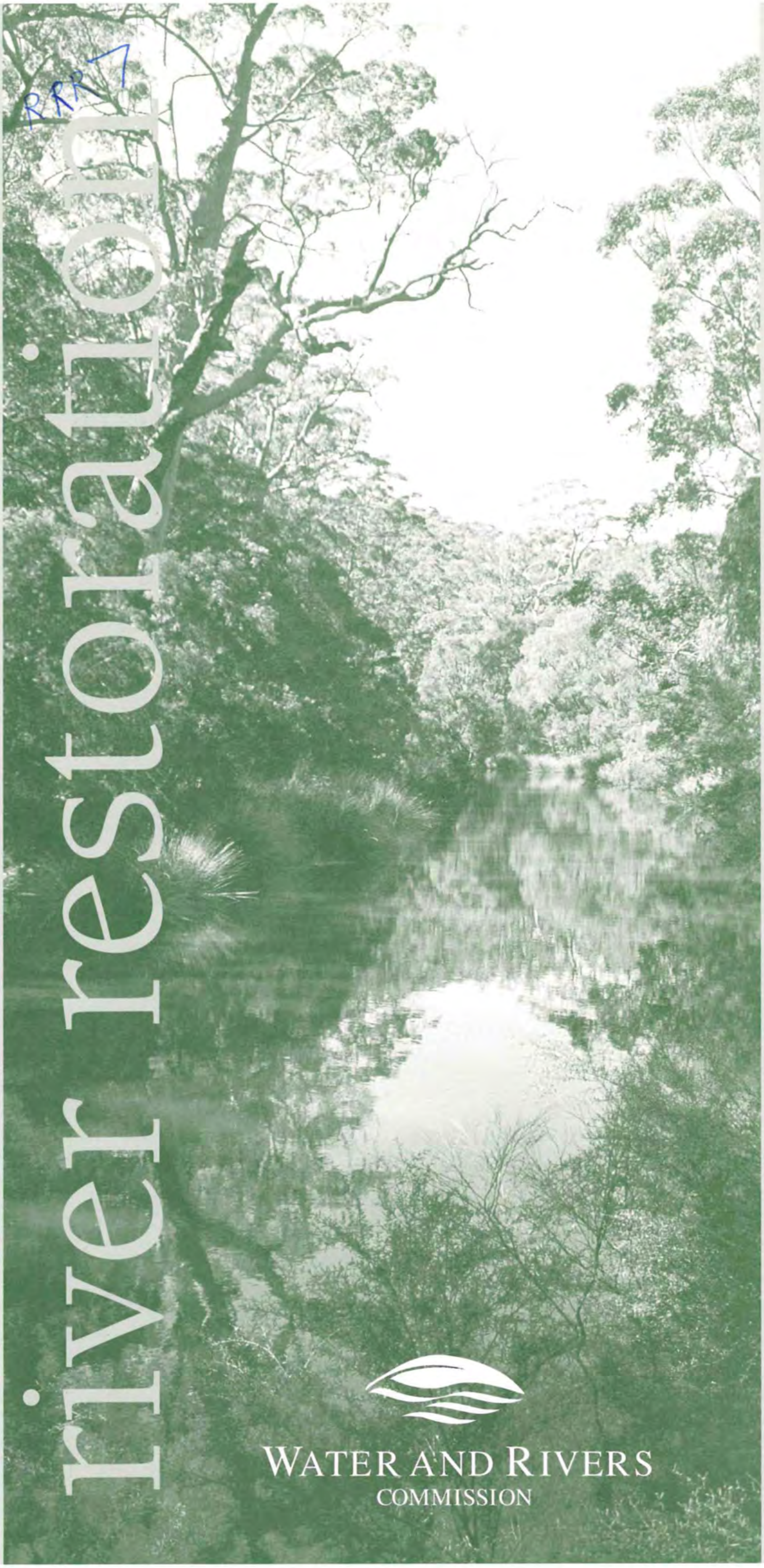

river restoration

THE GOVERNMENT OF WESTERN AUSTRALIA

Stream Ecology

WATER AND RIVERS
COMMISSION

July 2000
Report No. RR7

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STREAM ECOLOGY

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Foreword

Many Western Australian rivers are becoming degraded as a result of human activity within and along waterways and through the off-site effects of catchment land uses. The erosion of foreshores and invasion of weeds and feral animals are some of the more pressing problems. Water quality in our rivers is declining with many carrying excessive loads of nutrients and sediment and in some cases contaminated with synthetic chemicals and other pollutants. Many rivers in the south-west region are also becoming increasingly saline.

The Water and Rivers Commission is responsible for coordinating the management of the state's waterways. Given that Western Australia has some 208 major rivers with a combined length of over 25 000 km, management can only be achieved through the development of partnerships between business, landowners, community groups, local governments and the Western Australian and Commonwealth Governments.

The Water and Rivers Commission is the lead agency for the Waterways WA Program, which is aimed at the protection and enhancement of Western Australia's waterways through support for on-ground action. One of these support functions is the development of river restoration literature that will assist Local Government, community groups and landholders to restore, protect and manage waterways.

This document is part of an ongoing series of river restoration literature aimed at providing a guide to the nature, rehabilitation and long-term management of waterways in Western Australia. It is intended that the series will undergo continuous development and review. As part of this process any feedback on the series is welcomed and may be directed to the Catchment and Waterways Management Branch of the Water and Rivers Commission.

Contents

Stream Ecology

One of the primary reasons for attempting to restore rivers is to protect and conserve the biological diversity of these systems. It is, however, impossible to protect biodiversity of river systems without first protecting habitat and basic stream processes. Therefore, it is important to understand the ecology of streams. This document provides an introduction to some of the important ecosystem processes that "drive" the structure of stream communities and highlights some of the pressures that threaten Western Australian stream ecosystems.

1. Energy sources, nutrient cycling and transport

1.1 Deriving energy

In every stream there are hundreds of species and thousands of individuals. As with terrestrial organisms, each individual stream organism requires a continual input of energy in order to survive, grow and reproduce. The energy they need arises from the breakdown of complex organic compounds through an internal chemical process known as **respiration**.

$$\underset{\text{sugars}}{[CH_2O]} + O_2 \longrightarrow CO_2 + H_2O + \text{free energy}$$

During respiration, organic compounds such as sugars are combined with oxygen and broken down into simpler compounds such as carbon dioxide and water. Energy is released in this process and is then available for body movement or other internal processes.

Stream organisms, whether plants or animals, derive energy through the chemical process of respiration. In order to do so, they first need organic compounds (such as sugars) to break down. There are two major pathways by which these organic compounds are obtained:

- Autotrophic pathway
- Heterotrophic pathway

Autotrophic pathway: Green plants are autotrophs [Gk: *autos*, self; *trophe*, nourishment]. They are able to make their own organic compounds from simpler inorganic compounds that are available from air, soil and water. This is achieved through **photosynthesis**.

$$CO_2 + H_2O \xrightarrow[\text{chlorophyll -}a]{\text{light}} \underset{\text{sugars}}{[CH_2O]} + O_2$$

When exposed to light, green plants are able to convert carbon dioxide and water to simple organic sugars and oxygen.

Box 1: What is chlorophyll-*a*?

Chlorophyll-*a* is a green pigment that is required for the conversion of the radiant energy of sunlight to sugars in most photosynthetic plants.

Some of the energy fixed by the green plant, in the form of simple organic sugars, will be broken down in respiration and then used to maintain the plant. The remainder can be used in combination with nutrients taken from the soil and water to make cellulose, lipids, proteins, amino acids and other substances required by the plant to grow and reproduce. Green plants are primary producers and the amount of new plant material produced over time gives us a measure of primary production.

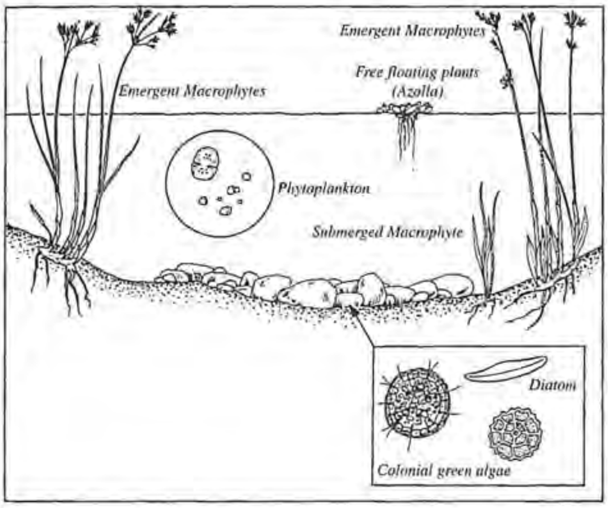

Figure 1: In-stream autotrophs.

