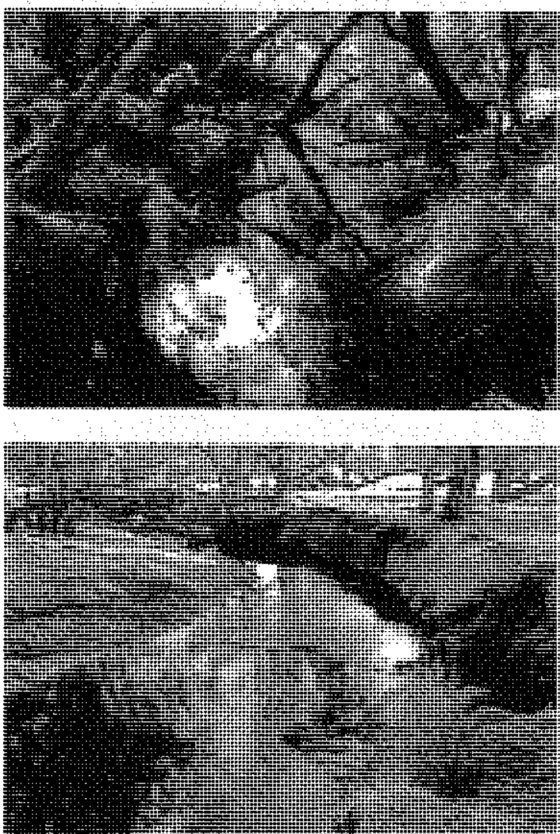

Plate 2. Channel condition on Gingin Brook, good riparian "health" in the headwaters (top) and more degraded channel in the lower reaches (bottom).

Weed species recorded from the riparian zones of the brooks included Kikuyu Grass (*Pennisetum clandestinum*), Arum Lily (*Zantedeschia aethiopica*), Water Couch (*Paspalum distichum*), Deadly Nightshade (*Solanum nigrum*), Slender Knotweed (*Polygonum salicifolium*), Elephant Ears (*Alocasia macrorrhiza*), Bullrush (*Typha orientalis*), Edible Fig (*Ficus carica*) and a parasitic annual creeper (*Cuscuta epithymum*) (WRC, 1998) (Plate 1).

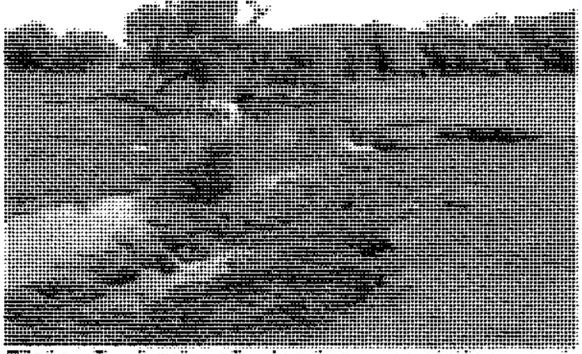

Plate 3. Lack of riparian vegetation and erosion from stock on Moondah Brook.

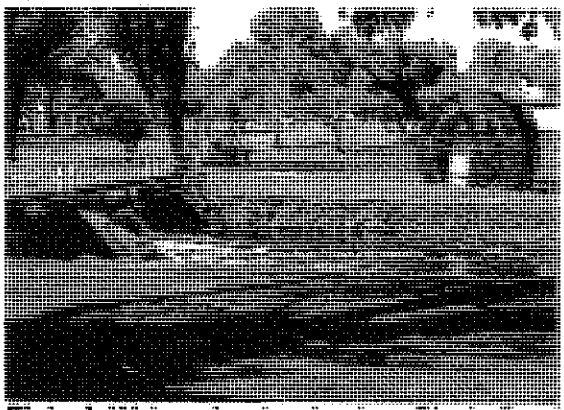

Plate 4. Weir and waterwheel on Gingin Brook at Gingin Townsite.

WRC (1998) assessed riparian vegetation/foreshore condition on the Gingin and Lennard brooks using the method of Pen and Scott (1995). They considered Lennard Brook to be in relatively good health, with a health of the riparian zone ranging from A3 – C1. Gingin Brook was reasonably healthy is places, especially in the headwaters where clearing and stocking was reduced. However, in other reaches the riparian vegetation was highly degraded to non-existent (Plate 2). The permanent inundation of some areas resulted in prolific green feed which resulted in targeted grazing in the riparian zone, resulting in high weed infestations.

The major source of disturbance to many parts of Gingin Brook, and some parts of Lennard Brook was clearing and grazing (Plate 3). In many places the riparian zone was only partially or not fenced at all and was used for grazing by cattle and sheep. This had resulting in erosion, increased sediment loads and introduction of weed species (WRC, 1998).

2.3 Water Abstraction

Currently, there are no public dams on the brooks, however, there are gauging stations and private weirs (Plate 4), and numerous bores. The surrounding area has been largely developed for horticulture and cattle grazing, and contains market gardens, large commercial orchards, pasture for grazing and rural residential development. The water requirements for these activities are greatest in summer months when rainfall is minimal. This coincides with low flow periods in the brooks. Water is abstracted either by directpumping from the brooks, or from production bores drilled into the unconfined and confined aquifer systems, water is also diverted from the watercourse through an extensive network of artificial drains and channels.

WRC (2000b), in a hydrogeological assessment of those reaches of the brooks on the Dandaragan Plateau between the Darling fault to the east and the Gingin Scarp to the west, cited 31 bores in the immediate vicinity of Gingin and Lennard brooks.

Additional direct pumping from the channel and diversions down drainage/irrigation channels occurs to both systems as they traverse the Coastal Plain.

2.4 Study Sites

The EWRs of dependent ecosystems were assessed for Gingin Brook at sites from the source on the Dandaragan Plateau to the confluence of Gingin Brook with the Moore River, and for Lennard Brook from the source to where it dissipates into the wetlands and surrounding paddocks of the Bampanup Nature Reserve west of Brand Highway. The location of the study sites is indicated in Figure 1. Sites were surveyed during autumn 2001. Opportunistic observations were also made at various points between study sites.

2.5 Past, Present and Future Ecological State

At present, the Gingin and Lennard brooks, are considered in reasonably intact "ecologically"; with reaches of both brooks characterised by intact riparian vegetation, albiet degraded by weed infestation. The hydrology has undoubtedly been impacted by abstraction. The system is the northern extent of several fish species and contains isolate populations of some native fish species (*e.g. Galaxiella munda*).

The present ecological state, although "reasonable", is characterised by some risk (due to the substantial change to the hydrology, the likelihood of increased abstraction and the possibility of an increased dry climatic period. and further weed invasion). In this context, the EWRs are designed to reduce, in the longer-term, ecological risk.

The desired future state (DFS) is the context of the EWRs. For the Gingin/Lennard system, this is considered to be that of no increased ecological risk to the present system.

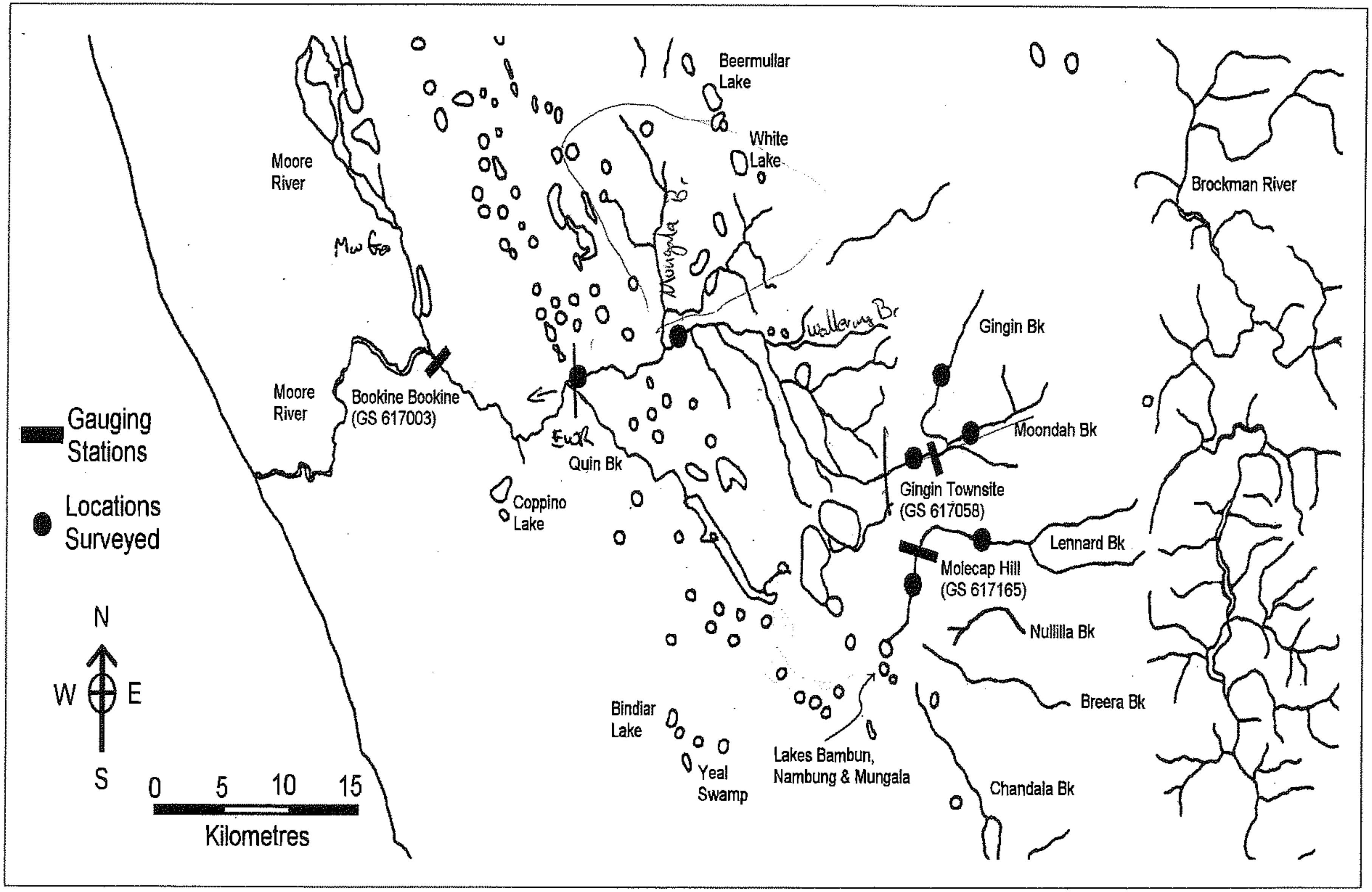

Figure 1. Map of the study area indicating location of Gingin and Lennard brooks, major tributaries and wetlands, and stream survey points.

3. DETERMINING THE HYDROLOGICAL STATE OF THE CATCHMENT

3.1 Current Hydrological State

The first stage of assessing adequate EWRs for a river system is to determine the current hydrological state of the catchment. This is important, as typically the further a river system is removed from its historic hydrology, the more the environment, and therefore, its ecological value is impacted.

Long term rainfall records for Gingin Post Office (Station 009018; 1907 to current) and hydrological data from three WRC gauging stations were used to assess the current hydrological state of Gingin and Lennard brooks:

1. Gingin Townsite on Gingin Brook (617058,),
2. Molecap Hill on Lennard Brook (617165), and
3. Bookine Bookine on Gingin Brook close to the confluence with the Moore River (617003),

The average annual rainfall for Gingin Post Office (Station 009018) for the length of record (1907 to 2000) is 732 mm (Figure 2). However, since 1975 there has been a significant reduction in annual rainfall in southwest WA. In the Gingin area, this has resulted in a statistically significant reduction in mean annual rainfall for pre-1975 (mean = 763 mm) compared with post-1975 (mean = 652 mm) (t-test, df = 92, t-value = 3.365, p = 0.001) (Figure 2). This reduction in rainfall is most evident in winter months, with total monthly rainfalls for the months April through to October lower in 1975-2000 compared to pre-1975 (Figure 3). It is estimated that mean annual rainfall for the period 1975 to 2000 is 89% of the long-term mean annual rainfall (1907 to 2000).

In contrast, Storey *et al.* (2001) recorded an 18% reduction in catchment rainfall in the Canning Catchment , which resulted in a 48% reduction in reservoir inflows. Reduced rainfall in the Gingin and Lennard catchments would also influence run-off.

Gauging data for the three stations are summarised in Table 1, and mean and median annual flows and frequency of flow occurrences are illustrated in Figure 4 and detailed in Appendix 1.

Mean annual discharge over each gauging weir for the duration of record was 13081 ML at Gingin Townsite on Gingin Brook, 6170 ML at Molecap Hill on Lennard Brook, and 38083 ML at Bookine Bookine on the lower Gingin (Appendix 1).

The decline in rainfall from 1975 onwards, is reflected in streamflow to some degree.. Stream flows in the upper catchment of Gingin Brook have been reduced in all months since 1975 (Table 2). In the lower Gingin Brook however, only winter flows have been influenced. I n the Lennard Brook there has been a slight increase in mean monthly flows since 1975. This may be influenced, to some extent, by changes in abstraction.

With increasing distance from the source, these reduced flows are likely counteracted by the effects of catchment clearing and drainage, which increase the proportion of precipitation resulting in run-off. Clearing reduces interception and transpiration and drainage causes more rapid "delivery" of the water to the creek. As a result a greater proportion of rainfall runs off the land. In addition, the speed of run-off is increased. Together, these change the shape of the flood hydrograph from a relatively slow, flat response (*i.e.* taking 24 hours for a flood peak to develop) to a more rapid response. Increased and more rapid run-off

The historic change in rainfall and associated change in runoff also has implications for calculating EWRs. The shape of the river channel is due to the action of bankfull discharge which is referred to as 'channel forming flows', and have been considered to have an average reccurence interval (ARI) of about 1:3 (note, gauging station data cannot be used to determine many hydraulic parameters due to upstream abstraction of flows) in south-western Australian streams and rivers. Reduced rainfall because of climatic change will mean that bankfull flows for the existing channel now occur at a lower frequency. Frequency of other extreme flow scenarios also will be changed.

The influence of reduced rainfall and catchment clearing on discharge in the Gingin and Lennard brooks is difficult to determine due to the absence of long-term historic gauging data. The only reliable data for the Gingin Brook on the coastal plain is from Bookine Bookine gauging station (S617003), however, the record for this station is from 1972 onwards, coinciding with most of the lower rainfall period. A longer time series is available for Gingin Townsite (1957 – current), but this encompasses only 15% of the catchment.

3.2 Variation & Seasonality of Stream Flow

Variability and seasonality of flows were determined for each gauging station. The variation, seasonality and magnitude of flow is highly influential on the ecological seasonal dynamics of stream communities and overall species composition.

Daily streamflow records were analysed to determine Coefficients of Variation (CV) for between-year variation in total annual flows (Table 3a), for each month across years (Table 3b), and across months within each year (Table 3c). These indices are particularly useful for describing temporal patterns in flow data. Both Gingin and Lennard brooks demonstrated exceptionally low CVs (for Australian rivers and streams, Puckridge *et al.* 1998) for annual discharge, with values around 20% in the upper catchment (Gingin Townsite and Molecap Hill), and 40% on the lower reaches (Bookine Bookine). This indicates very consistent between-year total annual flows, especially in the upper catchment. The higher inter-annual variability in total discharge for the lower catchment is most likely an attribute of the large catchment size and influence of rainfall events.

Coefficients of Variation for each month across years (Table 3b) also demonstrated extremely low variability, especially for Gingin Townsite and Molecap Hill, indicating relatively constant flows within the same month across years.

The highest CVs for each site were recorded for within-year changes in monthly flows, averaged across years (Table 3c), indicating a degree of seasonality in flows within each year.

Overall, analyses showed the flows for Gingin and Lennard brooks were highly "predictable" (*i.e.* high flows in winter and spring, with low flows in summer). The fact that flows never ceased is an important and highly predictable feature of the flow regime that should be maintained.

The variability of flow is illustrated for each gauging station in Figure 5, showing within and between-year changes in instantaneous flows. The predictable pattern in flows is notable. An important attribute of the upper catchment is summer baseflows. These are of particular importance to the maintenance of the ecology of the system in periods of most stress, maintaining refugia for low-flow periods. Baseflows are also of interest to local landholders, and are most likely to be reduced by abstraction.

These are illustrated in Figure 6, showing within and between-year changes in baseflows.

3.3 Catchment Hydrogeology

The perennial nature of the brooks and the very constant within and between-year flows for the upper catchment, is indicative of the groundwater contribution to the flows in the system (WRC, 2000b). The contribution of groundwater to the brooks is an important issue for determining EWRs because it buffers within and between-year variability in flows, and also has the potential to influence stream flows through changes in groundwater abstraction, altered groundwater levels and reduced discharge to the brooks.

Groundwater is believed to discharge to the brooks in the form of springs and seeps along the banks, arising from two main aquifers; the Mirrabooka aquifer and Leederville aquifer (WRC, 2000b). The Mirrabooka aquifer comprises the greensands units and the Mirrabooka Member of the Osborne Formation, while the Leederville aquifer consists of the Leederville formation and the Henley Sandstone Member of the Osborne Formation (WRC, 2000b). The attributes of each aquifer are described in detail by WRC (2000b). In summary, the Mirrabooka aquifer is unconfined and is readily recharged by rainfall, with most recharge occurring on the upper slopes and catchment divides. Groundwater discharges into the brooks at the lowest parts of the landscape, which tends to be along the valley floors. Groundwater salinity is typically less than 1500 mg/L TDS (often less than 500 mg/L).

