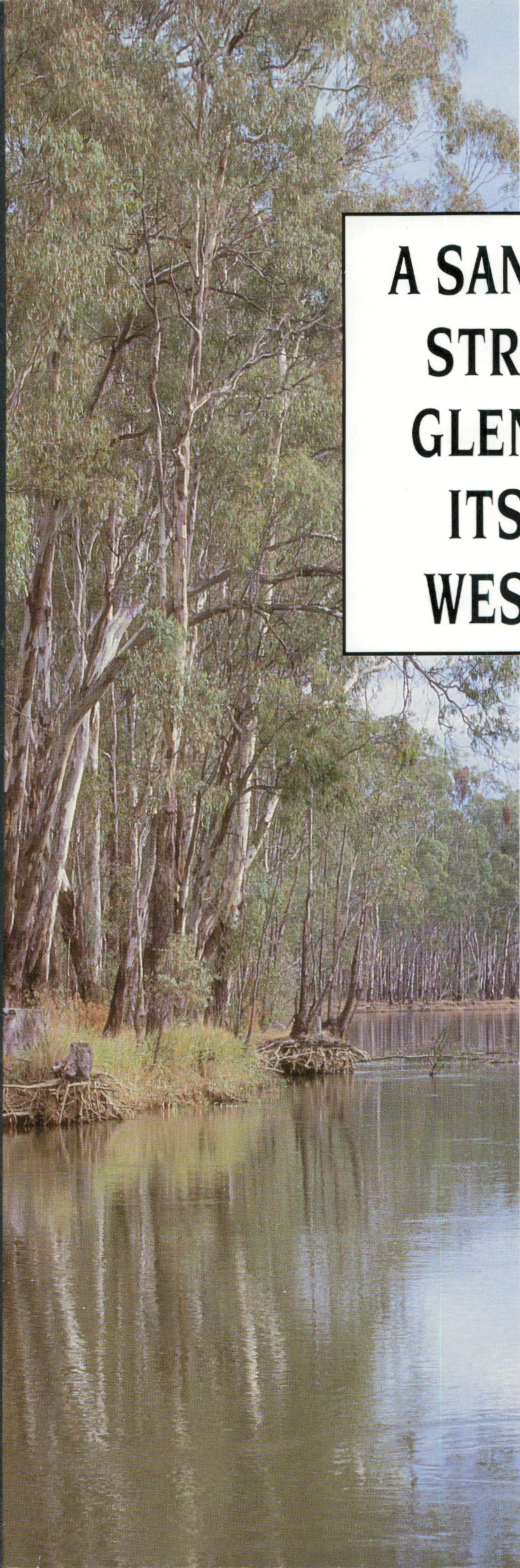

A SAND MANAGEMENT STRATEGY FOR THE GLENELG RIVER AND ITS TRIBUTARIES, WESTERN VICTORIA

A Report to the
Department of Natural Resources
and Environment, Victoria
and
Southern Rural Water

I. D. Rutherfurd
M. Budahazy

Report 96/9
December 1996

COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

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Preface

European settlement of SE Australia has led to a dramatic increase in erosion rates from pastoral lands. Improved land management techniques, combined with the healing of time, has meant that erosion rates have now declined dramatically. However, we are still left with the legacy of that early erosion. In many cases this legacy is streams filled with sterile sand, as we find on the Glenelg River.

The research project described in this report is exciting for two reasons. First, this is the first comprehensive, catchment-wide sand management strategy produced in Australia to our knowledge. The study demonstrates the merits of approaching the problem from this broad perspective. Second, the report attempts to turn the problem of sand into an asset by exploring how managed commercial sand extraction can be used to benefit the stream. It is our hope that the approach described here can be applied in the many other streams that have been degraded by sand slugs.

The goal of the Cooperative Research Centre for Catchment Hydrology is to bring good science to bear on practical problems, in cooperation with the water and land industries. We hope that this report reflects that aim. We thank the many people who have contributed to this study.