In-stream autotrophs (Figure 1) include:

- Submerged and emergent macrophytes: macroalgae, mosses, liverworts and flowering plants that are either rooted in the substratum or free floating.
- Periphytic algae: microfloral community living on the surface of submerged objects.
- Phytoplankton: photosynthetic planktonic organisms that drift within the water column.

Heterotrophic pathway: Organisms that are not able to manufacture their own organic compounds need to take up organic compounds made elsewhere. These organisms are heterotrophs [Gk: *heteros*, other; *trophe*, nourishment]. To meet this need, organic compounds made by autotrophic organisms are consumed by heterotrophic organisms. This can occur directly, whereby an autotroph (eg. green plant) is consumed by a herbivore [L. *herba*, green crop; *vorare*, to devour]. Alternatively organic compounds may be transferred indirectly, whereby plant material is broken down by physical and microbial processes into dead or decomposing tissue known as detritus that is subsequently consumed by a detritivore [L. *detritus*, rubbed off; *vorare*, to devour].

Herbivores and detritivores are secondary producers because they utilise the energy from primary producers in the form of organic compounds that they consume to grow and reproduce. However, not all of the energy from primary production is used for secondary production. Some energy from the primary producer is "wasted" and left to decompose, some is lost by excretion and some is lost in the process of maintaining the consumer via respiration.

Not all heterotrophs are herbivores and detritivores. Some heterotrophic organisms obtain their organic compounds and energy by consuming herbivores and detritivores and in turn they may be consumed. These are predatory heterotrophs.

In-stream heterotrophs include aquatic insects, crustacea (including zooplankton), molluscs, fish, amphibians and waterbirds (Figure 2).

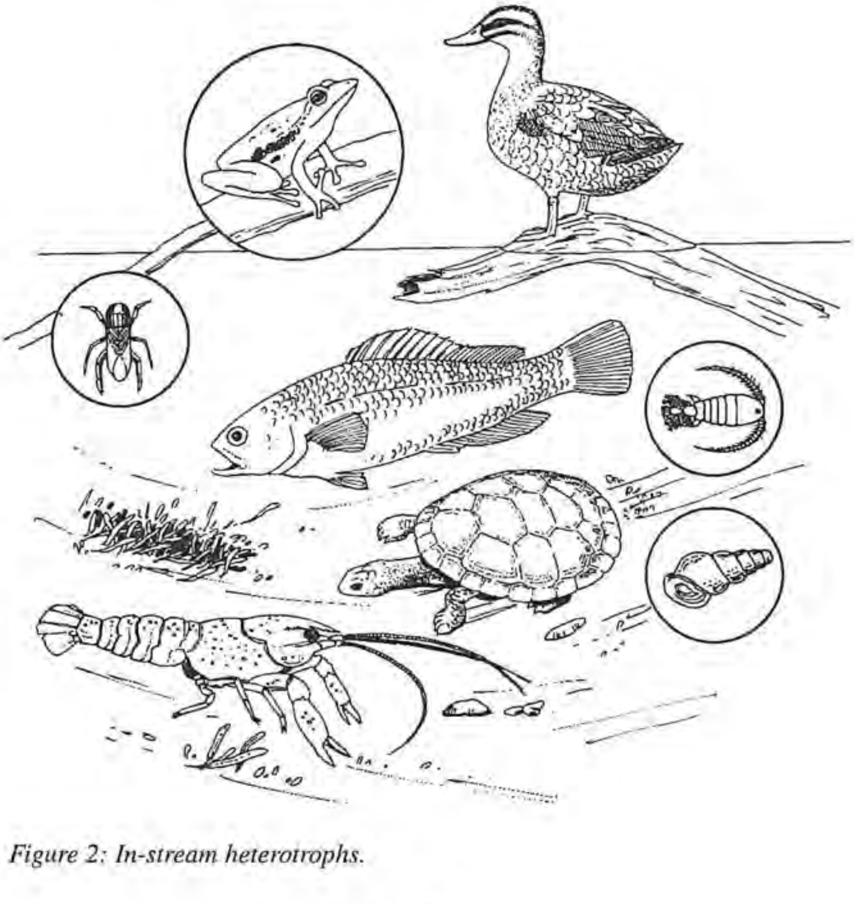

Figure 2: In-stream heterotrophs.

1.2 In-stream food web

Many in-stream heterotrophs have evolved morphological and behavioural characteristics that allow them to consume particular types of food. This is particularly true of aquatic invertebrates. These animals play an important role in the trophic dynamics within streams. Therefore, stream ecologists have divided them into guilds, known as functional feeding groups (Table 1).

Although some macroinvertebrates may change guilds with age and locality, functional feeding groups are useful for describing the complex processing of organic matter within streams.

Table 1: Feeding guilds of invertebrates.
Adapted from tables in Allen (1995)[1]; Merritt & Cummins (1996)[21].

Functional Feeding Group	Food resource	Feeding Mechanism	Examples
Shredders	Non woody, leaf material and associate microbes	Detritivores - chewing	Some caddisfly larvae, stonefly juveniles, amphipods, isopods
	Macrophytes	Herbivores - chewing, mine	Aquatic moth larvae
Gougers	Woody material	Detritivores - excavate, mine	Some midge larvae, beetle larvae and caddisfly larvae
Filterer collectors	Suspended fine particulates and associated microbes	Detritivores - filtering apparatus	Net spinning caddisfly larvae, blackfly larvae
Collector gatherers	Deposited fine particulates and associated microbes	Detritivores - browse surface deposits	Many mayfly and midge larvae
Grazers	Periphytic algae and associated microfauna	Herbivores - scrape and rasp	Some larval mayfly, caddisfly and snails
Macrophyte piercers	Macrophytes	Herbivores - piercing	Some larval caddisfly
Predators	Animal prey	Biting / Piercing	Some larval stonefly, dragonfly, caddisfly, beetles and midge
Parasites	Animal prey	Internal parasites	Nematodes

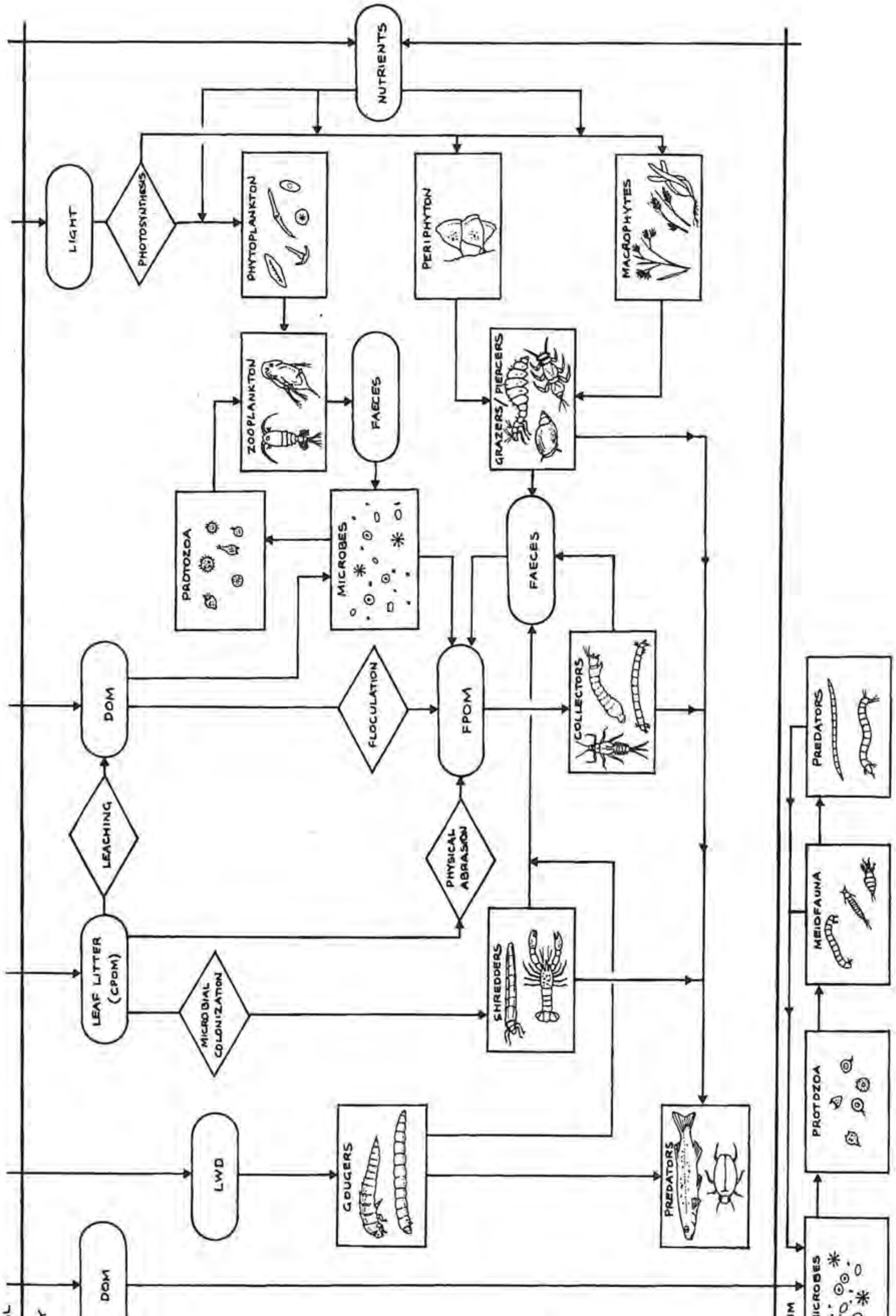

Figure 3: In-stream food web. DOM = Dissolved Organic Matter; LWD = Large Woody Debris; CPOM = Coarse Particulate Organic Matter; FPOM = Fine Particulate Organic Matter.