Between the Mirrabooka and Leederville aquifers, there is a confining layer called the Kardinya Shale, comprised of dense, dark green siltstone and shale. There does not appear to be groundwater discharge from this layer. However, below the Kardinya Shale is the Leederville Aquifer. This is a regional confined aquifer of the Perth Basin. In the downstream reaches of the Gingin and Lennard Brooks the aquifer becomes unconfined where the Kardinya Shale has been removed, allowing localised discharge from the Leederville Aquifer into the brooks. Salinity of the Leederville Aquifer is 700 to 900 mg/L.

WRC (2000b) noted that, although there are relatively fast streamflow responses to rainfall during winter, it is widely acknowledged that most water in the brooks is derived from groundwater. WRC (2000b) cited Sharma *et al.* (1995) who estimated that approximately 80% of water discharged from Lennard Brook is groundwater-derived. The Hydrology and Water Resources Branch of the Water & Rivers Commission estimated 60% of total stream discharge was derived from groundwater. Subsequently, WRC (2000b) assumed that baseflows for the brooks were comprised 80% from groundwater and 20% from surface runoff. Groundwater recharge for the catchments was estimated at 10% of annual rainfall, or the percentage of rainfall that makes-up baseflow in the brooks:

$$\frac{\text{(Ann. baseflow + Abstraction) x 80\% groundwater cont.}}{\text{Catchment area x Annual rainfall (720 mm)}}$$

WRC (2000b) noted that baseflows in Gingin Brook at the Townsite gauging station declined from the early 1990's up until 1998, when there was a recovery (Figure 6). The decline was most likely a response to declining rainfall and increased abstraction (WRC 2000b assumed abstraction from Gingin Brook was constant over this period), and the recovery was due to summer rainfall in 1998 and a wetter year in 1999. Since then, there appears to be a renewed decline in baseflow (Figure 6). WRC (2000b) suggested that summer baseflows in Gingin Brook increase when annual rainfall is above 650 mm and decline when annual rainfall is less than 650mm. Analysis showed a positive significant relationship between annual rainfall and annual discharge (Figure 7).

Baseflows in Lennard Brook at the Molecap Hill gauging station showed a slightly different trend, with declining baseflows between 1992 and 1995, but followed by recovery from 1995 to present (Figure 6). WRC (2000b) note that the decline was most likely a response to declining rainfall and abstraction, and the recovery appeared to be a response to Westralia Fruits switching from surface water abstraction to groundwater pumping from the Leederville Formation. In the last two years, baseflows appear to have stabilised at a relatively higher level (Figure 6). As for Gingin Township, analysis shows a significant relationship between rainfall and discharge for Molecap Hill (and for Bookine Bookine) (Figure 7).

Therefore, it would appear that surface abstraction from Lennard Brook had an effect on baseflows, however, pumping from the aquifer does not, as yet, appear to be impacting on streamflow.

WRC (2000b) noted, that although baseflows in Lennard Brook have "recovered", the potentiometric level within the Leederville formation (measured at a bore in the mid-reaches of Lennard Brook) has been showing long term decline, from approx. 77.5 m AHD pre-1985, with at most a 0.5 m seasonal fluctuation, to approx 73.5 m AHD in 1999, with over a 3 m seasonal fluctuation. The decline in aquifer level is attributed to surface and groundwater abstraction, with a recent (post-1995) additional decrease attributed to increased groundwater abstraction by Westralia Fruits.

Currently, surface water allocations from Gingin and Lennard brooks are about 2.4 Gl/yr and 1.1 GL/yr respectively. Based on summer baseflows, WRC (2000b) consider that the current abstraction from Gingin Brook is at or near to sustainable limits, and since Westralia Fruits have switched to groundwater pumping, the current abstraction from Lennard Brook appears to WRC (2000b) to be sustainable.

The main concern for both brooks is a regional decline in groundwater levels, as these potentially will threaten the perennial nature of the brooks if surface water discharge during summer is reduced.

Overall, measurements of instantaneous flow rates indicated a significant transmission gain in Gingin Brook from the Townsite (617 058) to Bookine Bookine (617 003), however during summer, there was a net loss between gauging stations (Figures 8 and 9), presumably due to groundwater recharge, although evaporation and uptake by riparian vegetation may also play a role.

Table 1. WRC gauging stations used in the EWR assessment.

Gauging Station	River	Site name	Location	Catchment Area (km^2)	Regulation	Period of record
617058	Gingin Brook	Gingin Townsite GS	On Gingin Brook, upstream of Gingin Townsite	120	No impoundments, some abstraction from bores into the adjacent aquifer or direct pumping from the channel	1957 - 2001
617165	Lennard Brook	Molecap Hill GS	Lennard Brook, east of Brand Hwy	62	No impoundments, some abstraction from bores into the adjacent aquifer or direct pumping from the channel	1962 – 2001
617003	Gingin Brook	Bookine Bookine GS	Gingin Brook upstream of confluence with Moore River	826	Abstraction from bores into the adjacent aquifer or direct pumping from the channel. Several private weirs and diversions along irrigation channels	1972 – 2001

Table 2. Observed mean monthly flows (ML) at Gingin Town site, Molecap Hill and Bookine Bookine Gauging Stations for "average climatic conditions" (1962 to current) and for "dry period conditions" (1975 to current).

Month	Gingin Town site GS (617058) (1957 – 2001)		Molecap Hill GS (617165) (1962 – 2001)		Bookine Bookine GS (617003) (1972 – 2001)	
	1957-2001	1975-2001	1962-2001	1975-2001	1972-2001	1975-2001
January	515.7	508.8	321.3	327.9	342.2	348.5
February	464.1	451.1	284.0	292.2	285.1	287.7
March	578.5	570.6	327.9	343.3	323.2	326.6
April	782.3	727.8	374.3	399.3	499.1	465.1
May	1145.7	1104.1	523.1	573.5	1407.6	1251.3
June	1643.2	1500.1	666.7	692.7	4156.1	3965.7
July	2184.0	1915.2	826.6	844.8	9362.8	8963.3
August	2044.8	1889.6	847.6	871.3	10409.2	10116.0
September	1511.7	1481.9	727.6	762.2	6803.3	6775.8
October	1204.2	1124.8	622.0	642.2	2959.3	3030.6
November	851.9	826.6	460.2	474.1	1019.6	1006.6
December	616.8	609.2	365.8	372.0	472.5	471.9

Table 3a. Coefficient of variation for each site using total annual discharge, averaged across years.

Site	No. of obs	Coefficient of Variation (%)
Gingin Brook at Townsite GS	43	21.9
Lennard Brook at Molecap GS	38	19.9
Bookine Bookine GS	28	43.0

Table 3b. Coefficient of variation for each month averaged across years.

Month	Gingin Townsite		Molecap Hill		Bookine Bookine	
	No. of obs	Coefficient of Variation (%)	No. of obs	Coefficient of Variation (%)	No. of obs	Coefficient of Variation (%)
Jan	41	27.6	36	25.0	29	43.6
Feb	40	27.8	35	25.2	29	58.1
Mar	40	22.0	33	23.1	29	36.7
Apr	40	26.5	37	26.7	29	47.8
May	40	19.5	36	28.2	29	80.3
Jun	42	28.6	37	21.5	28	59.3
Jul	41	37.9	37	22.4	28	60.0
Aug	42	27.2	38	21.0	28	50.1
Sep	40	21.0	38	20.9	28	55.1
Oct	42	26.5	37	21.6	28	72.3
Nov	42	23.0	38	20.7	29	39.0
Dec	41	24.5	37	20.5	29	28.4

Table 3c. Coefficient of variation of monthly flows within each year, averaged across years.

Site	No. of obs	Coefficient of Variation (%)
Gingin Brook at Townsite GS	43	53.3
Lennard Brook at Molecap GS	38	40.5
Bookine Bookine GS	28	120.9

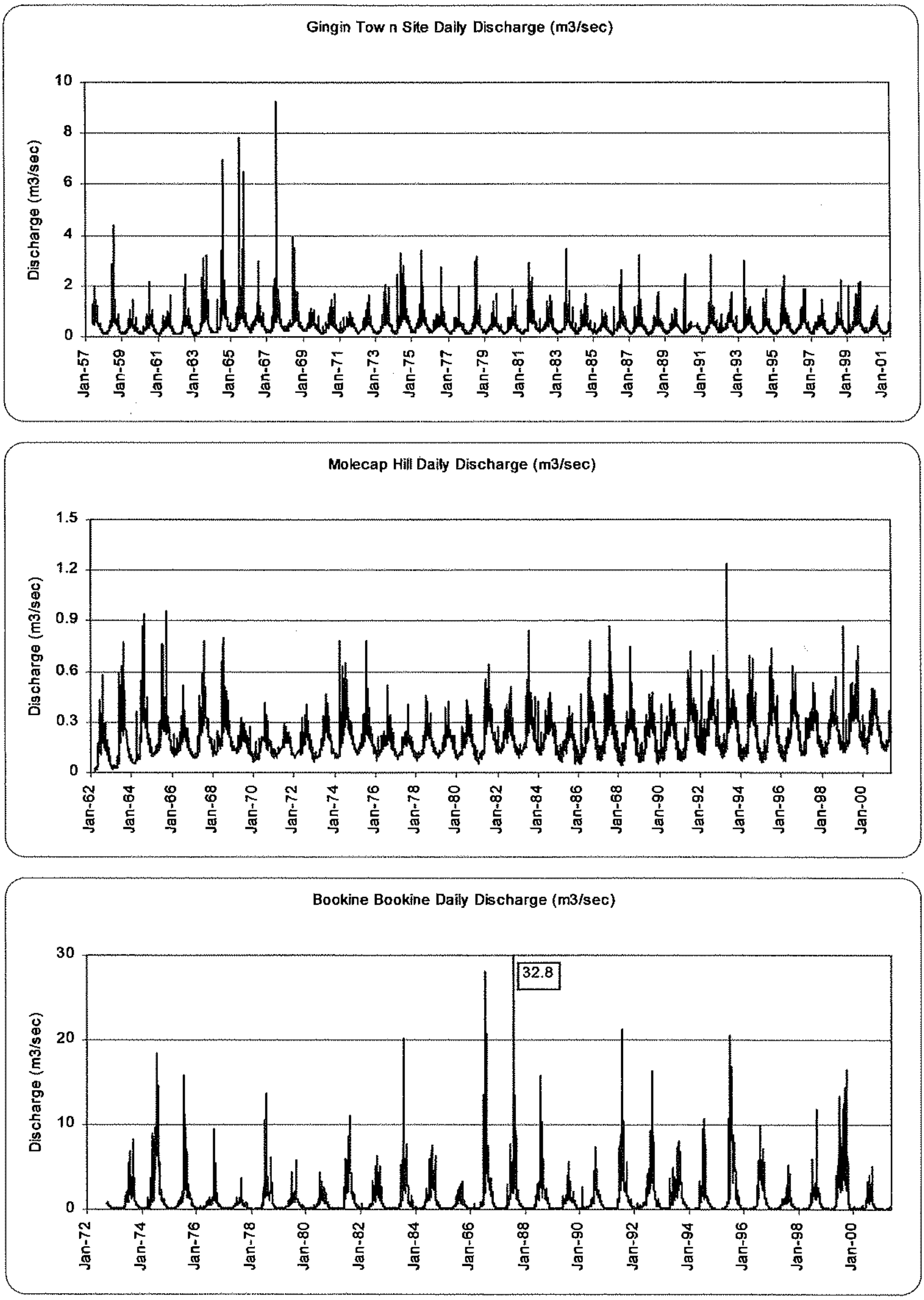

Figure 5. Instantaneous daily discharge for each gauging station over duration of record, indicating within and between year variation in discharge.

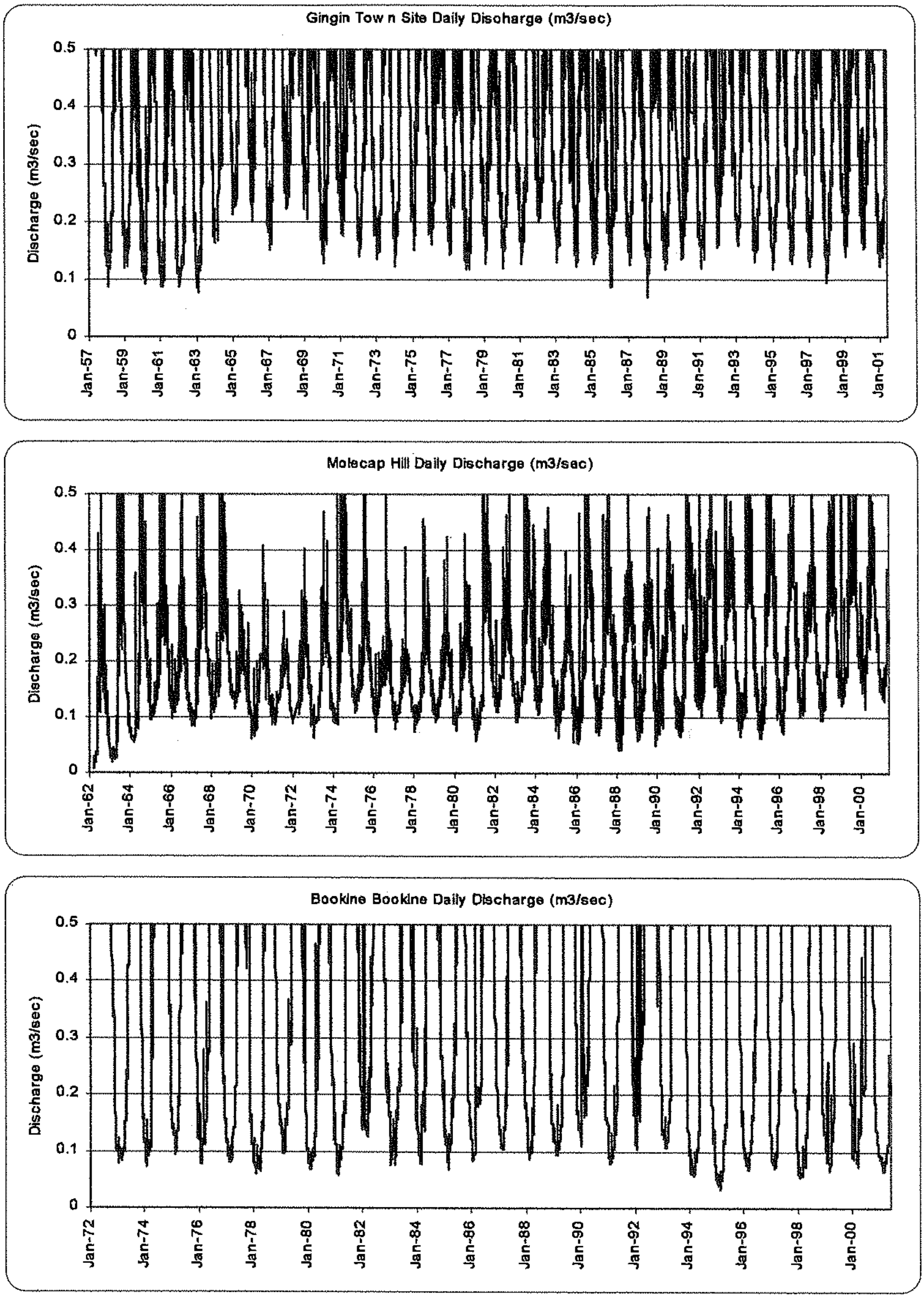

Figure 6. Instantaneous daily flows indicating variation in baseflows within and between years for each gauging station.

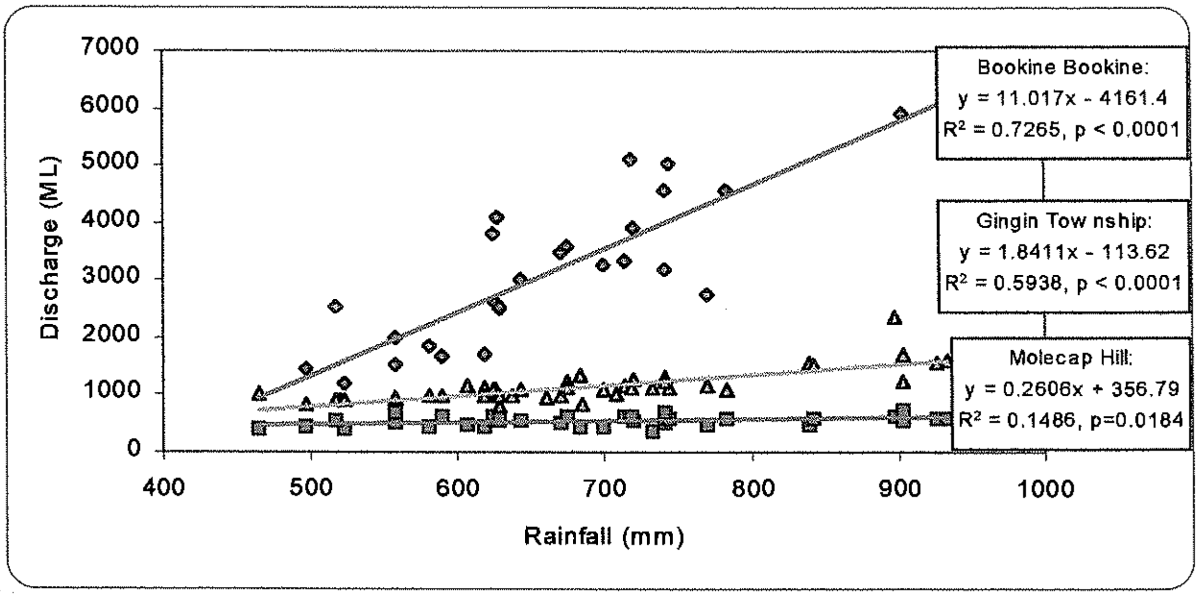

Figure 7. Significant positive relationships between annual discharge and annual rainfall for Bookine Bookine and Gingin gauging stations.