Dr Peter Hairsine

Program Leader, Waterways

Cooperative Research Centre for Catchment Hydrology

Synopsis

Sand accumulation in stream channels is the major stream management issue in the Glenelg River catchment. Sheet, rill, and gully erosion of granite portions of the catchment have filled the Glenelg and its tributaries with about six million cubic metres of sand. Little sand is now coming from the catchments, so the major source of sand to the Glenelg and Wannon Rivers is the lower reaches of certain tributary streams. These tributaries introduce discrete slugs of sand into the Glenelg and Wannon Rivers that often dam the main river, and move downstream. As these tributary junction plugs move downstream they attenuate, gradually giving way to a succession of small 'sluglettes'. Sand is moving through the stream network at a slow rate, with only tens of thousands of metres per year being removed by bedload transport. This low transport rate is, in part, because of regulation of the river from Rocklands Reservoir. Artificial sand extraction is the best management option for the sand. Past extraction has removed only a fraction of the sand that is in storage. Extraction from the tributaries should be discouraged, whereas, there are four specific sites on the Glenelg River from which more than 20,000 m^3 of sand could be extracted each year. Extraction of this magnitude would lead to considerable long-term improvement in the condition of the Glenelg River.

Acknowledgments

This project was made possible with the perseverance of John Oates (Department of Natural Resources and Environment) and Kieran Croker (Southern Rural Water). We would like to thank Sally Wace of DNRE Hamilton and the Glenelg Waterways Team (Nicole Davidson, Graeme Jeffery, Cathy Wagg, and Mark Towner) for their bountiful assistance with this project. Special thanks to John Laidlaw of "Runnymeade" for his help and hospitality. Finally we thank the numerous local people and public officers in the Glenelg catchment who allowed us access to their properties and offered invaluable local knowledge. Particular thanks to Russell Mein, John Oates, the Glenelg Waterways Team, and Mark Walker for reviewing the document. Rob Alexander of Civil Engineering drafted many of the line diagrams. Finally, a special thanks to Mark Pearse of Monash Civil Engineering whose tireless efforts are responsible for the excellent maps in this report.

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GLOSSARY OF TERMS

TERM	DEFINITION
Aggradation	A progressive build-up of the channel floor with sediment
Anabranch	A river channel that splits away from its parent channel, but rejoins its parent some distance downstream
Anastomosing	Multiple branching stream channel
Avalanche face	A flat wall of sand over which sand spills.
Backwater	This is the pool of slower water that develops upstream of a flow obstruction eg. a dam.
Base level	The lowest point a stream runs to
Bedforms	Dunes and other shapes moulded in the bed of the river, usually in sand
Bedload	The portion of the sediment load that moves along the floor of the channel (a pretty vague notion in a sand dominated system)
Benches	Flat deposits of sand within a channel
Desnagging	Removing large trees (usually willows and River Red Gum
Dune	A bedform formed in sand in the bed of a stream, usually on the order of tens of centimetres high and long
Floodplain	The surface adjacent to a stream that is regularly flooded
Flow regulation	Changes to the flow brought about by dams or other interference in a river
Incised stream	A stream that has eroded its bed and banks such that it has a very low flood frequency. In other words, the channel is obviously too large for its catchment area.
Junction	The point at which two streams join
migration	Erosion of the bank of a river such that the river progressively moves across or down the valley
Morphology	Shape
Planform	The shape of a stream as seen from the air
Point bar	A sandy deposit on the inside of a meander bend
Prograde	Slowly move into, usually used in the sense of sand gradually moving into a lake or other water body.
Rejuvenation	An increase in erosion following a fall in the base level
Riffle	The high point in the bed of the stream between two pools (it is often covered in gravel or coarser material)
Ripples	Bedforms that are smaller than dunes (usually centimetres in height)
Saline pools	Salt seeps into the deep hole in the stream bed, and settles in the bottom of the hole. Salinities in such deep holes in the Glenelg River can be almost as salty as sea water.
Sand Slug	A wave of sand that moves down a stream channel
Scour chains	
Sheet erosion	Erosion of the surface of a paddock or other portion of the catchment as a thin layer of soil
Sluglettes	Small slugs of sand that are deposited in certain reaches of the Glenelg River. The sluglette usually occupies a riffle area above a pool
Thalweg	Deepest point of a channel
Tributary	A smaller stream
Trunk stream	The largest stream in a catchment

i. SUMMARY

i.i Aims

Before European settlement, the upper Glenelg River and its tributaries were characterised by pools separated by densely vegetated reaches. Below Harrow the vegetated reaches of the Glenelg were less common, but there were still deep pools. Since the 1850s, gullying and sheet erosion of granite portions of the catchment have filled long reaches of the Glenelg and its tributaries with sand. The sand has destroyed the biological and aesthetic potential of much of the stream network. The sand is moving through the stream network in a complicated pattern, but it will take many decades for the sand to be stabilised and removed. This report aims to:

I. describe the volume of sand stored in channels in the Glenelg catchment;

II. describe the movement of sand through the catchment;

III. predict future movement of sand;

IV. consider various management options for the sand; and

V. develop a sand extraction strategy for the catchment by defining extraction zones.

i.ii Distribution and Volumes of sand in storage

There are between 4 million and 8 million cubic metres of sand stored in the major sand stores of the Glenelg River and its tributaries (ranging in the Glenelg from about 50,000 m^3/km of channel at Harrow, to an average of about 10-20,000 m^3/km elsewhere). The sand occupies a larger proportion of the cross-section in the tributaries (up to 80%) than in the Glenelg. Capacity loss in the Glenelg falls from about 60% between Harrow and Burkes Bridge, to 20% at Casterton, and 10% at Dartmoor.

The major slugs of sand were deposited in the lower reaches of streams very quickly, particularly during the 1946 flood. The original deep pools in the Glenelg River, combined with regulation from Rocklands Reservoir, have limited the movement of sand through the trunk stream. As a result, sand in the Glenelg River is stored in discrete slugs originating from several tributary streams: Mathers Ck, Deep Ck, Pigeon Ponds Ck, Chetwynd River, and the Wando River. The Wannon River similarly receives slugs of sand from Bryan, Henty and Dwyers Creeks. The backwater formed behind these tributary junction plugs (TJPs), in turn, limits the movement of sand down the Glenelg and Wannon Rivers. In long reaches of stream, where there are no TJPs (eg. below Burkes Bridge and below the Glenelg-Wannon junction), the sand has attenuated into discrete slugs of 200 m - 500 m in length. The lower-most of these slugs is now 28 km above the Heritage River reach, and progressing downstream at a maximum rate of about 1000 m per year.

Thus, we have identified four major types of sand storage in the stream system:

i. tributary bed deposits (about one third of the total volume);

ii. major slugs of sand in the Glenelg and Wannon Rivers originating from the tributaries (called tributary junction plugs - TJPs) (one third of total volume);

iii. prograding sand deposits into natural pools and lakes dammed behind TJPs, and;

iv. 'chains' of discrete slugs that develop in long reaches of the Glenelg River between TJPs (about 15% of volume).

In addition to the sand stored in the channel bed, an estimated 3 million m^3 of sand has been deposited on the floodplain of the Glenelg and its tributaries. This serves to raise the bank level by 0.5 to 1.5 metres.

i.iii Future sources of sand

Catchment and gully erosion released waves of sand that are moving through the tributaries of the Glenelg River. There is no doubt that the major period of catchment and gully erosion has passed in the Glenelg catchment, and that soil conservation activities have contributed to the reduced erosion rate. However, there is, as yet, no strong evidence that the active stores of sand in the lower reaches of streams are now responding to that catchment treatment by eroding (ie. that the peak of the wave of sand has passed). Local degradation of the lower reaches of some streams is explained by local activities (sand extraction and channelisation), and the lower reaches of streams appear now to be either aggrading or stable. In other words, the sand waves in the lower tributaries are still on their rising limb, or close to their peaks. Nevertheless, the major store of sand in catchments is now located in the lower few kilometres of tributary streams, and there are no large reserves of sand moving through stream networks toward the Glenelg River (with the possible exception perhaps of the Chetwynd River). Invasion of many stream beds by reeds suggests an overall decline in the rate of sand transport

Furthermore, only about two thirds of the sand in the streams will be available for downstream transport. About one third will be more permanently stored in benches, pointbars, and on the floodplain. Importantly, in smaller tributaries, large volumes of sand are stored in deep areas of the bed that have been abandoned by widening of the channel. In Bryans Creek and Pigeon Ponds Creek, this bed storage has removed up to half of the total volume of sand available for transport. This important type of sand storage has not been recognised before.