In any section of a river or creek, the total amount of organic matter present arises from either autochthonous (internal) or allochthonous (external) sources. Primary production by instream autotrophs, including macrophytes, periphytic algae and phytoplankton, represent important autochthonous sources.

Autochthonous [Gk. *autos*, self; *chthon*, ground] inputs of organic matter form the basis of the grazing food chain in streams. Periphytic algae is consumed by grazers (eg. aquatic snails) that scrape the surface of rocks and macrophytes. Macrophytes may be consumed directly by shredders (eg. aquatic moth larvae) that chew or mine the living tissue or piercers (eg. some caddisflies) that suck out vascular fluids. Phytoplankton may be consumed by herbivorous zooplankton (eg. daphnids).

Allochthonous [Gk. *allos*, other; *chthon*, ground] inputs of organic matter arise from the large amounts of terrestrial leaf litter, woody debris and soil particulates that fall or are washed into streams on a regular basis. This non-living organic material forms the basis of the detrital food chain within rivers and creeks. Non-living organic material takes three forms (Table 2):

- Coarse Particulate Organic Matter
- Fine Particulate Organic Matter
- Dissolved Organic Matter

Coarse particulate organic matter (CPOM) arises from leaf material and woody debris or the decline of macrophytes in-stream. Woody debris is slow to break down, but some macroinvertebrates known as gougers (including some midge and a few caddisfly larvae) assist this process by burrowing into and feeding on the surface layers. Leafy material is more readily broken-down. When this material enters a waterway it is often deposited in slow flowing areas or is trapped against large woody debris. It is here that some organic constituents are leached out of the leaves and they are colonised by microbes such as fungi and bacteria that "condition" the leaf material (see Box 2). Macroinvertebrate shredders (eg. some caddisflies, stoneflies, amphipods and isopods) are attracted to the accumulated leaves and will consume them, deriving nutrition either directly from the leaf material or from the microbes upon it (Figure 3).

Shredders are "sloppy" feeders and small pieces of leaf are broken off and transported downstream as the leaf is consumed. These smaller leaf particles, coupled with the faeces generated by shredders, as well as soil particulates, are known collectively as **fine particulate organic matter** (FPOM). Fine particulates may also arise through the precipitation and flocculation of dissolved organic material.

Macroinvertebrates known as collectors are morphologically or behaviourally adapted to harvest FPOM as it moves through the stream system (Figure 3). Some collectors, known as collector-gatherers feed on the FPOM that is deposited in slow moving areas or is captured by the sticky surface of periphytic algae. Collector-gathers include many midge and mayfly larvae. Other collectors, known as filterer-collectors are able to capture and feed on the FPOM that is in suspension within the water column. Some filterer-collectors, such as caddisflies spin silken nets between rocks to capture the suspended FPOM, while others, such as blackflies possess specialised fan-like appendages that filter FPOM from suspension.

Table 2: Organic matter and its origin.
Adapted from Allan (1995)[1].

Type of organic matter	Size	In-stream Source	Outside Source
Coarse particulate	> 1mm	Dying macrophytes	Leaf litter / woody debris
Fine particulate	0.5µm - 1mm	Animal faeces	Soil particulates
Dissolved	< 0.5µm	Leached from leaves	Soil water and groundwater

Dissolved organic material (DOM) arises from the organic material leached from leaves and other debris, as well as from soil water and groundwater. Not all dissolved organic material is biologically active, but that which is can be taken up by microorganisms such as bacteria and assimilated into their biomass (Figure 3). This constitutes an important energy pathway in streams that is often overlooked. The microbes themselves then enter the food web by being consumed by protozoa, that are in turn eaten by tiny consumer organisms such as zooplankton or sediment dwelling meiofauna (ie. tiny invertebrates < 0.5mm).

Box 2: Breakdown of eucalypt leaves

After a leaf enters a stream there are three recognised phases of decomposition and scientists generally measure these in terms of dry weight lost by leaves.

Phase 1: Leaching of inorganic compounds such as tannins. This can result in a 5 – 30% decrease in dry weight within one day.

Phase 2: After leaching, microorganisms such as bacteria and fungi colonise leaves and contribute to their breakdown.

Phase 3: Leaves are fragmented, either through abrasion by turbulence or by consumption by invertebrates.

Eucalypt leaf breakdown is a particularly slow process in comparison to other leaf types, (eg. Northern Hemisphere deciduous species). This is thought to be due to their high lignin content, their thick waxy cuticle and high concentration of polyphenolic compounds. Polyphenolic compounds are thought to act as deterrents to insect attack whilst leaves remain on trees and these are slowly leached in a stream. Within the eucalypts themselves, leaves from our Western Australian jarrah species, *Eucalyptus marginata*, are amongst the slowest to breakdown in-stream. This is thought to be due to the high tannin (a polyphenolic compound) content in jarrah leaves[11],which is thought to delay microbial colonisation for up to four months[5]. Jarrah leaves may take up to 15 months to be 90% decomposed (Figure 4), compared with eight months for many Northern Hemisphere deciduous species.

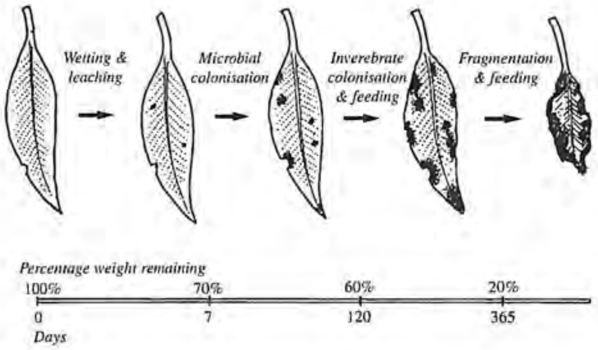

Figure 4: Eucalypt leaf breakdown.

1.3 Nutrient requirements and cycling

Various chemical compounds must be acquired by plants and microbes in order to synthesise new organic material and are therefore required by animals to sustain growth. These are known as nutrients. In streams, heterotrophic organisms obtain nutrients through the consumption of other organisms. Autotrophic organisms may obtain their nutrients either through their roots or directly from the water column.

In aquatic environments, nutrients occur in various chemical forms, as ions or dissolved gases. They may also be transformed into particulate forms by physical and chemical processes as well as by metabolic activity. Macronutrients such as nitrogen, phosphorus and silicon are required in significant amounts in streams and can be limiting to plant growth and yield. Their cycling is an important process in stream ecosystems.

Phosphorus cycling

Phosphorus can exist in both dissolved and particulate forms in the aquatic environment (Table 3), but is only available for uptake by plants and algae in its dissolved inorganic form (PO_4^{3-} or orthophosphate). Plants and algae utilise phosphorus in this form to promote growth. The phosphorus is then available to aquatic animals that consume the plants and algae. Eventually, phosphorus will find its way back to solution via animal excreta or the death of animals, plants and algae and with the action of microbial organisms (Figure 5).

Table 3: Components of total phosphorus in streams and its occurrence.

Component	Example of occurrence in-stream
Dissolved inorganic phosphorus (DIP)	Reactive orthophosphate = PO_4^{3-}
Dissolved organic phosphorus (DOP)	Excretion by animals
Particulate inorganic phosphorus (PIP)	Bound to clay particles/ sediment
Particulate organic phosphorus (POP)	Assimilated in algae

Dissolved inorganic phosphorus may also be adsorbed onto reactive clay particles. Eventually, these particles may settle out of the water column and be deposited on the creek or river bed (Figure 5). Under conditions of low oxygen, the phosphorus may be released from the sediment to become biologically available once more (see Box 3).