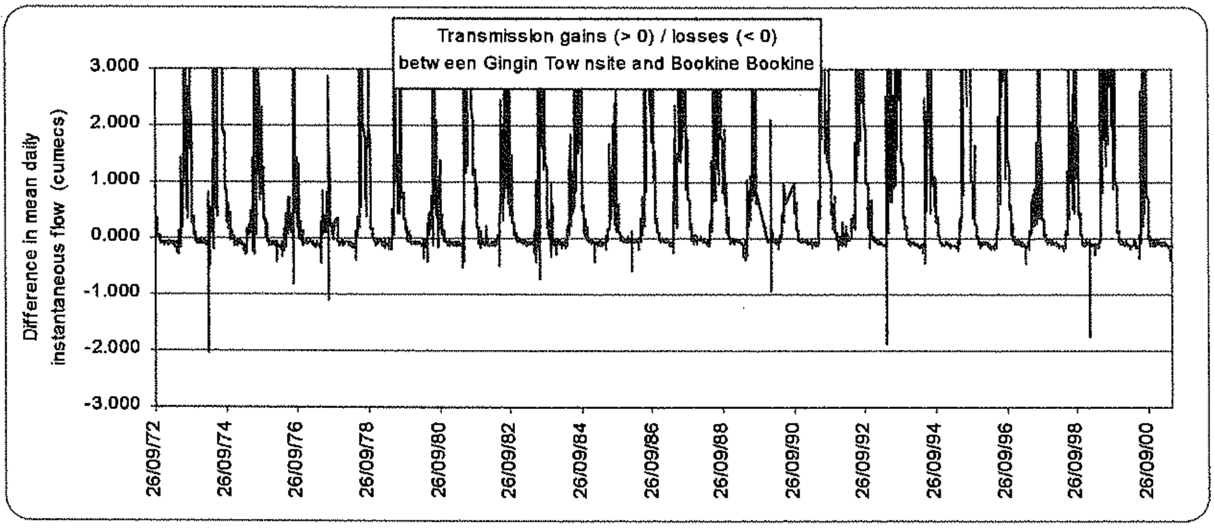

Figure 8. Daily transmission gains (+) and losses (-) between Gingin Townsite and Bookine Bookine in instantaneous flows (cumecs) from 1972 to 2001, emphasising losses during summer months.

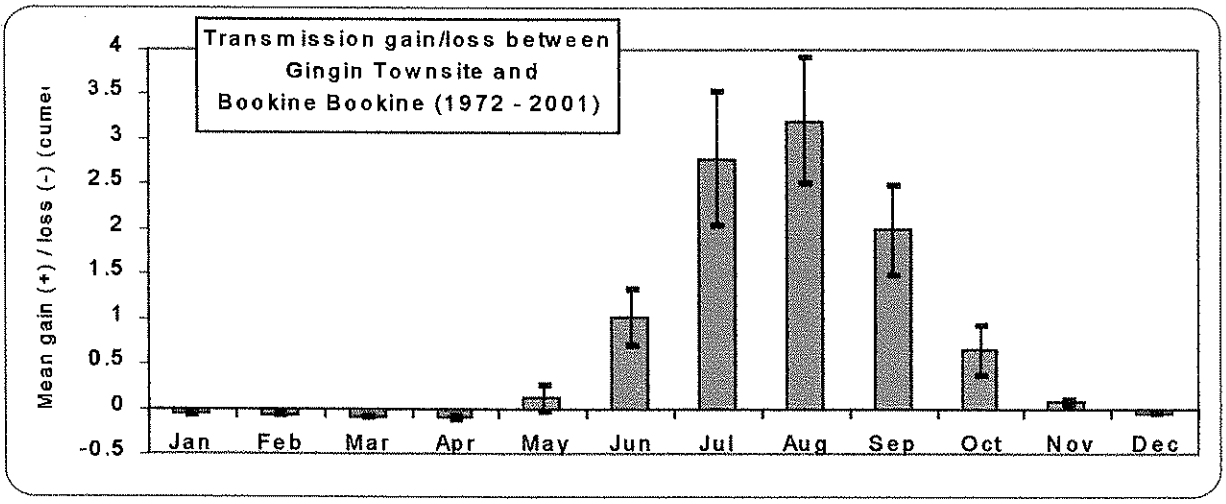

Figure 9. Mean monthly (± 95% CI) transmission gain (+) or loss (-) between Gingin Townsite and Bookine Bookine in cumecs (1972 – 2001).

3.4 Climate Change

The past 20 years, rainfall in southwestern Australia have been below average (WRC 1997). Climate change predictions (for the year 2030) for the southwest due to global warming are a temperature increase of between 0.3 and 1.3°C. Rainfall and streamflow are predicted to increase during summer and reduce during winter/spring. The intensity of rainfall events may increase, and their duration decrease (Welker & Davies 1999; calculated from CSIRO 1996). Correspondingly, the duration of drought events may also increase (CSIRO 1996). It has been estimated that a 10% reduction in seasonal rainfall would translate to a net decrease in streamflow of about 20%. As detailed above, to date there is an 11% reduction in rainfall in the Gingin catchment. The influence of this on streamflow is still to be determined.

3.5 River Morphology & Active Flows for Stream Channel Maintenance

In-stream flows influence channel form and channel maintenance through physical processes such as scouring (Arthington *et al.* 1994). Analyses of the hydraulic geometry of catchments has established that there is a significant relationship between existing (or active) channel width and drainage area, and channel depth and drainage area in most fluvially-dominated streams (Newbury & Gaboury 1993). However, the bankfull width in these streams is often more strongly correlated with bankfull discharge, as is bankfull depth (Arthington *et al.* 1994).

Erratic and high winter flows are often required to maintain existing (or active) channel dimensions, and prevent the accumulation of sediment and organic debris. Disturbances from these events can also be important in structuring benthic communities and may have a profound influence on ecosystem function (*e.g.* primary production, nutrient spiralling and decomposition) (see Resh *et al.* 1988). Scour of riverbeds, and undercutting of banks, is essential for producing and maintaining diversity of habitat.

Unseasonal and/or high velocity flows however, can also result in excessive scouring, destabilisation of banks and subsequent increased sediment loads downstream. The erosive power of a system increases disproportionately with its discharge, thus 1:100 year floods or runoff events are extremely important in forming landscapes. Such floods and events carry the largest quantities of sediment and nutrients. Prior to European settlement, natural vegetation provided a high level of resistance to flows. The clearing of vegetation for urban and rural development has made river systems sensitive to flooding, to the extent that ARI 1:10 year or similar sized floods may now cause catastrophic erosion (Lovett & Price 1999). The practice of de-snagging and of channelization can result in increased current velocity and thus also lead to increased bank and bed erosion, increased sedimentation and more severe flooding of downstream reaches (Lovett & Price 1999).

Flood control measures and construction of V-notches weirs and dams conversely have two major ecological effects: a reduction of flow, and the inhibition of upstream fish migration. With a reduction in flow, the stream has insufficient power to maintain the channel. This results in the accumulation of fine sediments and weeds, which in many cases, provides habitat for introduced fish such as the Mosquitofish (*Gambusia holbrooki*) (Pusey et al., 1989, Pen et al., 1993).

The practices of de-snagging and river training coupled with reduced river flows and a catchment probably generating substantial sediment have lead to the loss of many deep river pools (Riparian Technical Guidelines 1999). These pools typically provided increased habitat diversity for in-stream biota and act as refugia for aquatic fauna, waterfowl and water dependent terrestrial fauna during dry seasons.

Shear flows
In lowland rivers, such as the downstream reaches of Gingin Brook on the Coastal Plain, the river substrate can be categorised into three regions on the basis of near-bed water velocity: erosional areas, stable areas and depositional areas (Davies 1993; page 123). During summer and autumn, erosional areas occur predominantly in high shear velocity (20 -30 cm/sec) regions with mobile fine to course sands (see also Schmitz 1961). The stable regions are associated with intermediate shear velocities (5-15 cm/sec) and support extensive algal mats with relatively high rates of primary production. The algal mats further stabilize the substrate, inhibiting erosion to a greater extent than occurs on bare substrate alone, until the substrates are mobilised by substantially higher discharges during winter (Davies 1993, page 122).

At low shear velocities, deposition of organic matter occurs, and in some cases may both inhibit algal growth and lead to high levels of respiration (and a subsequent degradation of water quality due to anoxia).

In the Gingin system, high nutrient inputs from land-practices in the surrounding catchment "fuel" this algal growth. When nutrients in the river are not used to "drive" this algal community, they are exported downstream into the estuary, which may become further enriched.

3.6 EWRs to Maintain Active Channel Flows in Gingin and Lennard Brooks

From the previous section, EWRs for the maintenance of river morphology may thus be summarised as follows:

- Sufficient flows to scour pools and remove accumulated sediments and organic material.
- Sufficient flows to maintain the shape of the active channel.

To determine channel maintenance flows, extensive measurements were made of the channel at seven representative sites on the system:

Lennard Brook
- Immediately upstream of Westralia Farms at Ashby;
- Immediately to the west of Brand Hwy

Gingin Brook
- On the headwaters of Gingin Brook at Whakea Road;
- On the headwaters of Moondah Brook;
- On Gingin Brook immediately downstream of Gingin township;
- On Gingin Brook at "Glencoe";
- On Gingin Brook downstream of Nolan Bridge on Gingin Brook Road.

Detailed measurements of hydraulic geometry were made using a surveyors' dumpy level and staff. Measurements included; slope of the reach, mean bankfull width and depth, and the bed material.

The cross-sectional shape (profile) of the stream at each site was recorded at a homogeneous reach at each site. This included measuring width and depth and estimating bankfull level. The wetted-perimeter of the stream (in a cross section, being the length of the banks and bed in contact with the water) was measured

(Figure 10). These data were then expressed as the mean[2] width for the reach.

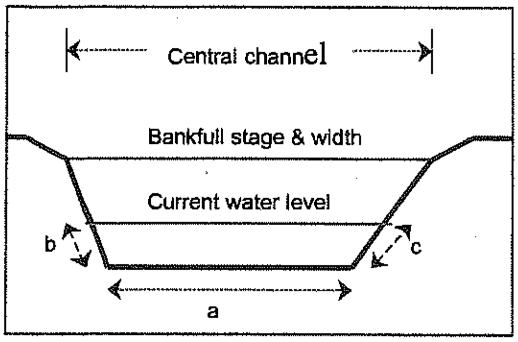

Figure 10. Stylised representation of wetted-width (a+b+c) and bankfull width parameters.

The active channel width and depth were determined as per the methodology outlined in Newbury and Gaboury (1993). Manning's n was calculated both by the formula below and through use of photographs of systems where n has been empirically determined.

The Strickler Approximation (*sensu* Newbury and Gaboury 1993) was used for situations where depth of flow is three times, or greater, the median particle size of the paving materials. This correction was only used to estimate Manning's n at low and baseflow conditions. At increased stage heights, the influence of in-channel debris was considered the overriding influence on channel roughness due to the height of roughess projections and their orientation to flow. Consequently they had greatest influence on discharge rates at a reach scale

> Manning's $n = 0.04 \times d_{50}^{\ 1/6}$
>
> where d_{50} = median bed particle size = 0.016 at active channel stage.

Average velocity was estimated as the velocity at 0.4 times the maximum depth of the stream (Newbury & Gaboury 1993).

To measure discharge, a confined segment of stream of uniform shape was selected and velocity measured using a Marsh McBirney Model 201M velocity meter. Discharge volume (Q) was calculated as:

> $Q = \text{width} \times \text{depth} \times \text{average velocity}$

Bankfull channel flows were calculated using Manning's Equation (this equation requires uniform depth and constant velocity):

> $Qbf = R^{2/3}.S^{1/2}/n_{bf}$
>
> where $R = A/p$
>
> A=cross section area
>
> P=wetted perimeter
>
> mean depth, S = slope of the active channel, n = Manning's roughness factor (Newbury and Gaboury 1993). Based on recommendations of the Water and Rivers Commission (2001) that for many southwestern Australian systems, the width can be substituted for wetted perimeter.

It is the common flood discharge (*i.e.* Q_2 or Q_3) that is most important in maintaining an active channel free from accumulated silt and debris (WRC 2001). Flows of this magnitude and return period also create and maintain the characteristic geometry of the stream channel (Newbury & Gaboury 1993).

The coefficients of variation of monthly flows were then used to estimate the desired magnitude of flow variation that would permit flushing flows and maintain the distinctive features of the winter flows downstream.

Flows required to generate shear velocities in Gingin and Lennard brooks were calculated using measurements of cross-sectional area and mean velocity at a number of sites. As there were no distinct

[2] Measurements of channel morphology made at each site.

riffle-pool sequences, one cross section per site was adequate to describe local channel conditions.

As in-stream flows require the measurements of velocity, depth and substrate type, these parameters were assessed in detail in sampling program (see following section 3.7).

3.7 HYDRAULIC PARAMETERS

All study sites were shallow (0.2-0.5m) with instantaneous mean velocities ranging from about 9 cm/s (Gingin Brook at Whakea) to 21 cm/s at Moondah Brook (Appendix 3). The bed paving materials had an estimated Manning's n of about 0.07 to 0.03 in downstream reaches (Appendix 2). The decrease in roughness indicates a depositional lowland system. The state of flow was uniform. (Appendix 2). The stream power (measured as dyn/s) was relatively low at all sites (Appendix 2), this was due to the low channel slopes. Reynolds Numbers and Roughness Shear Velocity at all sites again reflected the small particle sizes of the paving material and the low channel slopes (Appendices 2 and 3).

To determine the structure of channel maintenance (viz. bankfull) flows, flood hydrographs were prepared using hourly discharge data for each gauging station for a number of distinct, large rainfall events (i.e. summer and winter rainfall events of ≥ 50 mm in 24 hrs as recorded at the Gingin Post Office) (Appendix 4). In general terms, the hydrographs show a relatively rapid response to rainfall in the upper catchment (8 – 10 hrs), with an initial rapid, followed by a more gradual decline in discharge following the peak (12 – 20 hrs). The gradual descending limb may reflect the buffering of groundwater discharge following rainfall events.

A 15 to 20 hr lag exists between the event peaking at Gingin Townsite and at Bookine Bookine station near the junction with Moore River. The hydrographs also suggest that across the coastal plain there are transmission gains in winter, presumably indicative of high run off from saturated soils, but transmission losses in summer, presumably due to groundwater recharge, evaporation and uptake. However, interpretation is difficult because rainfall events in summer are likely more localised, following thunderstorm activity, whilst winter rains would be widespread following frontal activity. Current catchment conditions likely influences these hydrographs, with more rapid and greater runoff than would occur from an uncleared catchment.

4. AQUATIC INVERTEBRATE FAUNA

Aquatic invertebrates are a fundamental component of aquatic ecosystems. Modifications to flow (*e.g.* diversions, impoundments) can result in significant changes in invertebrate community structure. However, it has been demonstrated that such changes can be ameliorated or even reversed if compensation flows from tributaries are maintained. For example, ARL 1988a,b,c, and Storey *et al.* 1991 found that the structure of aquatic invertebrate communities on the escarpment below Canning Dam could be "re-set" back to pre-impoundment conditions using "compensation" flows from Stinton Creek, the first major tributary below the Dam.

While dams may act as barriers to gene flow between populations of fish (see below), this does not appear to be the case for aquatic insects. Preliminary genetic studies have suggested considerable differentiation among populations of fully aquatic species of invertebrates (*e.g.* atyid shrimps) suggesting little movement within and between streams (Bunn & Hughes 1997). Adult flight or overland dispersal appears to be the major mechanism for the dispersion of semi-aquatic insects and aquatic migration appears to be of little consequence (Bunn & Hughes 1997).

4.1 EWRs of Aquatic Invertebrates

There are two main features of flow regimes that influence aquatic invertebrate community structure in southwest rivers. These are:

1. Seasonality

Life histories of aquatic species are intrinsically linked to flow regimes (Bunn *et al.* 1986). The variation in the degree of seasonality can lead to changes in invertebrate community structure (Bunn *et al.* 1989) and changes in life history patterns. Stream permanence has been found to be an overall determinant of the aquatic invertebrate fauna. Streams with intermittent flows show distinctive aquatic faunal communities compared to permanently flowing streams (ARL 1989, Storey *et al.* 1990). Some macroinvertebrate species are found only in intermittent streams (Bunn *et al.* 1989), while other species show large differences in abundances in intermittent compared to permanent streams (*e.g.* Bunn *et al.* 1986; Storey *et al.* 1990).

Analyses of extreme flow events have shown that low-flow events have a far more pronounced effect on the river biota than high-flow events, though in streams of the northern jarrah forest, there is a linkage between near-bed water velocities and macroinvertebrate community structure (ARL 1988b,c,e). The problems associated with low flow include desiccation, de-oxygenation of the water column, and accumulation of leaf leachates (phenols, tannins *etc*) (Resh *et al.* 1988, Boulton & Lake 1992).

There are marked seasonal changes in the structure and functional organisation of invertebrate communities in upland streams in south-western Australia (ARL 1986b, 1989, Bunn 1986, Bunn *et al.* 1986). This has been attributed to the influence of a highly seasonal and predictable Mediterranean climate with high winter and low summer flows. Some fauna may be influenced by seasonal differences in water temperature, however, it appears that stream flow and/or flow related variables are the important underlying factors. Flow results in major seasonal differences in benthic organic matter, depth, width and aspects of substrate composition (ARL 1986c, 1987a, 1988a,c, Bunn *et al.* 1986, Storey *et al.* 1991).

These seasonal patterns in macroinvertebrate community structure are consistent at both species and family level (ARL 1987b) and fauna can be grouped into typically "dry" (summer/autumn) and "wet" (winter/spring) season communities (Bunn 1986, Bunn *et al.* 1986, Storey *et al.* 1990).

2. Predicability/Persistence

In addition to the high seasonality, another key feature of the stream fauna is the high degree of temporal concordance; that is, the flow regime is not only highly seasonal but also highly predictable year-to-year (McMahon 1989, Bunn & Davies 1990, Bunn 1995). The high concordance of Western Australian streams contrasts with streams elsewhere in Australia (Bunn et al. 1999). Gingin and Lennard brooks have particularly high concordance. Stable flows are a distinctive feature of southwestern Australian lowland rivers during the dry season. Species that are susceptible to high and variable flows can synchronise their life cycles so that the sensitive stages (*e.g.* the larvae of crustaceans or pupating stages of some insects) occur only during the dry season.

As a consequence, unusually high discharge events during the dry season may be detrimental to the persistence of these species. It is important, therefore, that dry season flows remain benign without dramatic changes in flow rate.

4.2 Flow Volumes to Meet Aquatic Invertebrate EWRs in Gingin and Lennard Brooks

Davies *et al.* (1999a) undertook a survey of aquatic macroinvertebrates at five sites on Gingin Brook and two sites on Lennard Brook on four occasions over three years (1996 – 1998), sampling twice in late spring and in late autumn. These are the only known documented data on the macroinvertebrate fauna of the brooks.

A total of 113 taxa were recorded, with the fauna dominated by species cosmopolitan to southwestern Western Australia. No species considered rare or restricted were recorded although the fauna contained a large proportion of taxa endemic to south-western Australia, with some taxa with Gondwanic lineages. Stonefly (Plecoptera) and Mayfly (Ephemeroptera) nymphs, and Caddisfly (Trichoptera) and Dragonfly (Odonata) larvae, considered sensitive to degraded habitats were recorded from most sites at some point in the survey. Davies *et al* (1999a) considered the fauna comparable to other rural and urban freshwater systems in the south-west. The relatively low species richness (ranging from 30 - 45 species per site) and the dominance by cosmopolitan species was seen as a reflection of degraded habitat and water quality conditions at most sites; nutrient levels were elevated at all sites, and generally there was little riparian cover and little or no in-stream habitat in the form of large woody debris at the areas within sites surveyed. There were no strong spatial or seasonal patterns in the fauna. Bunn *et al.* (1986) reported a "summer/autumn" and a "winter/spring" fauna from northern jarrah forest streams. The absence of seasonality in these brooks may reflect the relatively stable flows.

Elsewhere, water depth of 5 cm over riffle zones (habitat generally regarded as highly productive for macroinvertebrates and typically maintaining high biodiversity) is considered the minimum necessary to support benthic invertebrate communities (Streamtec 1998, 1999, 2000, 2001). Given the dominance of the macroinvertebrate fauna at all sites by cosmopolitan species and the absence of "rare" fauna, the maintenance of water flow across riffles zones (Davies 1993) is considered the major EWR for macroinvertebrate fauna. This depth is also considered appropriate for "run" type habitats which predominate the Gingin system.

In the Gingin/Lennard system, the position of woody debris in the channel (e.g. often at right angles to flow) and low flow depths (*e.g.* 5cm) over the streambed, would result in little diversity of hydraulic habitats. Raising flows to 10cm increases the influence of channel roughness through inundation of organic debris and could result in scour pools, chutes and backwaters; a prerequisite for hydraulic habitats. Although, this would need to be tested in the field.

Manning's Equation and field measurements of discharge were used to calculate water volumes required to maintain this minimum 10 cm level in Gingin and Lennard Brooks. Analysis of the flow record showed both brooks to be perennial, therefore this minimum of 10 cm depth is needed every month. A qualitative evaluation, in the absence of a trial release, suggests that a minimal depth of 5cm would be insufficient to generate the required diversity of hydraulic habitat.

5. FISH FAUNA

The southwest of Western Australia has a depauperate indigenous freshwater fish fauna with a high degree of endemism compared to the rest of the continent (Pusey *et al.* 1989). Within the region, temporary streams also have a reduced species richness compared to permanent waters, due to limited/ seasonal accessibility and limited food supply for young fish (Pusey & Edward 1990, Pen *et al.* 1993). The estuarine fish fauna of many southwest rivers is relatively diverse, and more often dependent upon the flow regime of the river to maintain energy flow (delivery of nutrients/organics *etc*), the salinity regime and even access to the sea for a seasonally-closed system. In many southwest rivers, estuarine species enter the lower reaches and may even extend some distance inland from the coast. Therefore, altering flow-regimes of a system have the potential to impact riverine species and those species in estuarine and in-shore marine environments into which these rivers flow.

Morgan *et al.* (2000) sampled 57 sites on the Moore River, Gingin Brook, Lennard Brook and associated tributaries and wetlands between 1996 and 1998 to document the presence and distribution of fish species in the systems; river, lakes, streams, swamps, road-side pools and drains were sampled by seine net, sweep net and collapsible traps. Fish distribution data from the Records of the Western Australian Museum also were accessed.

A total of 9 native species and 2 introduced species were recorded from Gingin and Lennard Brooks (Table 4). Of particular note were populations of the Mud Minnow (*Galaxiella munda*) and Balston's Pygmy Perch (*Nanatherina balstoni*). These populations represent outliers, with the next nearest populations 350 km south, near Margaret River. This is also the most northern population of the Freshwater Catfish (*Tandanus bostocki*).

Morgan *et al.* (2000) considered the structure of the fish fauna of the Gingin and Lennard systems to be unique. The region contains all but one of the species of freshwater fishes endemic to south-western Australia, it holds the most northern populations of three species, two of which (*Galaxiella munda* and *Nanatherina balstoni*) are listed as threatened and have been classified as either vulnerable or restricted by the Australian Society for Fish Biology. Morgan *et al.* (2000) consider the northern populations of the Mud Minnow and Balston's Pygmy Perch, which are very rare in the system and may themselves be in decline, to be surviving populations from a once wider distribution, now greatly diminished due to land degradation since European settlement. Of the other endemic species, the Pygmy Perch (*Edelia vittata*) and Nightfish (*Bostockia porosa*) are vulnerable to any increase in salinity.

In addition to species taken by Morgan *et al.* (2000), Black Bream (*Acanthopagrus butcheri*) were reported to have moved up Gingin Brook in recent times.

5.1 Ecology, Life Histories & Habitat Requirements

To understand how changes in flow regime may affect individual species of fish, a review of the life history requirements of all species recorded from Gingin and Lennard brooks was prepared. Some species have been extensively studied, whilst there is little information on other species. A range of sources were referenced for information on species encountered; Morrison (1988), Merrick and Schmida (1984), Allen (1989), Pusey *et al.* (1989), ARL (1990b), Pen & Potter (1990, 1991a,b,c,d), Hewitt (1992), Pen *et al.* (1993), Sarti (1994), Gill & Humphries (1995), Watts *et al.* (1995), Morgan *et al.* (1998), Davies *et al.* 1998.

Table 4. Summary of freshwater fish reported by Morgan *et al.* (2000) from Gingin and Lennard brooks.

Species	Recorded from Gingin Brook	Recorded from Lennard Brook	In Gingin Brook from WAM records	Known Distribution
Galaxias occidentalis (Western Minnow)	✓	✓	✓	Coastal drainages between Waychinicup Creek (80 km east of Albany) and Winchester (250 km north of Perth).
Galaxiella munda (Mud Minnow)	✗	✓	✗	Restricted to sw corner of WA between Margaret River and Albany (with an isolated population at Gingin, approx. 100 km north of Perth).
Edelia vittata (Western Pygmy Perch)	✓	✓	✓	Southwestern Australia between Hopetoun (Philipps River) and the Moore River, in lakes, creek, rivers and ponds.
Bostockia porosa (Nightfish)	✓	✓	✓	Coastal streams, lakes and ponds of southwestern Australia, between the Albany district and Moore River.
Tandanus bostocki (Freshwater Cobbler)	✓	✗	✓	Coastal drainages of southwestern Australia from the Frankland River on the south coast to the Moore River north of Perth.
Nanatherina balstoni (Balston's Pygmy Perch)	✗	✗	✓	Found between Two Peoples Bay in the east and Margaret River in the west (with an isolated population at Gingin, approx. 100 km north of Perth). Generally restricted to the coastal peat flats, but also acid peat wetlands of the Muir/ Unicup catchments
Pseudogobius olorum (Swan River Goby, Blue Spot Goby)	✓	✓	✗	Common in coastal drainages across southern Australia from Moreton Bay in Queensland to the Murchison River of Western Australia.
Afurcagobius suppositus (Big Headed Goby)	✓	✗	✓	Coastal rivers from Esperance in the east to Moore river to the north west. It also penetrates inland waters (*e.g.* Warren, Scott and Blackwood rivers) and is found in Lake Jasper in the far southwest.
Leptatherina wallacei (Swan River Hardyhead)	✓	✗	✗	Coastal drainages of southwestern Australia from the Pallinup River in the east to the Moore River in the northwest.
**Gambusia holbrooki* (Mosquitofish)	✓	✗	✓	Widespread throughout all states, except Tasmania.
**Carassius auratus* (Goldfish)	✗	✗	✓	Widespread throughout the southern half of Australia.

*Introduced species

5.1.1 Endemic Riverine Species

<u>Western Minnow (*Galaxias occidentalis*)</u>

This is one of the most widely distributed endemic freshwater species in south-west Western Australia, with a range extending from Winchester, about 150 km north of Perth, to Waychinicup Creek, 80 km east of Albany. Within this area, the Western Minnow occurs in rivers, streams, lakes, pools, and it readily invades seasonal creeks and swamps connected to permanent water. It is often found at the base of waterfalls (and V-notch gauging weirs) where the water is fast flowing and well oxygenated. This may indicate a preference for these conditions, or reflect fish that are prevented from continued upstream movement by a physical barrier.

Fish have been observed jumping through V-notch weirs and 'crawling' up wet rock faces in an attempt to traverse barriers (ARL 1990b). The species likes both open water and enclosed areas amongst riparian vegetation. Terrestrial insects form a major component of the diet, although dipteran larvae and pupae, and microcrustacea (cladocera and copepods) are also consumed.

Recent work suggests that the Western Minnow feeds at night on freshwater shrimp. A study of this species in the Collie River reported that at the end of the first year, males and females grow to approximately 70 and 75 mm respectively, and 90 and 100 mm at the end of their second year. They are sexually mature at the end of their first year, and some fish survive to spawn in the following year and a very limited number into a third, fourth and even a fifth year. Fish move upstream into tributaries (particularly seasonal creeks that start to flow) to spawn on flooded vegetation. This occurs between June and late September, with a peak in August when water temperatures start to increase.

Females produce approximately 900 eggs, although fecundity increases with age. Watts *et al.* (1995) studied the genetic structure of the Western Minnow in the Canning and North Dandalup River systems, and observed that populations on the Darling Scarp and Swan Coastal Plain were separate and non-mixing. It was suspected that scarp populations moved into tributary creeks on the scarp to breed, whilst coastal plain populations moved into drains and wetlands on the coastal plain.

Mud Minnow (*Galaxiella munda*)

This species is restricted in distribution to the south-west corner of Western Australia between Margaret River and Albany (with an isolated population at Gingin, approx. 100 km north of Perth). Normally it is rare throughout its distribution, but occasionally is abundant in headwaters and tributaries of rivers, and in shallow pools connected to creeks. Water of pools and streams in which it is typically found is generally dark (i.e. tannin stained) and acidic (pH 3 – 6) and exhibit marked seasonal temperature fluctuations (11 – 35 °C). Adults live close to riparian vegetation in streams and in the open water of pools. Larvae typically feed in very shallow (< 10 cm) water of pools amongst flooded vegetation, moving into deeper water as they increase in size. Terrestrial fauna (dipterans), and dipteran larvae and pupae are the main components of the diet in winter, spring and summer, while cladocerans and copepods are the most important dietary components in autumn.

The life cycle typically lasts one year. At the end of the first year, males and females reach approx. 43 and 47 mm respectively, and attain sexual maturity. The species is a multiple spawner and breeds between July and October, peaking in late August and early September when day length is increasing and water temperatures have started to rise.

Morgan *et al.* (1998) consider habitat alteration (*i.e.* alterations to flow, salinity, siltation and eutrophication from surface and groundwater contamination) and possibly exotic species as the main threats to this species.

Pygmy Perch (*Edelia vittata*)

This, endemic freshwater species has a wide distribution throughout southwestern Australia, with a range from Moore River, north of Perth, to Philipps River, east of Albany. It is common in rivers, streams, and lakes, and readily re-invades seasonal wetlands via flood-ways and up seasonal creeks/drains. The species is often associated with riparian/emergent vegetation and rarely occurs in open water.

The diet consists of a wide range of small benthic invertebrates, especially dipteran larvae, ostracods, copepods and Trichoptera (caddisfly) larvae, but also terrestrial insects. During winter, fish move from the river into either adjacent flood waters or tributary creeks in preparation for breeding.

Spawning takes place between late winter and late spring (July-November) in flooded riparian vegetation. The use of flood waters along the main channels of rivers as well as tributary streams, ensures the success of the protracted spawning strategy of this species. It may also reduce the pressure on food resources in tributary streams, which are the main spawning habitat of *Galaxias occidentalis* and *Bostockia porosa*.

Spawning in the Pygmy Perch continues over a period of about five months throughout spring, when there is a decrease in rainfall and creek water levels decline. Females may spawn more than once in a breeding season. Allen (1989) notes that females lay batches of 20 – 60 eggs at 6 – 8 week intervals, and the adhesive eggs sink and attach to the bottom or flooded vegetation. The eggs hatch and the larval stage lasts approximately 2 – 3 weeks. Sexual maturity is attained by both sexes at the end of the first year of life. The majority of fish live to three years, although fish up to six years old have been recorded.

Balston's Pygmy Perch (*Nanatherina balstoni* Regan)

This species is found only in Western Australia and is distributed between Two Peoples Bay in the east and Margaret River in the west (with an isolated population at Gingin, approx. 100 km north of Perth). The species is generally restricted to the coastal peat flats, but was relatively frequently encountered in the acid peat wetlands of the Muir and Unicup catchments (Storey, unpub. dat.). It is the rarest of all endemic freshwater fishes of southwestern Australia.

It is typically found in shallow, isolated pools with dark acidic water (pH 3.0 – 6.0), but also occurs in larger rivers and lakes and in seasonal creeks. In winter and spring the species is regularly found in inundated riparian vegetation, where it presumably feeds and spawns. Larvae and juveniles feed predominantly on cladocerans, while adults feed predominantly on terrestrial invertebrates (e.g. arachnids, adults of Hymenoptera, Coleoptera and Diptera). Males and females generally reach sexual maturity by the end of the first year, and spawn once between June and September, with a peak in mid-July to August when water levels are highest.

Nightfish (*Bostockia porosa*)

The Nightfish, *Bostockia porosa* Castelnau (Percichthyidae), is abundant in both lentic and lotic freshwaters throughout its range. Preferred habitat is under ledges, rocks, logs and inundated riparian vegetation. Adults are nocturnal while juveniles feed predominantly during the day. Nightfish predate largely on insect larvae and zooplankton, though decapods and gastropods are an important component of the diet of larger size classes. Like the Western Minnow, the Nightfish enters tributary streams as soon as these begin to flow in late autumn and early winter. It spawns in flooded creeks (Pusey, unpublished data) over a short period in late winter to early spring; *e.g.* in the Collie River spawning takes place between late August and early September.

The young fish feed on aquatic invertebrates produced under conditions of rising water temperatures, long day length and replenished flows in tributary streams (Pen *et al.* 1993).

Freshwater Cobbler (*Tandanas bostocki*)

This species is the largest (up to 40 cm) freshwater fish endemic to the southwest and can live for up to nine years. It is the only endemic species sought for recreational fishing. Preferred habitats are lakes and slow flowing rivers and streams. Information on diet and life history strategies comes primarily from Wungong Dam populations. Here larger adults feed mainly on Marron *Cherax tenuimanus* and, to a lesser extent insect larvae, ostracods and other fish (*i.e. Edelia vittata*). The diet of smaller cobbler appears to vary seasonally. In autumn they mainly consume marron, while for the rest of the year diet consists predominantly of insect larvae. Spawning occurs from November to January. The reproductive biology is similar to that of *T. tandanus* (Allen, 1989), in which the male constructs an oval or circular nest of 0.6 to 2.0m in diameter. The nest is made of gravel and rocks with a sandy central depression into which the female deposits her eggs. The eggs hatch in about seven days at 19-25°C.

Swan River Goby/Blue Spot Goby (*Pseudogobius olorum*)

The Swan River Goby is a native species with recent marine origins. It has a wide distribution from the Murchison River, north of Perth, as far east as Esperance, occurring in estuaries, rivers, and both freshwater and hypersaline lakes. It usually inhabits brackish lagoons and upper estuarine areas, but moves into the lower freshwater reaches of rivers for extended periods. It can penetrate long distances inland (*i.e.* upper reaches of the Blackwood River, Wheatbelt Region), and occurs in some isolated lakes.

This species has a high salinity tolerance, and inhabits bare muddy substrates, rocky areas and macrophyte beds. In the Swan River, it consumes algae and mats of fungi and bacteria, ingesting invertebrates only in winter, although Fairhurst (1993, cited Morgan *et al.* (1998)) noted that fish in Swan Coastal Plain lakes consumed invertebrates in all seasons.