Box 3: Nutrient release in the Swan River

Every spring, a dense "wedge" of saline water arising from the marine environment is driven upstream in the Swan River by tidal movement. The salty marine water is denser than water of riverine origin and therefore tends to sit on the bottom of the river. The layering of the freshwater over saline water is called stratification. Stratification restricts the mixing of upper and lower layers and therefore oxygen used by biological demand in the lower layer, is not replenished. Thus oxygen becomes depleted on the bottom of the river bed. Anoxic conditions can cause the release of nutrients and some heavy metals, previously bound to the sediment, into the water column. Under the right conditions of temperature and light, large algal blooms occur in response the available nutrient. The subsequent collapse and decomposition of these blooms can result in low oxygen conditions in the water column and localised death of fauna. Fish deaths are the most conspicuous outcome of this phenomenon.

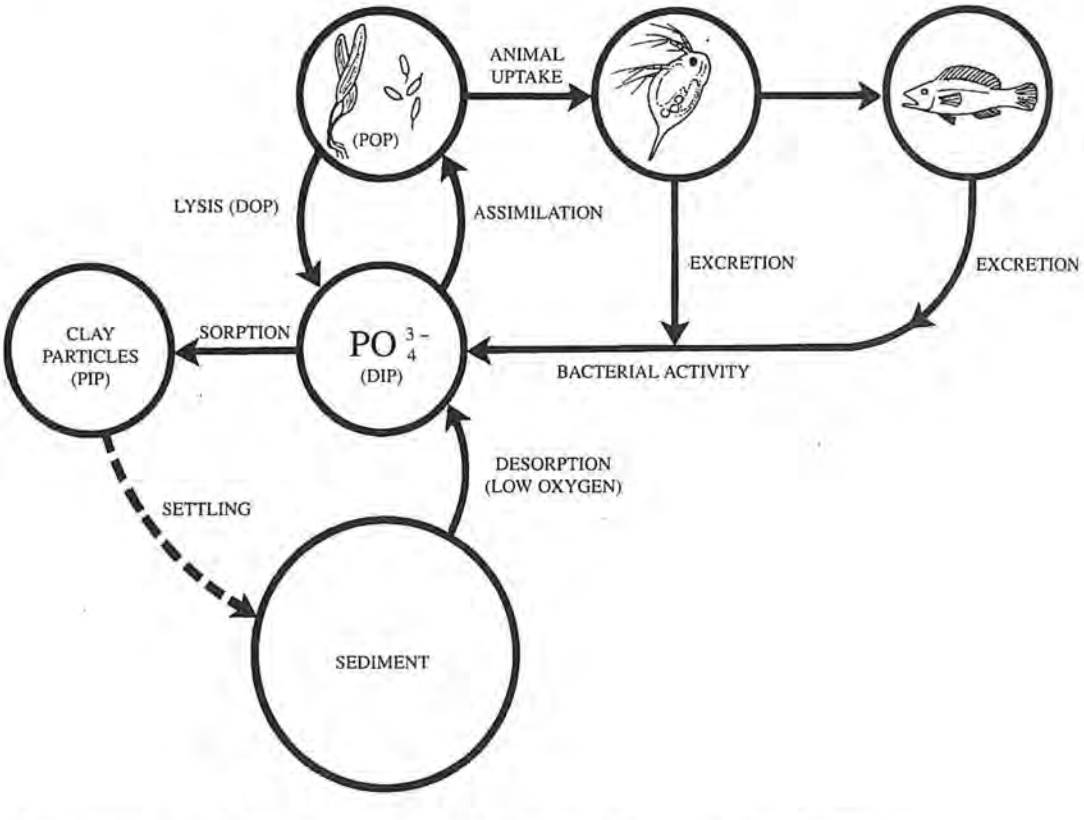

Figure 5: Components of the phosphorus cycle. PIP = Particulate Inorganic Phosphorus; POP = Particulate Organic Phosphorus; DOP = Dissolved Organic Phosphorus; DIP = Dissolved Inorganic Phosphorus.

Nitrogen cycling

Nitrogen is an important component of living tissue since it forms the building block for amino acids and protein molecules. Like phosphorus, nitrogen occurs in both dissolved and particulate forms in the aquatic environment (Table 4). It also exists in a gaseous state in solution.

Table 4: Components of total nitrogen in streams and its occurrence.

Components	Example of occurrence in-stream
Dissolved inorganic nitrogen	NO_3^-, NO_2^-, NH_4^+
Dissolved organic nitrogen	urea, amino acids, uric acid
Particulate organic nitrogen	assimilated in algae

The cycling of nitrogen in aquatic environments is complex and bacteria plays a central role in this process (Figure 6). There are five important processes involved:

Assimilation: Autotrophs, bacteria and fungi can assimilate nitrogen. In aquatic environments ammonium (NH_4^+) is used preferentially over nitrate (NO_3^-). Heterotrophs obtain nitrogen through the consumption of autotrophs, bacteria and fungi.

Decomposition: Organic nitrogen, made available through excretion and decomposition is mineralised back to its inorganic state (NH_4^+) principally through the action of bacteria and fungi.

Nitrification: Under aerobic conditions some nitrifying bacteria can oxidise ammonium (NH_4^+) to nitrite (NO_2^-) and nitrite to nitrate (NO_3^-). These chemoautotrophic bacteria obtain energy through this process.

Denitrification: Under anaerobic conditions denitrifying bacteria utilise nitrate in order to obtain energy via anaerobic respiration. In this process, some bacteria are able to reduce nitrate to nitrite, where as others are able to reduce nitrate to nitrogen (N_2) which is released as a gas.

Nitrogen fixation: Some bacteria and blue green algae (cyanobacteria) that have a special enzyme known as nitrogenase are able to break down nitrogen gas into ammonium and incorporate the ammonium into bacterial biomass. This process is known as nitrogen fixation.

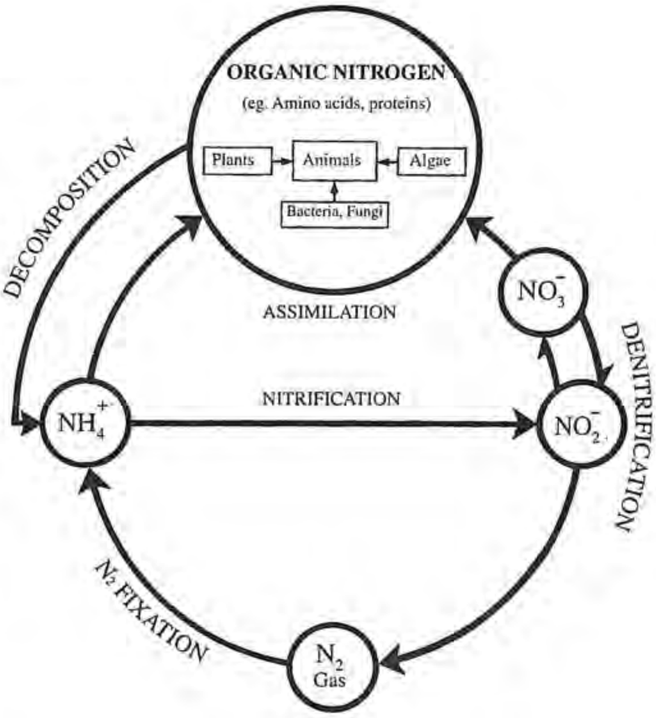

Figure 6: Nitrogen cycle.

Silicon cycling

Diatoms are microscopic algae that make up an important component of the periphyton in streams. Diatoms possess intricately patterned silica shells and thus silicon is an important nutrient for diatoms. Silicon is made available in streams through the weathering of rock and occurs in solution as silicic acid. This can be directly assimilated by diatoms and is released again through dissolution and microbial activity.

1.4 Nutrient spiralling

In static environments such as lakes and swamps, nutrients are readily recycled through the system. In rivers and creeks, however, water movement is longitudinal and thus nutrients may also spiral along a river continuum. The amount of nutrient that is retained at any one location is influenced by the amount of biological activity and flow rate. Systems with low amounts of biological activity and high flow rates tend to 'leak' more nutrients downstream than those with high amounts of biological activity and low flow rates. The amount of nutrient in a system may also influence retention. Where a system has reached its capacity to recycle nutrients, nutrients will be exported downstream.

Where this occurs in excess, the receiving system (eg. a downstream estuary) may become eutrophic (see sections 1.5 & 3.3).