The species life cycle is less than a year, and the species spawns in spring and autumn, and to a limited extent in summer. Progeny of the spring spawning will reproduce in the following autumn when only five months old, and vice versa for progeny of the autumn. Some individuals will survive to spawn a second time. The female lays approximately 150 eggs on the underside of a solid object (rocks, logs *etc*), and the male guards and fans the eggs during the incubation period, which lasts about four days. The larvae are planktonic and are swept downstream into estuaries, from where they juveniles migrate back into the rivers.

Big Headed Goby (*Afurcagobius suppositus*) (previously *Favonigobius suppositus*)

The Big Headed Goby also has a wide distribution from Moore River, north of Perth, as far east as Esperance. Like the Swan River Goby, it is a native species with recent marine origins and inhabits estuaries, rivers, streams and coastal lakes. It can penetrate inland waters (*i.e.* Warren, Scott and Blackwood rivers. It has a strong preference for heavy cover, and consumes hemipterans (waterbugs), diptera larvae, bivalves, terrestrial insects, Ephemeroptera (mayflies), Trichoptera (caddisflies) and small fish. The length of the life cycle and the reproductive biology is not known. Spawning probably occurs in spring. Morgan *et al.* (1998) suggested that the life cycle probably lasts two years, the species breeds after one year, and males guard a nest under stones or amongst aquatic macrophytes where several females have laid eggs. Breeding probably occurs between late spring and early summer.

Swan River Hardyhead (*Leptatherina wallacei*) (previously *Atherinosoma wallacei*)

The Swan River Hardyhead is another species with recent marine origins. It occurs from the Moore River, north of Perth, to the Pallinup River, west of Bremer Bay. Preferred habitats are clear, flowing freshwater streams and upper reaches of estuaries with reduced salinities. However, it can pass the whole of its life history in an estuarine environment, using sheltered, shallow-water bays. Prince and Potter (1983) suggested that this preference for sheltered peripheral bays reduces the probability of fish being carried out to sea on winter spates. It is often seen in schools near the surface or around the shoreline vegetation and amongst log debris. It ingests planktonic crustacea, terrestrial insects, polychaetes and unicellular algae. Elsewhere, in the Swan-Canning Estuary, males and females attain lengths of 45 and 55 mm at the end of their first year, when they are sexually mature. Few fish last beyond one year. They have a protracted spawning period that peaks during late spring.

5.1.2 Introduced Riverine Species

Mosquitofish (*Gambusia holbrooki*)

Mosquitofish were introduced to fresh waters around Perth in 1936 (Allen, 1989) to control mosquitoes and are now widespread and abundant in southwest catchments, dominating the fish fauna in lowland areas (Pusey *et al.* 1989). Fertilisation is internal and the female bears live young. In the Collie River breeding takes place during spring, summer and autumn, once water temperatures exceed 15 – 16°C. They are typically abundant in wetlands and wide, deep, slow flowing reaches of rivers. The Mosquitofish is widely regarded as a pest in Australian waters (Myers 1975; Arthington and Lloyd 1989). This species displays aggressive behaviour toward native species such as Western Minnow, Pygmy Perch and Nightfish. Where Mosquitofish are abundant, the numbers of native fish are often greatly reduced. The Mosquitofish is ideally suited to the warm waters found in south-western Australia, breeding throughout spring, summer and autumn. Evidence shows it is a prodigious breeder and able to rapidly increase numbers. There have been no successful management activities to reduce numbers of Mosquitofish in south-western Australia wetlands and, if ever eradicated from a waterbody, it is very likely that it would soon reinvade. Pen *et al.* (1993) noted that some species of native fish were able to coexist in large numbers in the Collie River due to a diversity of resources (both in the form of diet and habitat).

The Mosquitofish is either dominant, or the only species present in situations in which a diversity of resources no longer exists. Pusey *et al.* (1989) suggested that elevated winter flushing flows in an unimpounded river (the North Dandalup River) reduced numbers of Mosquitofish compared to populations in an impounded river may be because the Mosquitofish is not a particularly strong swimmer and cannot resist the flood waters.

Carp/Goldfish (*Crassius auratus*)

The Goldfish was introduced in 1876 and is now widely distributed in streams, ponds, and dams throughout the southern half of Australia. It is native to eastern Asia, but wild fish lack the bright colours of aquarium bred varieties. They are usually silvery/greyish or bronzy, with a maximum size of 40 cm and 5 kg, but those found in Australia are normally less than 0.5 kg. It generally inhabits quiet backwaters of rivers, swamps and lakes. Because it is a non-native species, there is little know of the life history, ecology, dietary requirements or reproductive cycle of Goldfish in south-western Australia.

This species is different from the Carp that dominates some south-eastern Australia rivers (*i.e.* the Murray-Darling River system) with devastating effects on the ecology of these systems. It is not known if the Goldfish in the Gingin/Lennard systems are recent introductions (*i.e.* probably released from domestic aquaria), or are part of a long established population. If the former, little can be done in the short-term because numbers are relatively low. If the latter, then conditions would not appear suitable to support large numbers. In either case, there is probably little that can be done to eradicate this species. Management should aim to maintain a diversity of resources, and keep the flow regime of the river as close to original as possible (*i.e.* maintain conditions to which native species have evolved and will be most competitive against any introduced species).

5.2 Relationships between River Discharge and Estuarine Productivity

Although this document focuses primarily on ecological water requirements of Gingin and Lennard brooks, the environment of the Moore River Estuary should also be considered as freshwater flows from Gingin Brook form a significant proportion of freshwater inputs to the estuary.

Estuaries are highly productive ecosystems which are influenced by river-flow and therefore, ultimately likely to be influenced by flow regulation. Davies *et al* (1999) noted high nutrient levels in Gingin Brook. High nutrient loads to the Moore River estuary without regular flushing to the sea could result in further nutrient enrichment.

The linkage between river flows and estuarine productivity is a function of a number of parameters, including the rates of influx of catchment-derived nutrients and input of freshwater. Given the importance of many southwest estuaries to recreational and commercial fisheries, this relationship was investigated by Davies *et al.* (1998). Catch Per Unit Effort (CPUE) for selected fisheries species (data supplied by Fisheries WA for 1976 - 1992) in the Peel-Harvey Estuary was correlated with flows from the Murray River at the Baden Powell Water Spout. There was a positive and significant correlation between discharge at the Murray River and the CPUE for Blue Manna Crabs (*Portunus pelagicus*) in the Peel-Harvey Estuary. Discharge the previous year was the important determinant for CPUE of Western School Prawns (*Metapenaeus dalli*) in the Estuary (Davies *et al.* 1998).

The above examples show the relationship between river discharge and fishery ecology in the estuaries. Therefore EWRs need to consider both the commercial and environmental importance of estuaries and the intimate relationship between river flow and downstream productivity.

5.3 EWRs of Fish

Generally, all native species encountered are widely distributed throughout the south-west of Western Australia and, therefore, cannot be considered threatened on a regional basis. However, native species such as Mud Minnow, Balston's Pygmy Perch and Freshwater Cobbler may be considered locally threatened because of their rarity in the system and the distance to the next nearest populations to the south.

For all species in Gingin and Lennard brooks, there is a pre-requisite for permanent water. Although several of the species readily invade seasonal creeks to reproduce, none of the species have adaptations to withstand desiccation. Therefore, increased abstractions must ensure sufficient depth of permanent water is maintained in the system.

Juveniles and adults of most species seem to have generalist diets, consisting of aquatic and terrestrial insects and invertebrates, with some species also consuming zooplankton and Crustacea. Given the generalist nature of the diets, it is unlikely most species will be limited by an altered flow regime to the extent whereby the species is unable to switch diet to survive. Therefore, components of the biology of native species most likely to be affected by altered flow regimes are fish migration and reproduction.

EWRs for fish species can be grouped into five categories:

1. Predictable winter/spring flooding must be maintained to ensure breeding success and strong recruitment in the Western Minnow, Pygmy Perch and Nightfish.

Water levels must be maintained so that migration is possible, and riparian vegetation is flooded during this time. All these species move into tributaries/drains (particularly seasonal creeks once they start to flow) to spawn on flooded vegetation. This occurs between June - November, with peak spawning times of August for the Minnow, late August – early September for the Nightfish and late September – mid October for the Pygmy Perch. This is a critical phase of the life cycle of these species. Together with the flooding of vegetation, the stimulus of fast-flowing waters in tributary streams also appears important for successful spawning (*e.g.* the Western Minnow; Pen and Potter 1991b). If water levels fall too soon, or fluctuate greatly, eggs may be left dry and desiccate. Flooded vegetation and shallow, flooded off-river areas also provide sheltered nursery areas for growing juveniles.

Reduced flooding and low water levels in tributary streams may also increase the probability of competition between Pygmy Perch, Western Minnow and Nightfish by reducing area of habitat.

2. Retention of the predictable natural pattern of river flows for the maintenance of Freshwater Cobbler "nests". Retention of water levels that maintain deeper pools for preferred Freshwater cobbler habitat.

Unpredictable or unseasonally high flows can dislodge cobbler "nests" downstream, while very low flows can result in exposure and desiccation.

Slow flowing waters of deeper river pools are typically the preferred habitat of cobbler. It is important that water levels are sufficient to maintain such pools.

3. The construction of dams and v-notch weirs can have a significant impact on the seasonal movements of migratory native species.

For example, dams and v-notch weirs can affect the reproductive biology and recruitment of juveniles (ARL 1986a,b,c, 1988d, EPA 1987, Pusey *et al.* 1989, Morgan *et al.* 1998). Impassable v-notch weirs (i.e. Narrow or Sharp-crested weirs) interrupt spawning migrations of the Western Minnow, which cut off access to creeks/tributaries/drains *etc*. On the escarpment, temporary headwater streams isolated above large dams appear to be colonised by residual minnow populations from within the reservoirs (Pusey *et al.* 1989, ARL 1990a).

Not all weirs, however, restrict fish passage. Migration of the Western Minnow does not appear to be affected by Crump-type weirs (ARL 1990a). Broad crested weirs and long based weirs (*e.g.* Crump-type weirs) pose less of a barrier to upstream migration as they are designed to be seasonally "drowned out" (submerged) during high rainfall periods. Fish appear able to negotiate these during wet months

(EPA 1987). Thus Broad-crested weirs present only a temporary obstacle to migration. V-notch weirs (*i.e.* Narrow or Sharp-crested weirs), however, are never completely submerged. Also, fish ladders can be retrospectively fitted to weirs (*i.e.* ref Bookine Bookine) to allow fish passage. The design characteristics of fish ladders is reasonably well understood and incorporates the necessary slope angle and "resting" areas in the ladder.

The maintenance of winter flows of sufficient volume and duration to ensure flooding on the Coastal Plain may be an issue in the vicinity of weirs, to compensate for lack of access to suitable tributary habitats further upstream. In some years and areas, winter rains and local runoff may achieve the same result. The use of weirs that do not reduce the existing potential for fish migration is an important consideration for regulated river systems. Most weirs, however, will prevent fish migration during extended dry periods.

Where ever possible, natural constrictions in the river channel should be used in place of artificial gauging stations. Gauging stations, which are no longer in use should be decommissioned and scouring plates removed. Fish ladders should be provided to allow upstream passage of native migratory species.

Constraints on gene flow may also be of some importance in terms of the maintenance of genetic diversity and fitness of native fish populations, which have been fragmented by the construction of large dams. The effects of v-notch weirs on fish movements and gene flow among populations on the coastal plain must also be considered.

4. Maintenance of the predictable natural pattern of base summer flows and winter spates for recruitment of estuarine species.

Effects of modified stream discharge and flow regimes on estuarine fisheries will be varied. The Gingin Brook is a significant source of freshwater input to the Moore River Estuary. Discharge occurs predominantly during winter-spring. In summer the entire estuary is brackish, however, in winter, waters become stratified with a layer of freshwater overlying saline marine waters.

The tolerance of fish to changes in salinity varies greatly both inter-specifically and intra-specifically and strategies for coping are both physiological and behavioural. Reduced or restricted flow during normally wet periods may lead to a summer pattern in community structure in the estuary. Unpredictable or unseasonal in-stream flow will also lead to a reduction in seasonally-available habitat for juveniles of migratory marine species.

5.4 Specific Flow Volumes to Meet Fish EWRs in Gingin and Lennard Brooks

EWRs of fish in Gingin and Lennard brooks may be summarised as:

EWRs for Riverine Fish:

- Sufficient water for reproductive migration.
- Sufficient water to maintain Cobbler "nests".
- Water to inundate streamside vegetation (*i.e.* marginal and trailing vegetation) and shallow-flooded off-river areas.
- Management of introduced species.

EWRs for Estuarine Fish:

- Sufficient water to maintain diversity of habitats (although catchment clearing and the resultant increase in flows may significantly override this effect).

- River flows to stimulate recruitment.
- River flows transporting nutrients and other material from the catchment.

The water volume required to meet fish EWRs was determined through the use of the Manning's Equation. For example, the native Western Minnow was common in the system during the current study. This species is generally only found in reaches where the water depth is greater than 20cm (Davies *et al.* 1999b, P. Davies, pers. obs.). Therefore, this stage height (20cm) was used as the minimum water requirement for the migration of *Galaxias* during the months August to September.

The Manning's Equation was used to calculate water volumes required to maintain this minimum 20 cm stage height. It was estimated that for the rest of the year, fish EWRs would be adequately met by the baseflow recommended for benthic invertebrates (i.e. 10cm depth).

During spring, increased flows to 20cm depth would be required for;

- fish migration (by "drowning-out" natural obstructions *etc*),
- to inundate trailing riparian vegetation to allow some species to attach eggs, and,
- to flood shallow, off-river areas as nursery areas for larval/juvenile fish.

Increased flows (>20cm depth) during September compared to August are required to allow deeper-bodied fish *(i.e.* the Nightfish) to traverse obstacles.

It should be noted, that these estimations of stage height for both fish and macroinvertebrates are essentially "first-estimates". They are based on personal observations and are used in absence of detailed information and, as such, should be treated as hypotheses to be tested and, if necessary revised.

6. WATER QUALITY PARAMETERS

Although provisions for EWRs should not be specifically designed as flushing flows to remove poor quality water, a discussion of water quality parameters is warranted, particularly with regard to the high nutrient status of Gingin and Lennard brooks reported by Davies *et al.* (1999a).

During 2001, seven sites sampled in Gingin/Lennard brooks, had moderate turbidities (3-20 NTU), low salinities (0.22-0.97 mg/L TDS), low conductivities (497-1886 μs/cm) and high dissolved oxygen levels in upstream reaches (~7-9 mg/L; 75-90% saturation) (Appendix 5). Typically, for dissolved oxygen levels (a good "surrogate" measure of ecological processes), there was a trend for increasing degradation downstream (Appendix 5).

Flow regulation can adversely affect downstream water quality through the concentration of nutrients and salts in the water column when river water levels are reduced. Clearing for urban development, agriculture and construction of drainage channels results in increased surface runoff and inflow. This in turn leads to higher sediment and nutrient loading, increased turbidity and salinity in both riverine and estuarine environments.

Data for selected water quality parameters are available for locations on Gingin and Lennard brook in Appendix 5.

6.1 Nutrient Management

Nutrient enriched water bodies are typically characterised by high algal growth and water quality problems. Nitrates (NO_3) and ortho-phosphates (PO_4) are typically the most important forms of nitrogen and phosphorus in terms of algal and macrophytic growth (if bioavailable), although not all studies cite nutrients in these forms.. Excessive and problematic growth is more likely in systems where these nutrients are high and riparian shading is negligible or absent. Ammonia (NH_3) is another bioavailable form of nitrogen which Davies *et al.* (1999a) reported to be in excessively high concentration in Gingin Brook. High levels of ammonia can be toxic to aquatic fauna (fish and macroinvertebrates) through deleterious effects on respiratory systems. Toxicity of ammonia increases as pH and temperature increase.

The EPA (1993) has listed indicative levels for nitrates and phosphates, "above which problems have been known to occur" (Table 5). Nutrient status in the rivers will vary with flow. During periods of low flow, when the system is reduced to a series of connected pools, conditions may be better described according to OECD trophic categories for warm (tropical) waters (Table 6). OECD categories are based on total phosphorus levels. Trophic categories devised by Wetzel (1975) for temperate lotic waters are also given in Table 7.

Table 5. Current EPA (1993) guidelines for nutrient concentration, for the protection of aquatic ecosystems.

WATER BODY	TOTAL P	TOTAL N	NH_3
	CONCENTRATION (mg/L)		
Rivers & Streams	0.01 – 0.10	0.10 – 0.75	0.02 – 0.03
Reservoirs & Lakes	0.005 - 0.05	0.10 – 0.50	0.02 – 0.03

Davies *et al.* (1999a) reported dissolved (i.e. 0.22 μm millipore filtered) nutrient levels in Gingin and Lennard brooks to be very high at all sites sampled (Total-N, 200 – 1650 mgL^{-1}; NH_3, 10 – 850 mg L^{-1}; Total-P, 5 – 105 mg L^{-1}). Concentrations were especially high in Lennard Brook. Nutrient levels were far in excess of EPA guidelines, and ammonia levels (NH_3) were at levels known to be toxic to fish and aquatic invertebrates (if bioavailable). The elevated nutrient levels, combined with reduced riparian cover (*viz.* shade) along much of the brooks may result in problematic algal blooms. It was considered that diffuse agricultural inputs (*i.e.* fertiliser application, horticultural activities, stock access to creeks *etc*) were responsible for the elevated levels.

Table 6. Mean annual total phosphorus levels (mg/l) for each trophic category for tropical lotic waters, under the OECD (1982) and CEPIS (Salas & Martino, 1991) classifications (means and range over 2 standard deviations).

Source	Category		
	Oligotrophic	Mesotrophic	Eutrophic
OECD (+ 2 SD)	0.008 (0.003 – 0.022)	0.0267 (0.08 – 0.091)	0.084 (0.017 – 0.424)
CEPIS (+ 2 SD)	0.021 (0.010 – 0.045)	0.0396 (0.021 – 0.074)	0.1187 (0.028 – 0.508)

Table 7. Categorisation of trophic status of temperate lotic waters, after Wetzel (1975).

CATEGORY	TOTAL P	TOTAL N	INORGANIC N
	CONCENTRATION (mg/L)		
Ultra-oligotrophic	< 0.005	0 - 0.250	0 - 0.200
Oligo-mesotrophic	0.005 - 0.010	0.250 - 0.600	0.200 - 0.400
Meso-eutrophic	0.010 - 0.030	0.300 - 1.10	0.300 - 0.650
Eutrophic	0.030 - 0.100	0.500 - 15	0.500 - 1.500
Hyper-eutrophic	> 0.100	> 15	> 1.5

Regulation of rivers and drainage schemes have reduced the natural flow variability and seasonally reversed some of the wetting and drying cycles. River flow and consequently the total nutrient input to the estuary are strongly seasonal; most of the nitrogen and phosphorous loading occurring during winter.

Increased irrigation flows/reticulation have the potential to increase the nutrient loss from agricultural areas of the catchment and contribute towards problematic algal growth in the receiving environments of the lower river and estuary.

Elevated nutrient levels are also associated with loss of biodiversity. For example, Western Minnow, Pygmy Perch and Nightfish are all absent or greatly reduced in number in eutrophic water bodies (Morgan *et al.* 1998, Storey 1998, 2000), with nutrient enrichment and associated changes partially responsible.

6.2 Dissolved Oxygen

Adequate concentrations of dissolved oxygen (DO) are fundamental for the survival of aquatic species and for the maintenance of ecological processes. Both physical (re-aeration) and biological (metabolic) processes determine the DO content of a river. Community respiration by aquatic plants and animals at night results in a net loss in DO concentration with a DO minimum reached just prior to sunrise. During daylight hours, in-stream primary production (photosynthesis) by algae and macrophytes results in a net gain in DO in the water column. In summer, the solubility of oxygen decreases with increasing water temperatures, while increased light intensity results in higher rates of primary productivity. In rivers where rates of metabolism are high, exceedingly low overnight DO levels can be lethal for aquatic fauna. Sufficient DO over 24h is a fundamental requirement of aquatic fauna. DO values of less than 2 mg/L pose considerable "stress" for resident aquatic fauna, particularly fish with high metabolic demand for oxygen.

Water quality problems can also arise with the release of nutrients and heavy metals from sediments under conditions of low DO.

6.3 Turbidity

Turbidity is the result of fine particles that are held in suspension. Natural turbidity and sedimentation are dependent on the hydrology and geomorphology of a site. They may however be elevated through activities such as mining, vegetation clearing, stock trampling and the resultant increase in surface runoff brought about by all these factors. Elevated turbidity in south-west rivers is typically closely associated with bank erosion and is strongly influenced by livestock and urban/industrial developments on or adjacent to riparian lands. In addition to affecting the appearance of water, when the particles causing turbidity settle, they can result in pool aggradation. Turbidity also interferes with light penetration and consequently photosynthesis and the feeding efficiency of visual predators such as fish and waterbirds (Lovett & Price 1999). Continuous, artificially high turbidity can adversely effect riverine biota – it can clog gills of fish and aquatic insect larvae, and reduce light penetration further reducing primary productivity. Increased urban and agricultural run-off and inflow may also be a causal factor in the decline of macroinvertebrates, through the alteration of river-bed substrate composition.

Because of the large variation in turbidity in Australian waters, guidelines for the protection of aquatic ecosystems recommend the maximum permissible increase in turbidity should be no more than 10% above the natural, seasonal mean concentration (EPA 1993). The measurement of turbidity has been suggested as a useful surrogate determination of catchment disturbance, though it must be noted that some Australian rivers are naturally turbid.

The maintenance of flushing flows, that allow some deposition of fine sediment while not contributing to excessive erosion, may aid in the restoration of those reaches of regulated streams that would naturally have possessed low turbidities and higher water velocities.

6.4 Pesticides

Pesticides vary greatly in their aquatic toxicity, persistence, and solubility in water and potential for bioaccumulation. Pesticides affect aquatic organisms both directly - through lethal effects and sub-lethal effects on behaviour, growth and reproduction of individual organisms - and indirectly at the community level – by decreasing inter-specific competition and/or reducing food availability.

No known monitoring for pesticides in aquatic fauna has been carried out in Gingin or Lennard brooks. In the Canning River, pesticide residues have been detected in freshwater mussels in Stinton Creek and Kangaroo Gully downstream from orchards (ARL 1988b; Storey & Edward 1989). Vineyards and fruit growing are present in the catchments.

As with nutrients, increased irrigation flows with high pesticide levels, will ultimately affect the receiving environments of the lower river and estuary.

6.5 Specific Flow Volumes to Meet Water Quality EWRs in Gingin and Lennard Brooks

7. RIPARIAN VEGETATION

Within the Gingin and Lennard catchments, clearing for agriculture, horticulture, urban development, and construction of drainage channels for flood control/irrigation has resulted in the loss of much of the original riparian habitat along many reaches. Even where native trees remain, much of the original understorey is dominated by introduced pasture and weed species.

Riparian vegetation condition was assessed by WRC (1998) using the rapid assessment methodology of Pen and Scott (1995). This was done in order to estimate the extent of ecologically significant remnant riparian vegetation. These surveys will assist is assessing the likely impacts of flow regulation. Lennard Brook was considered to be in relatively good riparian health, with vegetation rating of A3 – C1. Stock access, weed invasion and siltation were recorded as issues on Lennard Brook. Gingin Brook was in a more advanced state of degradation. The brook has extensive areas totally cleared, and high levels of siltation. Invasive weeds were also a problem.

7.1 Wetland Vegetation

There are a large number of ecologically-significant freshwater wetlands associated with the lower reaches of Gingin and Lennard brooks (*i.e.* wetlands in the Bampanup and Yeal Nature reserves), much of the coastal plain in this area is seasonally waterlogged. The wetland classification system of Semeniuk (1987) refers to these areas as either palusplain (seasonally waterlogged flats) or damplands/floodplains. These are the most abundant wetland types on the Swan Coastal Plain in terms of area occupied (Table 8).

Table 8. Total area and percentage total area on the Swan Coastal Plain of wetland categories of Semeniuk (1987) as mapped by the Water Authority of Western Australia.

Landform Geometry	Category	Total wetland area (ha)	% of total area
	Lake	7546	4.5
Basin	Sumpland	17083	10.2
	Dampland	23057	13.8
	Floodplain	9040	5.4
Flat	Palusplain	96475	57.5
Channel	Rivers	1168	0.7
	Estuaries	13270	7.9

Within the Gingin area, many are considered to be of sufficient ecological value for wildlife conservation and have been placed in the conservation reserve system. The interaction between groundwater levels and discharge from the brooks is unknown. However, the potential exists for increased abstraction to alter current water levels in these wetlands, particularly in periods of high demand (*i.e.* late summer/autumn). However, historical water levels may have already been influenced by catchment clearing.

7.2 Estuarine Vegetation

Though a study of the estuarine reaches of the catchment was outside the scope of this report, comment needs to be made with regard to downstream water allocations that could ultimately effect flows into the Moore River Estuary.

Moore River estuary is intermittently-open to the sea (Young *et al.* 1997), and so tidal regimes are restricted to periods when the river mouth is open. Access to the sea usually occurs when winter discharge is sufficient to breach the sandbar. Although the Moore River experiences greater maximum flows than Gingin Brook, they both have comparable mean annual discharge (~ 40 GL per year) (Figure 11). Therefore, reduced river flows may influence the frequency when the river is open. Reduced inputs of freshwater from Gingin Brook compared to more saline waters from the Moore River, potentially may alter salinity regimes of the estuary when closed and may affect community structure and distribution of plants (and fauna).

It is recognised that alterations to freshwater inputs to estuaries may alter community structure and distribution of plants. Subsequently, the distributions of estuarine and aquatic invertebrates, which inhabit these plant communities, will also alter (Keally *et al.* 1995). Keally *et al.* (1995) found invertebrate species richness and abundance in estuaries to be higher during winter months, when inundation resulted in increased export of productivity from estuarine marshes to adjacent waters.

Changes in seasonal salinity regimes due to altered flow patterns are likely to effect germination of seed of riparian and aquatic plant species. Loss of sedge and fringing estuarine vegetation may occur due to discharge of freshwater drains into the vegetation rather than running through it (Pen 1983, 1992). In parts of Leschenault Estuary, insufficient discharge of freshwater has led to the replacement of estuarine fringing *Juncus-Melaleuca* associations by samphire. This is a result of increased salinities as drains pass through fringing vegetation (Pen 1983, 1992). Frequent, short high flows in the naturally wet months are necessary to flush the substrates and saline reaches. Some erosion and siltation may also be essential to maintain these associations.

In the Collie River system to the south, construction of Wellington Dam has reduced the duration and amount of freshwater flow to the estuary. In 1951, a new connection (The Cut) between the estuary and the sea was opened opposite the mouth of the Collie River. These two developments led to extensive changes in estuarine vegetation (LCCG 1995).

7.3 Specific Flow Volumes to Meet Riparian Vegetation EWRs in Gingin and Lennard Brooks

Duration, frequency and depth of flooding will have varying effect on germination, recruitment and successful colonisation of plant species. Changes in biodiversity through succession of one plant assemblage by another is a natural progression, however interruption or loss of any one successional stage can severely degrade the efficiency of the vegetation system as a whole (Pen 1983).

Vegetation of the riparian zone can either intercept groundwater or directly extract channel water. Determination of the extent to which riparian vegetation is reliant on groundwater was beyond the scope of the current study.

Paucity of research into water relations of Western Australian species makes it difficult to predict the impact of flow changes on floodplain trees such as the flooded gum (*E. rudis*) or paper bark (*M. rhaphiophylla*). In the absence of this information, EWRs for riparian vegetation were calculated conservatively assuming total reliance on surface flows (NB it is acknowledged that groundwater discharge from aquifers will be a significant, but unquantifiable, source. Studies could be conducted using O_{18} to assess the relative contribution of surface and groundwater to water relations of riparian trees, however this remains a costly exercise and takes considerable time for completed isotope analyses). Water should be allocated to maintain and/or allow for the restoration of riparian vegetation in winter-wet pastured floodplain regions and along the periphery of drainage channels. Future water allocations should also ensure the protection of endangered riverine flora.

In Australian wetlands, greatest numbers of plant species germinate during autumn under waterlogged conditions and fewest germinate over summer months (Britton & Brock 1994). Decreased winter flows may thus have greater impact on the germination of fringing vegetation, than increased summer flows.

Froend and McComb (1994) noted alteration of growth and reproduction patterns in *Baumea articulata* in south-western Australia in response to fluctuating water levels, enabling the species to tolerate gradual, moderate change. *B. articulata* can only germinate under water-logged conditions and although reproduction is usually *via* rhizome extension (as with most emergent macrophytes), colonisation of non-adjacent habitat is dependent on seed dispersal (Froend & McComb 1994). Effects of water regime and salinity on seed banks, however, are poorly understood (Britton & Brock 1994).

8. ENERGY FLOWS

Ecological boundaries of streams are often the entire catchment. Catchments provide water (surface, groundwater), nutrients and food for aquatic fauna (*e.g.* leaf litter). Therefore, any disruption within the catchment will be translated to impacts to the stream and river ecosystem. Important ecological linkages for energy flows in the Gingin/Lennard system are considered in three dimensions:

(i) Upstream-downstream linkages.
(ii) Channel-wetland linkages.
(iii) Surface-groundwater linkages.

Upstream-downstream linkages

Existing models of ecological processes differ in the interaction between a river and the catchment. The River Continuum Concept (RCC) (Vannote *et al.* 1980) emphasises an upstream-downstream linkage in energy flow, where material derived from forested regions "subsidises" downstream ecosystems. To support this notion, analyses conducted in other south-west river systems (Davies 1993, Welker & Davies 1998, Davies *et al.* 1998) have shown upland reaches to be reliant on the input of terrestrial carbon from forested reaches.

Channel-wetland linkages

The Flood Pulse Concept (FPC) (Junk *et al.* 1989) emphasises the links between the river and its floodplain and channel-associated wetlands. These links occur during large flood events and material from the floodplain is transported back into river channels when floods recede.

Surface-groundwater linkages.

The ecological significance of surface to groundwater linkages is little-understood. Whether the groundwater supplies nutrients and other energy to the surface water system is the subject of debate. However, an undoubted function of this linkage is to maintain water levels and flows in the surface system.

9 OTHER ECOLOGICAL ISSUES

A number of riverine/wetland regions of the Gingin and Lennard catchments have been identified as having ecological significance. Although there are no Ramsar-listed wetlands in the area, and none of the wetlands are listed in The Directory of Important Wetlands in Australia (ANCA, 1996), there are Nature Reserves in the catchments that contain important wetlands (Figure 11). Those closest to the brooks are Bampanup and Yeal Nature reserves. Both contain wetlands with high vegetation and medium waterbird values. The hydrological state of these wetlands, being surface expressions of the groundwater must be linked to the level of abstraction from the aquifers and rate of recharge. This relationship is unknown, but the potential for impacts on lake levels, particularly in late summer due to localised drawdown of the groundwater levels due to abstractions must be considered.

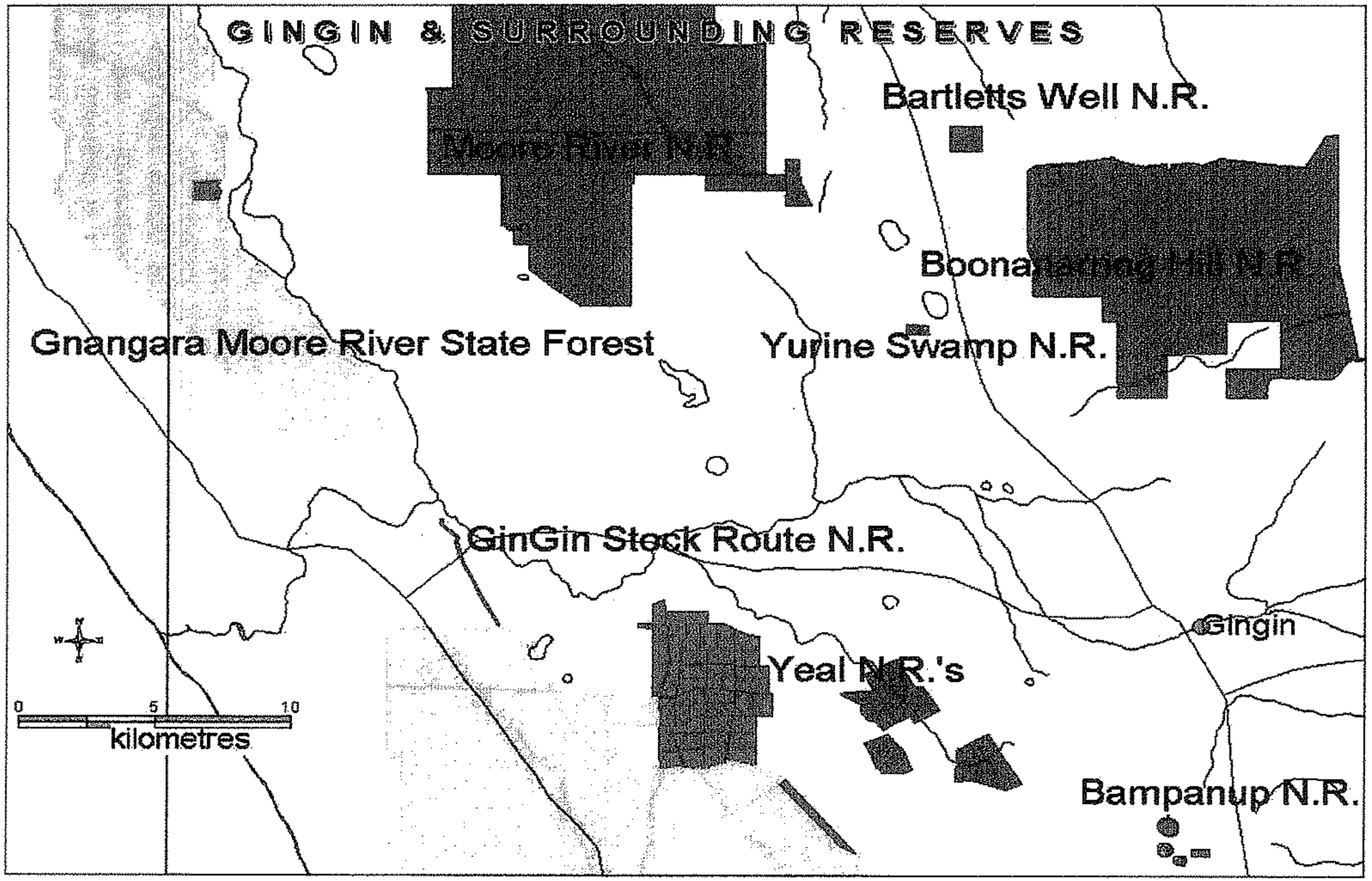

Figure 11. Location of Nature Reserves in the vicinity of Gingin and Lennard brooks

10. RECOMMENDED FLOW REGIME FOR GINGIN AND LENNARD BROOKS

Recommended flow regimes are presented for four "nodes" on the system, each "node" representative of sections with similar hydraulic geometry. These "nodes" and the sections they represent are:

(1) Lennard Brook ("Ashby" & Brand Hwy).
(2) Moondah Brook & upper Gingin ("Whakea").
(3) Mid- Gingin ("Hotel").
(4) Lower Gingin ("Glencoe" and Nolans Bridge).