1.5 Trophic status

The trophic status of a waterbody is determined by its nutrient content and productivity. Waterbodies with low nutrient concentrations and low productivity are termed oligotrophic [Gk. *oligos*, little; *trophé*, nourishment]. Waterbodies that exhibit high nutrient concentration and high productivity are termed eutrophic [Gk. *eu*, well; *trophé*, nourishment]. The mid range between these two states is termed mesotrophic [Gk. *meso*, middle; *trophé*, nourishment]. The transition between an oligotrophic system towards a eutrophic one is natural. As waterbodies age, they increasingly deposit both inorganic and organic material and thereby increase their productivity. The process is known as eutrophication.

Human activity can increase the rate of eutrophication of a waterbody through the input of excessive amounts of nutrients. This form of eutrophication is known as cultural eutrophication. Waterbodies in south-west Western Australia are thought to be predisposed to eutrophication[20]. The sandy soils of catchments have a poor capacity to retain nutrients. When fertiliser is added to these soils, the nutrients readily make their way into our waterways through the shallow groundwater. In addition, streamflow tends to be highly seasonal and most estuaries are poorly flushed. This is also true for many deep pools.

1.6 Stream metabolism

Stream communities are mixtures of both autotrophs and heterotrophs and the dominance of autotrophic or heterotrophic pathways of energy transfer is dependent on whether conditions of light and nutrient availability favour primary production. A waterway or section of a waterway is considered to be autotrophic when in-stream photosynthesis exceeds respiration (P/R > 1). If respiration exceeds photosynthesis (P/R < 1) then the system is defined as being heterotrophic.

Upland streams that flow through heavily shaded, forested catchments are usually heterotrophic because photosynthesis is limited by light. In these streams, heterotrophic pathways of energy transfer are dominant and driven through the input of allochthonous organic material (ie. leaves).

Streams that do not flow through dense forest (eg. those in arid or semi-arid areas) receive a much greater input of energy through photosynthesis. Where there is adequate input of nutrients, photosynthesis may exceed respiration and the stream may be considered autotrophic. In these streams, autotrophic pathways of energy transfer are dominant and driven through autochthonous primary production in the form of growth of in-stream plants and algae.

Box 4: Measuring stream metabolism

At the University of Western Australia, Dr Peter Davies has developed a methodology for monitoring stream metabolism. By attaching perspex domes to the bed of a stream, Dr Davies is able to measure dissolved oxygen changes and relate these to the photosynthesis equation in order to reflect changes in the production and consumption of carbon. In work conducted with Dr Stuart Bunn, Dr Davies has shown that many forest streams are heterotrophic and have low primary productivity levels, even with relatively high light availability[7]. They attribute this to the naturally low levels of nutrient available in undisturbed streams. The under-representation of algal grazing invertebrates and fish fauna in Western Australian streams in comparison to eastern Australia may be a consequence of low nutrient levels[7].


[P. Davies]

Photo: Perspex domes, specially designed to measure dissolved oxygen changes, rest on the stream bed.

2. Structure and function of rivers

Organisms, resources and processes are distributed in patches in streams and the factors that influence these may be both large scale (eg. climatic, hydrologic, geomorphic) or small (eg. biotic). In order to efficiently manage our rivers it is essential that we have some understanding of the patterns and processes that occur in our rivers and the factors that influence them. For this reason, many stream ecologists look for and describe generalised ecological patterns of rivers within their natural state.

2.1 River Continuum Concept

One of the best known approaches to describing patterns in the structure and function of rivers is the River Continuum Concept (RCC)[32,22]. Essentially this concept provides a framework to explain biological changes along the length of a river within the context of changes in the terrestrial setting. The model describes small headwater streams as heavily shaded, with poor light penetration and for which important energy sources are mainly derived externally from the input of riparian leaf material (CPOM). These upland streams exhibit heterotrophic metabolism where respiration exceeds photosynthesis (P/R<1) and macroinvertebrate communities are dominated by collectors and shredders (Figure 7).

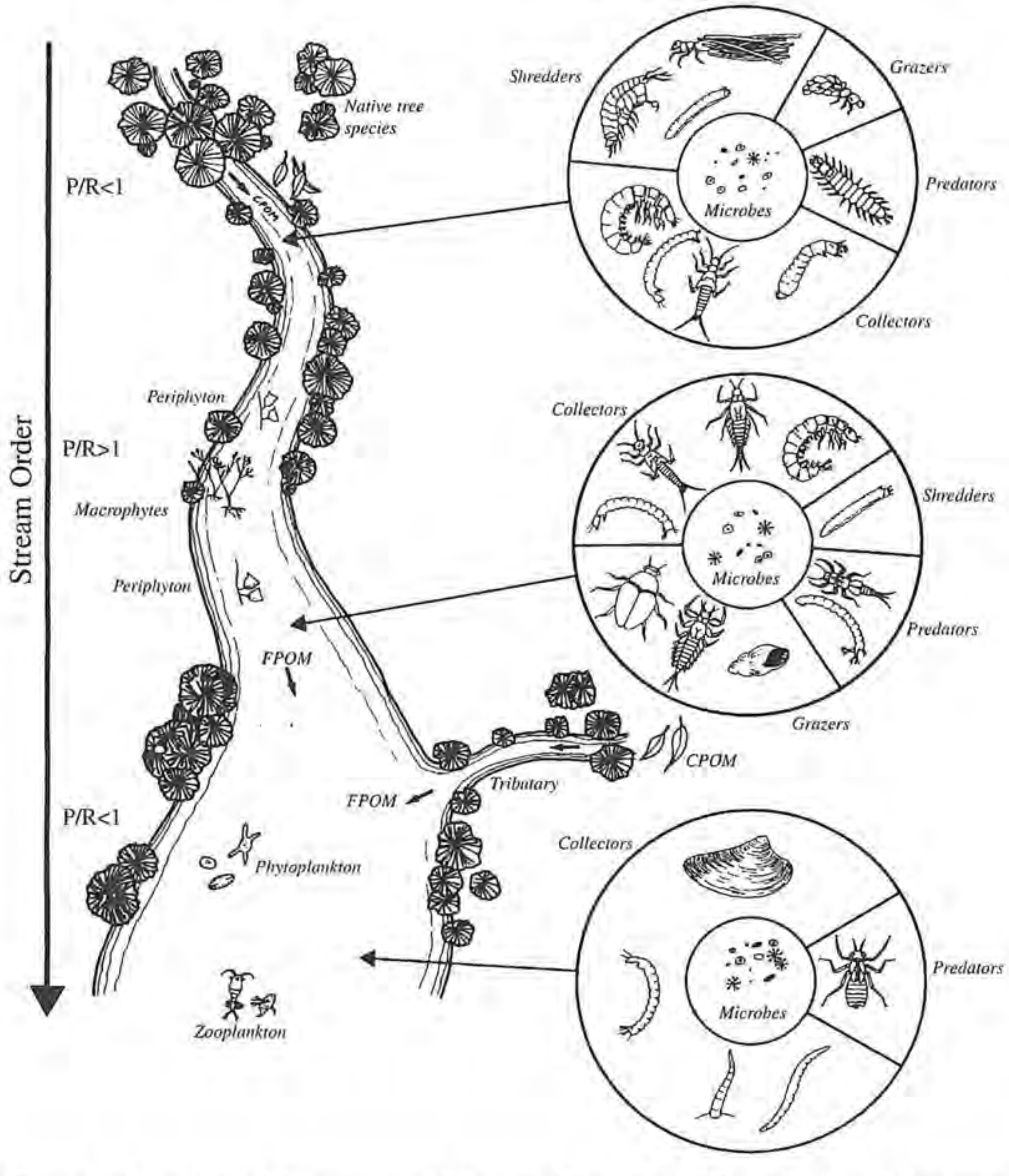

Figure 7: Generalised depiction of the structure and function of a river according to the River Continuum Concept.

As the river widens downstream, the influence of riparian vegetation decreases along with reduced shading and CPOM input. Increased light penetration to the stream bed and the availability of nutrients spiralling from upstream make conditions suitable for significant periphyton production and macrophyte growth. Thus the system shifts from one that is heterotrophic to one that is autotrophic, where photosynthesis exceeds respiration (P/R>1). Macroinvertebrate communties reflect the change in energy availability and are dominated by collectors and grazers (Figure 7).

In large rivers the RCC predicts that turbidity, depth and substratum instability limit photosynthesis. Large rivers are described as heterotrophic with energy inputs largely derived from upstream "leakage" of FPOM. Macroinvertebrate communities in this part of the river continuum are dominated by collectors that either burrow into the soft sediment or filter FPOM directly from the water column (Figure 7).

With the advent of the River Continuum Concept, many stream ecologists tested the framework within a variety of settings and consequently numerous other models have been proposed.