Although the important water-dependent features are similar in the Gingin/Lennard system, differing channel morphology, hydraulic geometry requires different flows to achieve similar ecological goals for the different sections.

10.1 Recommended Flows to meet EWRs

As discussed in the sections above, important water dependent components of the riverine ecosystem were identified in a value-identification process. Significant EWRs of these components comprised:

(i) Channel/pool maintenance flows.
(ii) Flows to maintain benthic macroinvertebrate communities (particularly in channel runs).
(iii) Flows for fish passage and inundation of spawning habitat.
(iv) Water for maintenance and recruitment of riparian vegetation.
(v) Flows to maintain pools in summer to support fish and waterfowl.
(vi) Energy flows (to maintain upstream-downstream linkages).

Once these EWRs were determined, channel surveys of hydraulic geometry, analysis of the current and historic flow record and the holistic methodology were then used in a "building block approach" to determine specific flow volumes to meet the monthly EWRs.

- The monthly flow requirements for each ecological parameter, as determined for one year, are presented in Tables 9a-d.

After monthly allocations were made for each of the critical flows, the total monthly flows were adjusted in accordance with the known seasonal pattern of unregulated systems, based on the proportion of the median annual flow in each month. These values were also compared to the percentile flows recorded at WRC/WC gauging stations. Where no current or historic flow data were available, data from the nearest comparable gauging stations were used.

The annual water needs of the riverine ecosystems were calculated from the sum of the low flow requirements throughout the year and the additional small and medium-sized floods.

It should be noted that recommended flow allocations only pertain to the defined water dependent ecosystems. There may be other undefined ecological systems that also require water allocation. These systems may or may not be adequately provided by the recommended allocation.

At all sites, the flows required for wetland flooding and riparian inundation are also adequate for maintenance of channel form. "Freshers" need to be maintained in the spring hydrograph to stimulate fish migration.

Lennard Brook (Node 1).

The EWRs are as follows:
Channel form flows are an EWR that represents elevated monthly flows with an intense flood event over 24 hours every three years. The form of a flood event, based on flood hydrographs from the Gingin and Lennard Brook catchments (Appendix 4), but also comparable events for an uncleared catchment in the jarrah forest, is approximated to have an eight-hour ascending limb, four hours at bankfull and twelve hours at the descending limb. This flow corresponds to 72 ML ascending limb, 72 ML at bankfull and 108 ML at the descending limb; totals 250ML. For the remaining days of the month, the EWR is 26 ML/d (about one-tenth the bankfull stage is 778 ML).

It could be argued that an "inverted V" better represents a typical hydrograph rather than the "plateau" presented here. However, based on observation of flood flows in southwestern streams, a short duration at the bankfull stage does not meet the flow requirements of channel maintenance (typically, material is left unscoured from pools). It could be also argued that the difference in water volumes between an inverted V and a plateau represent a mitigation rather than an ecological water requirement.

Baseflows each month maintain flow permanence and upstream-downstream connectivity, and energy linkages. Fish passage flows are to allow reproductive migration and represent flows over the riverbed of about 20cm, with additional "flushers" (small largely unpredictable flows) to stimulate migration. Additional, riparian and wetland connectivity flows are to both inundate the riparian zone (stimulate seed set and recruitment) and to connect adjacent associated wetlands to the channel. These flows are necessarily greater than Q_{bf} and would coincide with about a 1:3 event (e.g. WRC 2001)

The total annual EWRs for Lennard Brook are about 6 GL (Table 9a). This is about the 40-50th percentile of current flows. Some flows (*e.g.* the channel forming and riparian flows) exceed the 90th percentile, however these flows are only required once every three years. Overall, there is little "excess" water for further abstraction.

Moondah Brook, upper Gingin at Whakea (Node 2).

Channel form flows are required and represent elevated monthly flows with an intense flood event over 24 hours. As described above, this event is approximated to have an eight-hour ascending limb, four hours at bankfull and 12 hours at the descending limb. This flow corresponds to 69 ML ascending limb, 69 at bankfull and 104 ML at the descending limb; totals 242ML. For the remaining days of the month, the EWR is 0.3 cumecs (about one-tenth the bankfull stage= 752 ML).

Permanent monthly flows are required to maintain upstream-downstream connectivity, and energy linkages. Fish passage flows represent flows over the substrate of about 20cm, with additional "flushers" to stimulate migration. An additional riparian and wetland connectivity flow are to both inundate the riparian zone (stimulate seed set and recruitment) and to connect adjacent associated wetlands to the channel. These flows are greater than Q_{bf} (coincide with an ARI of about 1:3).

It is not possible to assess the EWR in the context of existing flows, as no relevant long-term hydrological information is available. The total annual EWR is estimated at over 3 GL (Table 9b).

Mid-Gingin (Townsite) Node 3.

The EWRs for channel forming flows represent elevated monthly flows with an intense flood event over 24 hours every three years. As described above, this event is approximated to have an eight-hour ascending limb, four hours at bankfull and 12 hours at the descending limb. This flow corresponds to 210 ML ascending limb, 210 at bankfull and 315 ML at the descending limb; totals 736 ML. For the remaining days of the month, the EWR is 1 cumec (about one-tenth the bankfull stage= 2851 ML).

Permanent flows are required to maintain upstream-downstream connectivity and energy linkages. Fish passage flows represent flows over the substrate of about 20cm, with additional "flushers" to stimulate migration. Additional riparian and wetland connectivity flows are to both inundate the riparian zone (stimulate seed set and recruitment) and to connect adjacent associated wetlands to the channel (Table 9c). These flows are greater than Q_{bf} (ARI 1:3). The seasonal adjustment maintains the shape of the natural hydrograph and were based on Gingin Townsite (S617 058) (Table 9c). The EWRs for one month (July) are about 80-90th percentiles. However, these flows are only required one year in three, Other EWRs correspond to about the 20-30th percentiles of the current flow regime.

Lower Gingin (Node 4).

The EWRs require channel-forming flows with an intense flood event over 24 hours every three years. As described above, this event is approximated to have an eight-hour ascending limb, four hours at bankfull and 12 hours at the descending limb. This flow corresponds to 172 ML ascending limb, 172 at bankfull and 259 ML at the descending limb; totals 603 ML. For the remaining days of the month, the EWR is 2.2 cumecs (about one-half the bankfull stage= 5702 ML). Permanent flows are required to maintain upstream-downstream connectivity and energy linkages. The EWRs for fish passage represent flows over the substrate of about 20cm, with additional "flushers" to stimulate migration. EWRs for riparian and wetland connectivity flows are to both inundate the riparian zone (stimulate seed set and subsequent recruitment) and to connect adjacent associated wetlands to the channel. These flows are greater than Q_{bf} (ARI 1:3).

The total EWRs for the lower Gingin are about 23 GL/a and, for the winter/spring months, are about the 30-40th percentile of current flows. During this summer/autumn period, there is little "excess" water for further abstraction.

10.2 Further Water Abstraction

Abstraction/impoundment should never result in reaches of the river becoming dry. This could lead to localised extinction of aquatic fauna which, due to the extent of isolation, may be prevented from recolonising from elsewhere.

10.3 Monitoring and Revision

It must be emphasised that the estimated EWRs for the Gingin/Lennard system are essentially a "best scientific guess". The EWRs have been formulated, as is always the case, in the context of an incomplete ecological record and limited hydrological data. In the absence of sound ecological understanding, the best available approximations of significant flow events and temporal patterns of flow should be used. An important corollary of this is that the initial in-stream flow recommendations for most rivers should be regarded as first estimates (Davies *et al.* 1998).

Parameters to monitor to assess the success of the proposed EWRs should include:

- water quality, particularly in riverine pools during summer/autumn,
- aquatic invertebrates at key locations to assess improvement in habitat quality,
- adult and larval fish species composition and population structure to assess recruitment success, habitat condition and flushing of exotics from the system.
- The dynamics of oxygen levels in pools during summer.
- Riparian condition and the extent of seed-set and subsequent recruitment.
- Channel condition including pool aggradation.

10.4 Adaptive Management

It is critical, that any proposed changes to flow regulation are considered in an adaptive management context (*e.g.* Adaptive Environmental Assessment and Management: AEAM). In adaptive management, the ecological consequences of increased abstraction should be carefully monitored and management procedures subsequently reviewed/revised in the light of monitoring results. Managers should also endeavour to keep abreast of any new scientific developments in the relevant fields of environmental biology/ conservation.

The maintenance of a flow regime should be considered only a component of rehabilitation of stream channels. Without the restoration of the other critical components (*i.e.* riparian vegetation, channel morphology, water quality from catchment landuse) of the ecosystem, suitable EWRs will have little impact.

River restoration involves a number of issues aside from adequate EWPs. These include:

- adequate water quality,
- suitable in-stream habitat,
- channel stability, and
- suitable riparian-stream linkages.

The loss of in-stream habitat, cleared riparian vegetation and channel instability are the major causes of degradation, particularly in the lower reaches of south-west rivers. Restoration of the riparian zone requires revegetation, limiting livestock access and fencing (to enable regrowth of the understorey).

Channel stability requires some engineering solutions and in-stream habitat requires the installation of large woody debris (LWD) to create a diversity of habitat types (*e.g.* riffles and pools).

The restoration of these rivers should be considered at a catchment scale as an Integrated Catchment Management (ICM) process.

10.5 Operational Monitoring of EWRs

The recommended EWRs should be monitored using the existing gauging station network. The critical months for monitoring are during summer and autumn when the combined effects of abstraction and seasonally-low rainfall and groundwater discharge result in low stage levels in the river systems. The table below identifies gauging stations to be used as representative sites. When the EWRs represent a significant proportion of the MAF, the frequency of monitoring of flows should be more often. Due to the transitory nature of groundwater-surface water connection, the transmission gains and/or losses from the gauging stations to the survey sites was assumed to have little influence on the desired flow rate.

Station	Monitoring sites	Frequency
617165	Lennard	Summer/Autumn
617058	Mid Gingin	All
617003	Lower Gingin	Summer/Autumn

10.6 Concluding Remarks

The EWRs presented here are the initial "request" for the optimum water to the environment to maintain the ecological values of the system at a low level of risk. The final allocation (the EWP) is determined after social, economic and industrial users have also been considered (*i.e.* there is the need to cater for *Bylaw 11* and other consumptive users).

10.7 Recommendations

1. The Gingin/Lennard brooks should be maintained as permanently flowing systems, even under local-drought conditions.

2. The effectiveness of the resultant EWRs should be monitored in an adaptive context (*i.e.* AEAM).

3. EWRs should be evaluated during summer when other issues (*e.g.* pool viability) are critical for long-term maintenance of aquatic fauna in the system.

4. EWRs should be recognised as part of an overall river restoration program, in an ICM plan.

Table 9a. Recommended EWRs for Node 1 (Lennard Brook).

Month	Existing median flows (ML)	Flow (ML) to maintain: Channel form[1]	Energy flows/ macro-invertebrates[2]	Fish passage[3]	Riparian vegetation/ wetland connectivity[4]	Seasonal adjustment[5]	EWR	Flows as percentiles of existing flows[6]
January	297.48		288				288	40-50
February	270.26		261[7]				261	40-50
March	302.66		288				288	40-50
April	364.31		278			345	345	40
May	486.78		288			410	410	30-40
June	660.53		288			557	557	30-40
July	848.36	1030	288		1103		1103	>90[4]
August	876.18		288	859			859	40-50
September	726.11		278	832			832	70-80
October	641.95		288			622	622	40-50
November	454.98		278			407	407	30-40
December	342.92		288				288	20

1. Channel form flows represent elevated monthly flows with an intense flood event over 24 hours. This event, based on flood events in the jarrah forest, has an eight-hour ascending limb, four hours at bankfull and 12 hours for the descending limb. This flow corresponds to 72 ML ascending limb, 72 at bankfull and 106 ML at the descending limb; totals 252ML. For the remaining days of the month, the EWR is 0.3 cumecs (about one-tenth the bankfull stage= 778 ML).
2. These monthly flows maintain upstream-downstream connectivity, permanent flows and energy linkages.
3. Fish passage flows represent flows over the substrate of about 20cm, with variation or "flushers" to stimulate migration.
4. Riparian and wetland connectivity flows are to both inundate the riparian zone (stimulate seed set and recruitment) and to connect adjacent associated wetlands to the channel. These flows are greater than Q_{bf}. These flows are only necessary one year in three.
5. The seasonal adjustment maintains the shape of the natural hydrograph.
6. Based on Molecap Hill (S617 165).
7. These values are calculated from daily totals and scaled-up for the month. Therefore, February with 28 days has the lowest monthly requirement.

Table 9b. Recommended EWRs for Node 2 (Moondah Brook and upper Gingin).

Month	Flow (ML) to maintain:					
	Channel form[1]	Energy flows/ macro-invertebrates[2]	Fish passage[3]	Riparian vegetation/ wetland connectivity[4]	Seasonal adjustment[5]	EWR
January		110.9				111
February		100.2				100
March		110.9				111
April		107.4			142	142
May		110.9			176	176
June		110.9			310	310
July	992	110.9		1020		1020
August		110.9	331			331
September		107.4	320			320
October		110.9			185	185
November		107.4				107
December		110.9				111

1. Channel form flows represent elevated monthly flows with an intense flood event over 24 hours. This event, based on flood events in the jarrah forest, has an eight-hour ascending limb, fours hours at bankfull and 12 hours at the descending limb. This flow corresponds to 69 ML ascending limb, 69 at bankfull and 104 ML at the descending limb; totals 240 ML. For the remaining days of the month, the EWR is 0.3 cumecs (about one-tenth the bankfull stage= 751 ML).
2. These monthly flows maintain upstream-downstream connectivity, permanent flows and energy linkages.
3. Fish passage flows represent flows over the substrate of about 20cm, with additional "flushers" to stimulate migration.
4. Riparian and wetland connectivity flows are to both inundate the riparian zone (stimulate seed set and recruitment) and to connect adjacent associated wetlands to the channel. These flows are greater than Q_{bf}.
5. The seasonal adjustment maintains the shape of the natural hydrograph. (Based on Gingin Townsite with an adjustment for catchment area).

Table 9c. Recommended EWRs for Node 3 (mid Gingin Brook).

Month	Existing median flows (ML)	Flow (ML) to maintain: Channel form[1]	Energy flows/ macro-invertebrates[2]	Fish passage[3]	Riparian vegetation/ wetland connectivity[4]	Seasonal adjustment[5]	EWR	Flows as percentiles of existing flows[6]
January	455.63		487				487	60
February	430.27		439				439	50-60
March	525.48		487				487	20-30
April	705.37		471			640	640	20-30
May	1101.73		487			937	937	20-30
June	1498.82		471			1355	1355	20-30
July	1814.23	3241	487		3312		3312	80-90[4]
August	1920.07		487	1563			1563	20-30
September	1470.27		487	1504			1504	50
October	1143.81		487			705	705	20-30
November	835.23		471				471	20-30
December	595.60		487				487	20-30

1. Channel form flows represent elevated monthly flows with an intense flood event over 24 hours. This event, based on flood events in the jarrah forest, has an eight-hour ascending limb, four hours at bankfull and a 12 hour descending limb. This flow corresponds to 210 ML ascending limb, 210 at bankfull and 315 ML at the descending limb; totals 735 ML. For the remaining days of the month, the EWR is 1 cumecs (about one-tenth the bankfull stage= 2506 ML).
2. These monthly flows maintain upstream-downstream connectivity, permanent flows and energy linkages.
3. Fish passage flows represent flows over the substrate of about 20cm, with additional "flushers" to stimulate migration.
4. Riparian and wetland connectivity flows are to both inundate the riparian zone (stimulate seed set and recruitment) and to connect adjacent associated wetlands to the channel. These flows are greater than Q_{bf}. These flows are only required one year in every three.
5. The seasonal adjustment maintains the shape of the natural hydrograph.
6. Based on Gingin Townsite (S617 058).

Table 9d. Recommended EWRs for Node 4 (Lower Gingin Brook).

Month	Existing median flows (ML)	Flow (ML) to maintain: Channel form[1]	Energy flows/ macro-invertebrates[2]	Fish passage[3]	Riparian vegetation/ wetland connectivity[4]	Seasonal adjustment[5]	EWR	Flows as percentiles of existing flows[6]
January	308.28		298				298	40
February	243.99		269				269	50-60
March	289.79		298				298	40-50
April	433.73		288			396	396	30-40
May	1143.24		298			865	865	30-40
June	3440.23		288			2550	2550	30-40
July	8010.27	6305	298		6438		6438	40-50
August	8845.42		298	4716			4716	20-30
September	5593.45		298	4564			4564	30-40
October	2667.34		298			1998	1998	30-40
November	924.65		288			720	720	30-40
December	462.84		298				298	10-20

1 Channel form flows represent elevated monthly flows with an intense flood event over 24 hours. This event, based on flood events in the jarrah forest, has an eight-hour ascending limb, four hours at bankfull and 12 hours at the descending limb. This flow corresponds to 172 ML ascending limb, 172 at bankfull and 259 ML at the descending limb; totals 603 ML. For the remaining days of the month, the EWR is 2.2 cumecs (about one-tenth the bankfull stage= 5702 ML).