2.2 Flood Pulse Concept

The Flood Pulse Concept[17] was introduced partly in response to the shortcomings of the river continuum concept as a model for large rivers. This concept suggests that periodic changes in water level are crucial to the biota in floodplain rivers and that the primary source of productivity in lowland rivers are the nutrients and particulate material derived from the lateral exchange between the floodplain and the channel.

2.3 Riverine Productivity Model

Another concept, the Riverine Productivity Model[29] stresses the importance of local autochthonous production and allochthonous inputs to food webs of large river. It contends that carbon from local autochthonous sources is more easily assimilated than refractory carbon arising from the floodplains and tributaries. Further, it suggests that in periods outside flood pulses, the allochthonous material arising from the immediate riparian zone, and which accumulates in slow flowing, shallow areas at edge of river, is an important carbon source since it is "available" over long periods.

2.4 Structure and function of Western Australian river systems

All of these models have in common an attempt to describe patterns at the stream scale using energetic parameters. Their applicability to Western Australian systems depends on river size and geomorphology. The River Continuum Concept seems most appropriate for headwater streams, but is clearly inappropriate for rivers and creeks in arid areas of the State. The Flood Pulse Concept may be limited to large floodplain rivers with regular flood events, such as those found in the Pilbara and Kimberly region. The Riverine Productivity Model is probably most relevant to large rivers with constricted channels and firm substrates in areas of high light availability.

In Western Australia, three university studies have been conducted to examine the structure and function of streams in the jarrah[9,12] and karri[15] forests. Upland streams in the jarrah forest have an invertebrate composition similar to that predicted by the river continuum concept, but changes over time in the abundance of shredders do not coincide with peak litter fall as predicted by the model[22]. In part, this has been attributed to the prolonged poor quality of jarrah leaves as a food resource after entering these streams (see Box 2). While upland jarrah forest streams have been shown to be heterotrophic as predicted by the model, lowland rivers have been shown to be autotrophic[12].

In contrast to the jarrah forest, streams of the karri forest largely follow the predictions of the River Continuum Concept both in terms of invertebrate composition and changes in shredder abundance over time[15] This has been attributed to the abundant supply of leaves from riparian species other than eucalypts.

An alternative to the energetic models described above, and one that has been tested in karri forest streams, is that of the hydraulic model[27]. This model proposes that the physical characteristics of flow are major determinants of stream organisation. Patterns of stream invertebrates are thought to show zones of transition along a continuum and these reflect factors such as discharge and gradient. The gradual longitudinal changes in invertebrate community composition within a karri forest stream were found to be associated with flow parameters[16].

Flow is an important determinant of the patterns and processes that occur in river systems since it influences the physical structure of the substratum, a major factor determining the distribution of invertebrates. The speed at which water flows and the turbulence created will also influence the distribution of fauna. Furthermore the intermittent and variable nature of flow in Western Australian streams has an important influence on the distribution of fauna[25].

Box 5: Adaptations to fast flow

Swift flowing and turbulent water presents special challenges to biota. Animals occurring in these areas will often show anatomical and behavioural adaptations that allow them to withstand the current and not be swept downstream. Most macroinvertebrates that occur in fast flowing areas are benthic (living on the bottom) and are often flattened or streamlined in shape. Others have suckers or hooks or use silk threads to enable them to remain within the flow. Others have behavioural adaptations and hide from the current in crevices, cracks and under rocks or between gravel. Generally, fish that occur in swiftly flowing water are streamlined and round in cross section. Some have behavioural adaptations that allow them to withstand flow. Benthic fish species that are dorsoventrally flattened will spread their pectoral fins and alter their position against the flow in order to withstand the current. Lampreys have specialised mouthparts that allow them to sucker against rocks and waterfalls as they move against the flow in their upstream migration.

[D. Macey]

Photo: Lamprey showing specialised mouthparts for attachment.

A large number of our upland rivers and creeks flow for only part of the year. Many native aquatic fauna are adapted to cope with these recurrent periods of drought and utilise upland streams throughout the year. These species may 'over-summer' (ie. survive the dry period) in moist habitats deep within the streambed, under moist leaf litter or in burrows made by freshwater crayfish, such as gilgies and koonacs. Some macroinvertebrates lay resistant eggs in the streambed so that when flow resumes juveniles will hatch from the eggs and readily colonise the stream. Other species of aquatic fauna require permanent water and are behaviourally adapted to seek areas that are permanently wet. Many fauna will leave a drying upland creek and move downstream in search deep pools and permanent stream sections during the dry period[25]. They then migrate back to the upland sites when flow resumes.

2.5 In-stream habitats

In every stream, there are a variety of habitats. These can be described as the environment in which a living organism occurs, and defined according to the distribution of the organism (eg. a plant or animal) in question. Habitats can be very large or very small, ranging from the river or creek itself through to the area under a river stone or log. Typical habitats in streams include:

- Submerged and emergent vegetation
- Riffles
- Sand
- Large woody debris
- Backwaters, edgewaters, pools
- Flooded zones
- Hyporheic zones

Submerged and emergent vegetation

Submerged and emergent rooted plants as well as floating vegetation provide an important habitat for invertebrate fauna. The vegetation also provides shelter for our native fish, water birds and frogs in which they can escape predators and the harsh summer sun. Food resources are also abundant for fishes amongst the vegetation as many macroinvertebrates favour this habitat. These may be feeding directly on the vegetation or upon the attached algae. Other macroinvertebrates, including some molluscs attach or cling to the vegetation and use it as a substratum. From here they are able to obtain their food by filtering small particles from the water column.

Riffles

Swift flowing areas, where the water is rippled or broken and cascades over rocks, logs are known as riffle zones. Riffle zones are often turbulent, well-aerated areas and are favoured by filter feeding macroinvertebrates (eg. blackfly larvae) that are able to exploit the current for gathering food.

Sand

Sand is a poor habitat for macroinvertebrates because of its unstable and mobile nature. The invertebrates that inhabit sand are often burrowers with long thin bodies and thick body walls that enable them to withstand the abrasive action of sand.

Large Woody Debris

In sandy rivers, large woody debris, which is submerged or semi-submerged along the watercourse, provides a stable substratum for macroinvertebrate fauna. These animals are often more abundant, diverse and productive on wood than elsewhere in sandy rivers[3]. Some macroinvertebrates, such as caddisfly and midge larvae are specifically adapted for inhabiting woody debris and have specialised mouthparts with which to gouge and tunnel into the submerged wood.

Large woody debris provides secure roosting and preening sites as well as excellent feeding vantage points for cormorants, herons and other birds. Native fish are more abundant and diverse in rivers where woody debris is present[2]. The fish take advantage of the slower flowing water upstream of woody debris to escape the river flow. Also food resources, such as invertebrates, are often more abundant in these areas. Large woody debris provides protection from predatory birds and the fin-nipping habits of the introduced mosquitofish (*Gambusia* sp.). Pools created by woody debris are important habitats for fish, particularly during summer dry periods when many Western Australian rivers and creeks stop flowing. In these pools, wood provides shade under which fish can escape predation and the harsh summer sun.

Backwaters, edgewaters, pools

Slower flowing areas within rivers and creeks such as channels or runs, pools, backwaters or edgewaters are often the preferred habitat of species that are unable to cope with fast flow. Many of Western Australia's native fish species occur in these areas[23]. Suspended sediments often settle out in slower flowing waters. Where this occurs in shallow areas with abundant light penetration, rooted plants are able to grow in-stream. Benthic macroinvertebrates that occur in slower flowing areas are adapted to tolerate the sandy environment and lower oxygen levels that occur in these areas. Tiny planktonic plants and animals, typically inhabit slower flowing areas of rivers and creeks.

Riverine pools are a particularly important habitat for aquatic fauna during Western Australia's hot, dry summers when long sections of our rivers and creeks dry out. In these systems, permanent, deep river pools provide a refuge for the aquatic fauna that do not have physiological adaptations to tolerate drought. These fauna are able to survive in the shrinking river pools until flow begins again in winter and they can recolonise previously dry reaches.

Flooded zones

Areas adjacent to rivers and creeks that are seasonally flooded during high flows provide an important habitat to small crustacea, wading birds, frogs and fish. For some species, the inundation of the floodplain is crucial to part of their life cycle. During winter, many native fish species migrate out from rivers and into annual creeks or the floodplain in order to spawn in flooded vegetation[23]. Juvenile fishes then develop in these "nursery" areas before moving downstream to more permanent waters.

Hyporheic zones

An often overlooked habitat in streams is that of the hyporheic [Gk: *hypo*, under; *rheic*, flow] zone. This zone occurs under the sediment of the stream bed and beyond the banks. Depending on the porosity of the substratum, this saturated habitat may provide ample oxygen and food supply to support an array of invertebrate life often to depths of up to 60cm below the bed. Some invertebrates are highly specialised and only found in this habitat, while others may utilise it as a short-term refuge to escape sudden increases in current velocity.

Box 6: Hyporheos of Western Australian streams

Little is known of the hyporheic zone in Western Australian streams. Two recent studies have shown that in streams of the karri[30] and jarrah[25] forest, invertebrates occur predominantly in the first 5 cm of the bed. However, some taxa found deeper in the bed of karri forest streams and are adapted to a permanent interstitial (between the sand grains) existence. These taxa are characteristically blind and unpigmented (Figure 8).

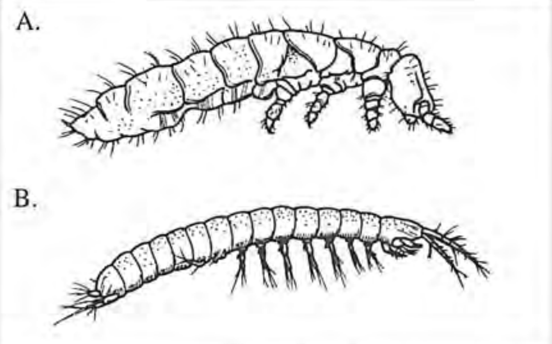

Figure 8: Examples of the blind and unpigmented intersitial fauna occurring in karri forest stream.
A: Onychiurid Collembolla;
B: Bathynellid Syncarid.
Size: 0.5 - 1mm.

3. Threats to stream ecosystems

3.1 Degradation of riparian zones

The emergent and terrestrial vegetation along banks of watercourses collectively define the riparian zone. Riparian zones provide important habitat both terrestrially and in-stream, through the provision of large woody debris. They also act as corridors and provide safe cover for the movement of fauna between areas of remnant bushland.

Riparian vegetation plays an important role in the overall ecology of streams, delivering important allochthonous sources of energy to the food web (see Section 1.2). By providing shade to streams, the riparian vegetation also influences the pathways in which energy is transferred. Clearing riparian vegetation will alter the amount of allochthonous material and light available to a stream system and, depending on where riparian clearing occurs along a river continuum, this can dramatically influence the patterns and processes that occur in-stream. For example, clearing riparian vegetation from shaded upland streams may cause a shift in energy dynamics such that a stream system moves from being heterotrophic to autotrophic with concurrent changes in stream fauna.

Box 7: The impact of logging

A recent study in the karri forest of Western Australia compared the aquatic invertebrate fauna of undisturbed streams with streams located within logged coupes[31]. The latter had had their riparian zones removed during clearfell logging activity in 1992. Both the abundance of invertebrates and the number of different types of invertebrates were higher in the undisturbed streams. The composition of the aquatic invertebrate community of the streams within the logged coupes differed markedly from that of the undisturbed streams (Figure 9). Under the current forest management[10], undisturbed zones of riparian vegetation are left alongside streams in order to minimise the impact of clearfell logging practices on these systems.

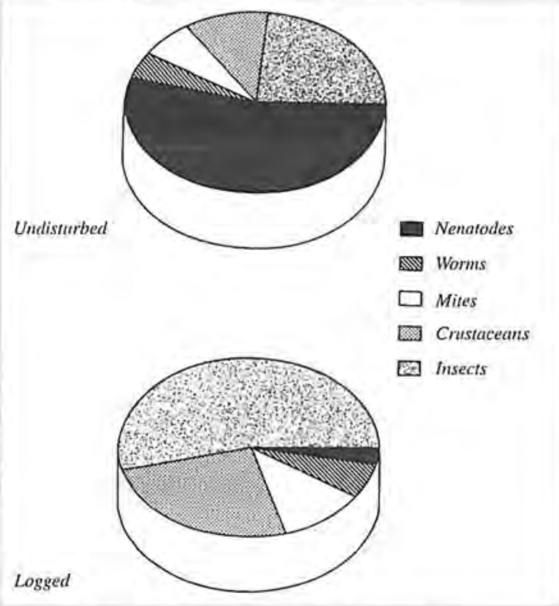

Figure 9: Diagram showing differences in invertebrate composition between streams with fringing vegetation removed and those in undisturbed areas.

Widespread clearing has led directly to the loss of riparian vegetation and subsequent changes to stream ecosystems. There are, however, a number of ways in which riparian vegetation may become degraded and decline gradually. These include trampling and damage through unrestricted vehicular and stock access; prevention of regeneration due to grazing by stock and feral animals; direct competition for light and nutrients by weed species; and increased incidence of wild-fire as a result of a weed-generated increase in fuel loads.

The roots of riparian vegetation provide stability to watercourse banks enabling them to resist the erosive power of the flowing water. When riparian vegetation is lost or becomes seriously degraded, the soil along the banks and bed of the watercourse may become exposed and prone to erosion. This is particularly problematic where widespread clearing in a catchment increases the rate and amount of water run-off. Increased flow may increase erosive power and the potential to undercut the stream bank, particularly at the outside of meander bends. In addition, larger flood flows may saturate the bank, causing it to collapse under the added bulk weight of the water. This is particularly common where the root zone has been undercut. The consequences of erosion are further loss of the riparian zone and increased fine sediment transport in-stream (see section 3.2).

3.2 Stream sedimentation

Although fine sediment is a natural component of rivers and creeks, it can be damaging to the stream ecosystem when it is present in excess. There are a number of mechanisms by which this can occur. These include:

- Altered stream process
- Infilling of natural riverine pools
- Altered in-stream vegetation and flow dynamic
- Altered macroinvertebrate and fish communities

Altered stream process: When large amounts of sediment are suspended in the water column, conditions become turbid and light penetration is reduced. Water plants and algae require light for photosynthesis and if light is reduced their growth rate will decline. This effect may be particularly problematic in mid-order streams where turbidity is generally low and an open canopy permits light to reach the stream-bed. Often, in these areas, autotrophic pathways of energy transfer are dominant. Reduced light and photosynthesis will alter the structure and function of stream communities in these areas and potentially influence the system as a whole.

Excess deposition of sediment may also slow the breakdown of terrestrial leaf litter in streams[6]. When sediment smothers leaves it reduces the availability of oxygen to the leaf surface. As a result the leaves are not available to the oxygen-loving microbes and macroinvertebrates that break leaves into finer particles. This will influence the stream ecosystem since the breakdown of leaf litter is most important basis to the heterotrophic pathway of energy transfer (see section 1.2).

Infilling of natural riverine pools: Riverine pools often comprise areas of deep water and slow baseflow current. It is natural for sediment to settle out in pools and for the sediment to accumulate until large floods scour it out. Large amounts of sediment may be deposited in riverine pools where the upstream catchment and watercourse are highly degraded. In southwest Western Australia, the generally low gradient landscape means that many streams do not have the power to scour out the pools, except in extreme flood events. Since these events are uncommon, sediment may remain in pools for long periods. The infilling and thus loss of riverine pools with sediment has serious consequences for the stream ecosystem.

Loss of riverine pools may cause localised extinctions of aquatic fauna that rely on deep river pools to "over-summer" in our dry Mediterranean climate (see section 2.5). Furthermore, the loss of pools may contribute to the nutrient enrichment of our estuaries and nearshore marine areas. Where pools are able to provide slow flow and stable substrata, they become suitable for growth of benthic algae and submerged water plants. These can strip the water column of nutrients, thereby reducing the nutrient load being transported downstream (see section 1.4).

Box 8: What's happening to the river pools in the Avon?

The Avon River between Beverley and Toodyay once comprised a series of deep permanent river pools separated by braided river reaches. As a result of the combined effect of extensive catchment clearing and the implementation of the River Training Scheme (1958 - 1972), the river has experienced significant sediment relocation resulting in the filling of many of the permanent river pools. Fortunately the major natural pools at Beverley, Gwambygine, York and Katrine / Glen Avon remain substantially intact.

Rehabilitation works are planned for the Avon River pools. This will involve regeneration of natural vegetation, revegetation and excavation of sediment from selected pools. A recent estimate of the amount of sediment removed annually from Burlong Pool was 10000 m^3. The recovery of these pools is dependent upon the collaborative efforts of the community, local government, the local management authority, Aboriginal groups and state agencies.

Altered in-stream vegetation and flow dynamic: Where sediment accumulates in shallow, slow flowing areas of a river, it provides a substrate for the colonisation of semi-aquatic plants. Weeds, which readily colonise new habitats, may prevail in these areas. The colonisation of plants will slow the flow across these areas and cause further sediment to settle out. These areas may become islands within a stream channel causing flow to divert around them and altering the channel shape. The accumulation of sediment may also raise the channel bed and thereby reduce channel capacity to carry high flows.