2 These monthly flows maintain upstream-downstream connectivity, permanent flows and energy linkages.

3 Fish passage flows represent flows over the substrate of about 20cm, with additional "flushers" to stimulate migration.

4 Riparian and wetland connectivity flows are to both inundate the riparian zone (stimulate seed set and recruitment) and to connect adjacent associated wetlands to the channel. These flows are greater than Q_{bf} and are required one year in three.

5 The seasonal adjustment maintains the shape of the natural hydrograph.

6 Based on Bookine Bookine (S617 003).

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12. APPENDICES

APPENDIX 1. MEANS, MEDIANS & PERCENTILES OF FLOWS.

Gingin Townsite (617058) (1957 - 2001)

Month	No.	Mean	Median	pctl10	pctl20	pctl30	pctl40	pctl50	pctl60	pctl70	pctl80	pctl90
Jan	44	489.99	455.63	332.29	396.58	429.84	446.43	455.63	479.87	522.89	641.00	775.44
Feb	42	448.78	430.27	292.72	354.76	391.39	405.30	430.27	449.80	474.60	566.01	626.31
Mar	43	561.24	525.48	429.41	472.52	490.67	513.99	525.48	573.35	614.56	705.46	749.35
Apr	44	749.10	705.37	536.11	606.36	646.36	670.64	705.37	758.51	805.85	952.73	1008.89
May	44	1104.92	1101.73	848.97	929.66	1003.36	1035.07	1101.73	1147.39	1211.41	1256.95	1428.28
Jun	44	1609.08	1498.82	1174.78	1241.31	1345.16	1409.44	1498.82	1608.68	1698.11	1856.91	2236.12
Jul	43	2162.45	1814.23	1429.66	1559.00	1640.39	1776.99	1814.23	2044.40	2392.42	2682.63	3354.13
Aug	43	2020.71	1920.07	1531.27	1560.90	1673.65	1808.61	1920.07	1974.24	2167.00	2248.39	2771.02
Sep	44	1443.99	1470.27	1070.32	1122.85	1302.31	1388.36	1470.27	1537.75	1632.96	1788.74	1945.47
Oct	42	1204.24	1143.81	909.45	971.40	1014.34	1080.43	1143.81	1195.86	1262.30	1301.88	1667.87
Nov	43	844.86	835.23	599.53	669.69	727.83	789.52	835.23	868.58	945.91	987.12	1097.37
Dec	44	594.41	595.60	390.53	457.92	523.32	556.42	595.60	617.59	664.33	707.79	838.08

Mean Annual Discharge	13081.58	No.	43
Median Annual Discharge	12868.42		

Bookine Bookine (617003) (1972 - 2001)

Month	ndisch	meanmon	medmon	pctl10	pctl20	pctl30	pctl40	pctl50	pctl60	pctl70	pctl80	pctl90
Jan	29	342.23	308.28	228.44	239.76	252.63	287.37	308.28	350.27	378.95	405.22	443.66
Feb	29	285.09	243.99	175.48	197.86	212.98	223.69	243.99	270.86	281.40	293.41	463.19
Mar	29	323.24	289.79	205.98	238.64	266.80	283.56	289.79	318.90	338.95	380.85	499.91
Apr	29	499.09	433.73	273.20	345.60	383.01	409.54	433.73	485.48	560.22	592.27	735.87
May	29	1407.56	1143.24	595.12	678.76	860.28	950.31	1143.24	1214.01	1292.03	1688.60	2726.18
Jun	28	4156.13	3440.23	1912.55	2097.10	2444.77	3003.09	3440.23	4008.44	4519.50	6572.88	8603.02
Jul	28	9362.82	8010.27	2941.57	4844.36	5943.89	6510.24	8010.27	9740.48	11284.79	13738.98	18406.57
Aug	28	10409.16	8845.42	4931.37	5648.66	5847.90	7551.27	8845.42	11386.22	13508.12	15921.27	18810.49
Sep	29	6578.74	5593.45	2814.65	3119.21	4196.36	4877.37	5593.45	7176.82	8218.02	10210.15	11361.00
Oct	29	2879.99	2667.34	1273.45	1469.40	1964.30	2174.34	2667.34	2872.71	3043.09	3613.42	4520.71
Nov	29	1019.56	924.65	557.71	676.86	721.35	840.76	924.65	1110.50	1249.86	1379.81	1621.90
Dec	29	472.51	462.84	304.91	360.03	402.80	449.71	462.84	475.29	550.02	576.55	635.90

Mean Annual Discharge	38083.71	No.	28
Median Annual Discharge	37060.20		

Molecap Hill (617165) (1962 - 2001)

Month	ndisch	meanmon	medmon	pctl10	pctl20	pctl30	pctl40	pctl50	pctl60	pctl70	pctl80	pctl90
Jan	39	302.47	297.48	204.51	256.87	266.63	273.97	297.48	315.71	351.73	369.88	413.68
Feb	37	275.22	270.26	218.68	237.08	239.93	248.92	270.26	294.11	308.53	328.23	369.19
Mar	39	293.09	302.66	91.84	258.25	267.49	286.85	302.66	329.79	344.48	365.39	432.00
Apr	40	359.22	364.31	213.58	298.73	332.04	355.23	364.31	387.29	416.92	435.02	464.88
May	40	493.55	486.78	251.77	391.22	412.95	439.04	486.78	576.16	599.79	644.07	680.57
Jun	39	638.58	660.53	455.50	498.96	543.72	588.38	660.53	712.71	754.88	802.14	871.26
Jul	39	806.66	848.36	496.54	570.33	711.76	793.33	848.36	866.16	927.59	996.36	1052.18
Aug	39	843.03	876.18	619.14	668.65	707.96	799.89	876.18	915.84	968.11	1003.02	1067.56
Sep	39	718.99	726.11	474.68	571.54	613.44	707.62	726.11	764.29	823.31	863.65	932.08
Oct	38	616.27	641.95	451.09	483.15	529.55	575.77	641.95	660.61	686.71	710.81	777.69
Nov	39	454.18	454.98	328.41	365.82	388.63	419.73	454.98	482.80	526.26	543.97	595.38
Dec	39	354.11	342.92	252.03	289.70	309.66	330.74	342.92	374.89	416.88	439.69	464.75

Mean Annual Discharge	6169.70	No.	38
Median Annual Discharge	6478.10		

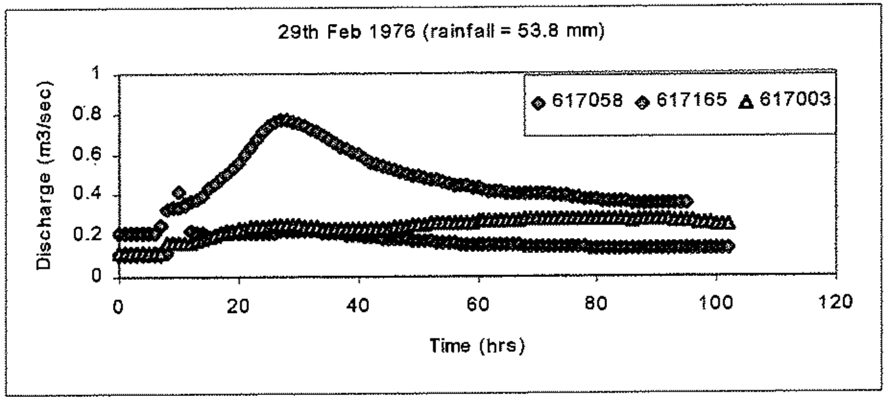
APPENDIX 2. HYDRAULIC PARAMETERS OF THE SEVEN STUDY SITES

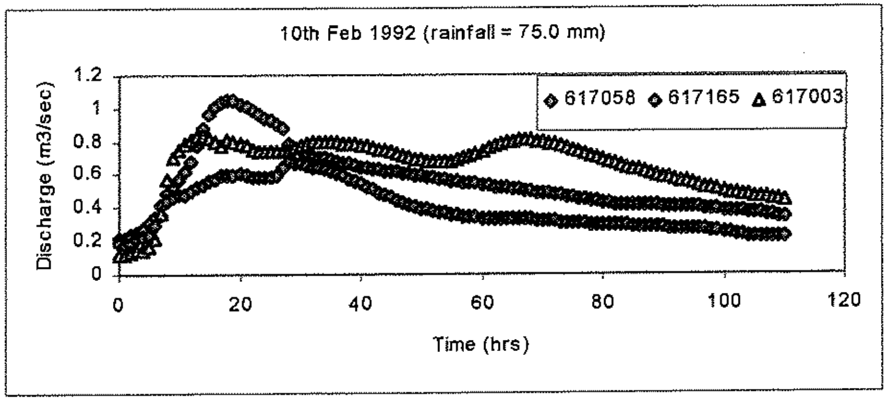
Parameter	Units	Lennard Brook Site 2	Lennard Brook Site 3	Moondah Brook	Gingin Brook (Whakea)	Gingin Brook (Hotel)	Gingin Brook (Glencoe)	Gingin Brook (Nolans Bridge)
Depth	m	0.54	0.33	0.21	0.52	0.51	0.28	0.50
Mean velocity	cm/s	18.2	17.3	21.4	8.92	12.94	8.66	12.48
Substrate roughness		0.55	0.55	0.58	0.56	0.52	0.51	0.52
Mannings n		0.06	0.06	0.07	0.05	0.04	0.04	0.03
Stream power (per unit channel area)	dyn/s	22.3	23.4	18.9	15.6	17.6	16.7	12.5
Roughness shear velocity	m/s	0.89	0.93	0.98	0.78	0.76	0.80	0.69

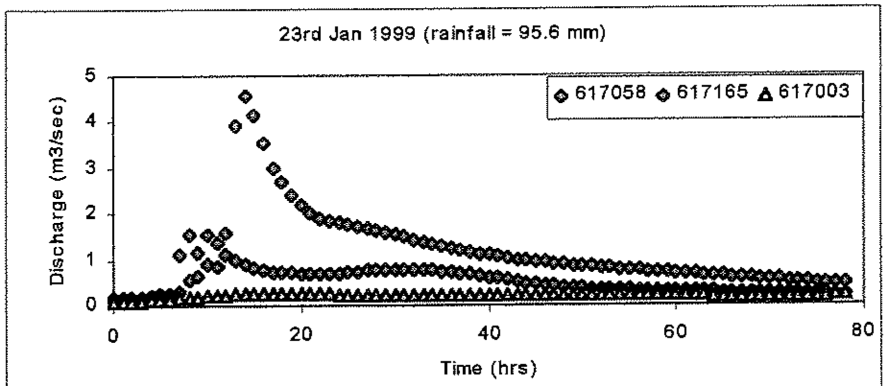
APPENDIX 3. CHANNEL MORPHOLOGY OF THE STUDY SITES.

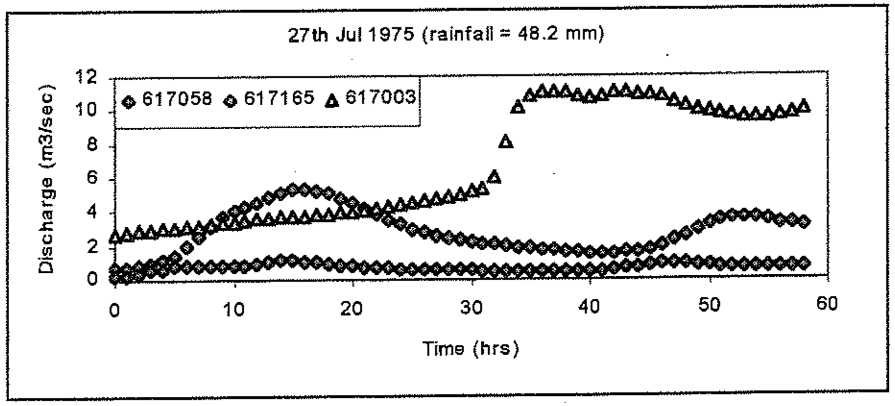
Parameter	Units	Lennard Brook Site 2	Lennard Brook Site 3	Moondah Brook	Gingin Brook (Whakea)	Gingin Brook (Hotel)	Gingin Brook (Glencoe)	Gingin Brook (Nolans Bridge)
Stream order (Strahler 1957)		2	2	2	1	3	3	4
Link magnitude (Shreve 1967)		2	2	3	1	4	12	20
Active channel width	m	2.35	4.22	3.01	5.02	3.60	6.20	4.20
Max active channel depth	m	0.54	0.33	0.21	0.52	0.51	0.28	0.50
Bankfull channel width	m	4.6	4.9	8.9	8.2	18.9	16.1	19.0
Bankfull depth	m	0.87	1.93	0.74	0.72	1.32	0.82	0.68
Wetted perimeter of flow (active)	m	3.43	4.88	3.43	6.06	4.62	6.76	5.20
Wetted perimeter of flow (Q_{bf})	m	6.34	8.76	10.38	9.64	9.94	17.74	20.36
Stream gradient	%	0.068	0.010	0.012	0.024	0.083	0.051	0.023
Mean velocity	cm/s	18.2	17.3	21.4	8.92	12.94	8.66	12.48
Flow rate	m^3/s	0.23	0.23	0.13	0.23	0.24	0.15	0.26
Baseflow (est.)	ML/m	596.1	596.2	350.1	603.4	622.1	389.5	679.1
Bed materials (Cummins 1962)		sand	sand	sand	sand/gravel	sand/silt	sand/silt	sand/silt
Median particle size	m	797.3	812.8	823.4	921.7	700.5	756.9	710.8
Manning's n (active = sampling stage)		0.05	0.05	0.05	0.04	0.05	0.08	0.04
Manning's n (at Q_{bf}) (est.)		0.15	0.15	0.10	0.10	0.15	0.15	0.10
Cross sectional area (active = sampling)	m^2	1.27	1.39	0.63	2.61	1.84	1.74	2.10
Cross sectional area (at Q_{bf})	m^2	4.00	9.46	6.59	5.90	188.35	13.20	12.92
Mean velocity (at Q_{bf})	cm/s	12.78	7.02	17.32	35.30	142.87	39.09	35.41
Bankfull flow (Q_{bf})	m^3/s	5.67	5.14	4.84	5.98	14.6 (269.10: floodplain)	21.5	17.2

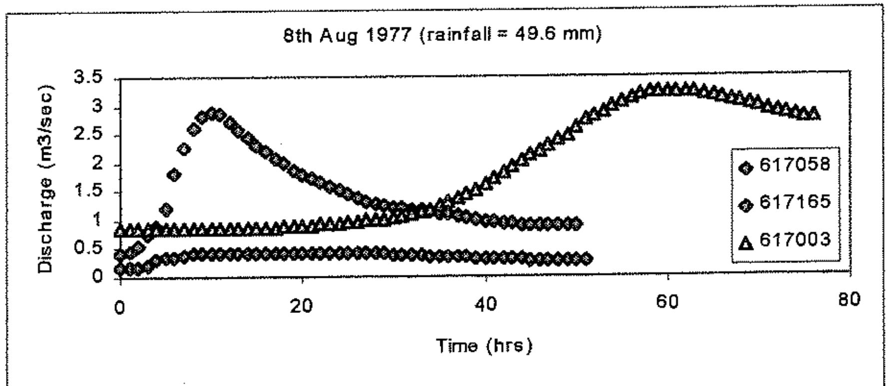
APPENDIX 4. FLOOD HYDROGRAPHS

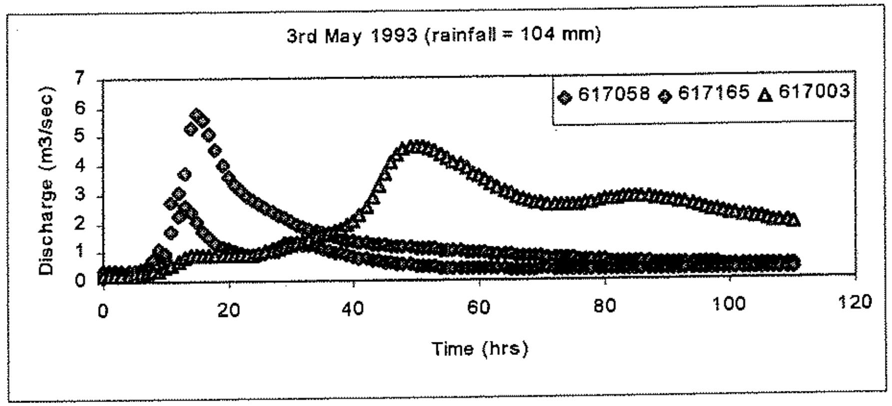












APPENDIX 5. WATER QUALITY DATA

Parameter	Units	Lennard Brook Site 2	Lennard Brook Site 3	Moondah Brook	Gingin Brook (Whakea)	Gingin Brook (Hotel)	Gingin Brook (Glencoe)	Gingin Brook (Nolans Bridge)
Time of sampling	hrs	1000	1120	1330	1400	1445	1615	1800
Turbidity	NTU	3.6	21.3	14.8	5.1	6.3	9.8	2.9
Econd.	s/cm	870	998	802	497	777	1117	1886
Salinity	mg/L	0.41	0.48	0.38	0.22	0.37	0.54	0.97
pH	units	6.65	7.07	7.05	6.67	6.70	7.54	7.28
Redox	ORP mV	220	51	104	171	152	194	192
Temperature	^0C	16.7	16.3	17.5	16.8	16.2	18.0	17.2
Dissolved oxygen (sat.)	%	77.5	91.9	95.1	83.2	82.4	74.5	35
Dissolved oxygen (conc.)	mg/L	7.5	9.0	9.0	8.6	8.1	7.0	3.2
Canopy cover (est.)	%	30	0	0	20	25	10	65