Altered macroinvertebrate and fish communities: Aquatic macroinvertebrates are particularly vulnerable to deposited sediment as the composition of the streambed is a major factor contributing to their distribution. Typically, streams subjected to increased sedimentation have a less diverse macroinvertebrate fauna. Macroinvertebrates, such as caddisflies, stoneflies and mayflies, which like to inhabit clean gravel beds become less abundant, while worms and midge larvae, which prefer finer sediment, become more abundant.

Excess sediment may also influence the availability of food for fishes. Some fish, such as gobies, feed partially on algae, while others have a diet of macroinvertebrates. Changes to the abundance and distribution of algae and macroinvertebrates as a result of increased sedimentation may indirectly influence fish populations in streams. Fish may also have more difficulty finding their food because of increased turbidity.

Box 9: Response of Aquatic Macroinvertebrate Communities to Dam Construction

A study undertaken in Victoria, examined the aquatic invertebrate community of the Thomson River during the construction of the Thomson Dam[14]. They found that sedimentation resulting from the construction activity depressed the number of species and their abundance. There were also differences in the invertebrate community above and below the dam, with some mayfly and stonefly and beetle larvae being disadvantaged by the increase in sedimentation below the dam. Some species of caddisfly favoured the increase in sediment. The scientists undertaking the study attributed the increase in sedimentation associated with the dam construction to inadequate sediment trapping mechanisms.

3.3 Pollution

Pollutants enter a waterway through a range of land uses across a catchment. Pollution may be point source (its origin is localised) or diffuse (arising from a wide area) and include nutrients, herbicides, pesticides, petroleum products, heavy metals and hydrocarbons, as well as pathogens (arising from sewage) and litter. Many pollutants may be toxic to riverine life or may alter or influence the life cycle of various organisms.

When excessive amounts of nutrients, such as nitrogen and phosphorus enter waterways, they may alter the ecology of these systems. Under conditions of adequate light and temperature, increased nutrient availability may stimulate the growth of phytoplankton, macroalgae and submerged macrophytes. Algal blooms can result in the de-oxygenation of a waterbody and the subsequent loss of other aquatic organisms (see Box 3 & 10). Increased plant biomass may also alter the composition of the fauna by favouring the grazing food chain (see section 1.2), increasing food availability or by providing shelter from predation for some species.

Box 10: Nutrient enrichment and the risk to seagrass meadows

Seagrass meadows in estuaries and near-shore areas provide an important habitat for many aquatic invertebrates and fish species. They are also an important component of the estuarine food web. While mild increases in nutrient concentration will favour the growth of seagrasses, enrichment can lead to their elimination over wide areas[20]. In Albany, during the mid 1980's, large banks of drifting algae eliminated seagrass from many areas of Oyster Harbour, by out-competing the seagrass for light. The seagrass is recovering today. A similar situation occurred in the Peel Inlet, near Mandurah.

The leaves of seagrasses provide stable substrata for attachment of epiphytic [Gk. *epi*, upon; *phyton*, plant] algae and sessile animals. Nutrient enrichment can result in the prolific growth of epiphytes on seagrasses to the point where light availability is growth limiting. Seagrasses in Princess Royal Harbour, Albany, were once threatened by the growth of epiphytic algae responding to nutrient enrichment arising from industrial effluent.

3.4 Salinisation

Widespread clearing of deep-rooted natural vegetation and its replacement with shallow-rooted annual crops and pastures has altered the natural hydrological regime. Shallow rooted crops are unable to make use of and evapotranspire the rainfall that percolates deep into the subsoil. As a result more water enters the deep groundwater and the watertable rises. As this occurs, the groundwater brings with it large amounts of salt that has been accumulated in the soil profile over thousands of years (Figure 10). When the saline groundwater reaches and evaporates at the land surface, the salt is concentrated causing what is known as secondary salinity. Salt enters waterways either via surface runoff or directly through groundwater discharge.

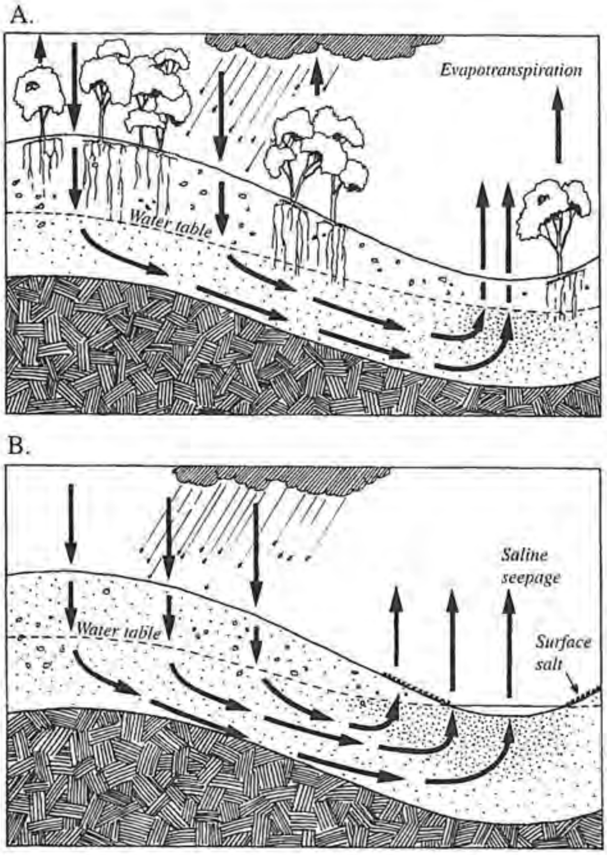

Figure 10: Diagram showing the effect of clearing native vegetation on the water table and saline discharge. A: Before clearing; B: After clearing.

Salinisation is a major threat facing our waterways. Salt intolerant riparian species are being lost and thereby altering stream processes. The loss of riparian integrity, coupled with increased run-off associated with clearing has increased erosion and subsequently sedimentation. Salinity is also a major threat to biodiversity in waterways. Studies indicate that freshwater communities will begin to alter when salinity exceeds 1 ppt[18]. It should be acknowledged that the effects of salinity are variable since many flora and fauna exhibit different tolerances and many wetlands and streams in the south-west are naturally saline. In general, however, microbial and invertebrate communities will show some effect at salinities above 1 ppt and many freshwater macrophytes will disappear at salinities exceeding 4 ppt.

Box 11: What's in our water?

The concentration of the major ions in Australian rivers varies markedly from those of overseas rivers and creeks[13]. Our rivers have higher concentrations of sodium, bicarbonate and chlorine than do overseas rivers where calcium and bicarbonate are dominant ions. Within Australia, the ionic concentration of rivers vary seasonally and with location and flow permanency.

Our understanding of the impact of increased salinity on our rivers systems is still in its infancy. Rising salinity is thought responsible for the disappearance of marron from many rivers in the south-west of the State[24] and also freshwater mussels and cobbler from the Avon River[19]. Studies undertaken on the Hotham[8] and Avon Rivers[26] show that the aquatic invertebrate faunas of these saline systems are numerically dominated by crustacea and have high invertebrate densities but low richness (68 and 100 taxa, respectively). This is in contrast to freshwater systems elsewhere in the State, which are typically dominated by insects and exhibit high richness (110 - 287 taxa)[9,15,28,31]. Crustacea are considered to be the most salt tolerant of all macroinvertebrate groups[18] and it has been postulated that increased salinisation may favour a shift from an insect dominated system to one dominated numerically by crustacea.

3.5 River regulation

Hydrological variability typifies the natural flow regime in many Australian rivers[4]. River regulation, either through water extraction or through impoundment can alter the natural water regime. This regime will differ across different systems and is defined by the timing, frequency, duration, extent, depth and variability of flow. River regulation that does not account for the requirements of natural hydrological variability will generally alter a water regime towards a system with greater stability, whereby it is more continuously inundated or dry. The consequence of changing the natural water regime are many-fold and include alteration of the growth, viability and reproduction of species, modified population and community structure, invasion by exotic species and altered water quality. These changes influence the environmental health of the river system and consequently impinge upon the aesthetic, cultural and economic values of the system[4].

Reduced connectivity between the river and its floodplain may occur as a result of changes to the natural water regime. This will have important consequences for riverine fauna through the loss of important habitat for small crustacea, wading birds, frogs and fish. In addition, the disconnection of the floodplain may impact upon the productivity of large river systems that exchange nutrients and particulate material with the floodplain during flood events. Floodplain vegetation may be stressed and germination reduced where disconnection with the river system occurs over the long-term.

The impoundment of rivers will influence the longitudinal movement of organic material and nutrient spiralling, thereby affecting structure and function of communities along the river continuum. Dams also disrupt the migration of fauna between upstream and downstream areas.

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