i.iv Impacts of sand

The movement of sand into the Glenelg River and its tributaries has had a devastating biological impact. The effect on flood frequency is less clear. Rainfall-runoff modelling for this project suggests that filling half of the channel cross-section with sand will have minimal impact on the size of flood peaks or their time-to-peak because of the decreased roughness associated with the sand sheets. In addition, deposition on the floodplain has meant that, in many reaches, the rise in bed elevation has been matched by an increase in bank height.

i.v Movement of the sand

The available evidence suggests that the present distribution of sand in the Glenelg catchment (ie. the pattern of TJPs and sand slugs) was in place by the 1940s, and changed very little over the next half-century. Discrete sand slugs below the Wannon Junction have remained in the same position since 1947. Contrary to earlier estimates of huge bedload transport rates in the Glenelg River (100s of thousands of tonnes per year), several lines of evidence suggest that bedload transport rates are in the order of 10 - 30,000 m^3 per year. The major tributaries transport less than 5000 m^3 each. Thus the great bulk of the sand in the Glenelg River has been in storage for half a century, with new sand simply moving across the top of the bed. At this rate of transport it will take centuries to evacuate the sand from the stream system, even if much of the sand is stored in benches.

There are some reaches, however, that have experienced major changes in the volume of sand in storage over the last twenty years. These reaches are associated with simple sand slug migration (eg. aggradation of the lower Chetwynd River), channelisation and desnagging works (eg. the Wando River and Wando Vale Ponds), and sand extraction (eg. Pigeon Ponds and Bryans Creeks).

Below the major sources of sand (eg. the Chetwynd and Wannon Rivers) the continuous slugs of sand break-up into discontinuous slugs that occupy riffles (called here: sluglettes). Sluglettes remain in the same position on riffles between pools in a bend, but new sluglettes are progressively deposited downstream by the 'velocity reversal' mechanism. Since the late 1940s sluglettes of sand have migrated about 30km below Killara Bridge (about 800m per year). Extrapolating past rates of sediment movement, we estimate that the first sluglettes of sand will reach the Heritage River in 30 to 40 years.

As sediment supply from the catchment declines the various types of sediment store will erode in the following way.

A major flood could move large volumes of sand. This certainly occurred in the 1946 flood when large volumes of sand were deposited in the Glenelg River and on its floodplain. However, the Rocklands Reservoir has dramatically reduced the frequency of large floods, and so the rate of sand transport.

i.vi Management Options

There are three major management options for artificially managing sand in the Glenelg River: flow regulation through Rocklands, channelisation, and artificial extraction of sand (including sand interception weirs). It may be possible to alter the flow regime out of Rocklands to influence the movement of sand through the network eg. to flush more sand through some reaches. However, with the existing diversion of flow from Rocklands Reservoir, and the limited capacity to release flow from the dam, flow regulation is not an important management option. The proposed environmental flow allocation to the Glenelg River will have minimal impact on sand transport. Stream desnagging carried out in the past may have increased sand transport slightly, but it does not provide a useful management option today.

Direct sand extraction is the most important management option.

i.vii Volumes of sand already extracted

Official records suggest that about 500,000 cubic metres of sand has been removed from the Glenelg catchment since the 1960s. Nearly ninety percent of this volume has been taken from Bryans Creek, and most of the rest from Pigeon Ponds Creek, and from the Glenelg immediately above Casterton. Thus, extractors have removed about 5% of the total sand available in the Glenelg system, but possibly up to 10% of the 'active storage' (ie. the sand that will not enter long term storage). Leaving aside the Bryans Ck figures, extractors have removed less than 2% of the estimated volume of sand in storage which is well within the margins of error of the volume estimates, and probably close to the estimated annual sand transport rate. Sand extraction rates are going to have to increase dramatically if they are to affect the volume of sand stored in the Glenelg system.

i.viii Consequences of extraction

Sand extraction has consequences for bed and bank erosion.

Extraction of sand slugs, at any extraction rate, is unlikely of itself to trigger erosion below the depth of the sand slug. Erosion at the upstream end of sand slugs (eg. in Bryans Creek) is probably explained by the removal of the sand slug itself. Sand slugs buffer channel morphology from hydrological changes in the catchment. Hydrology has changed because of catchment clearing, and because gully development has increased the efficiency of the drainage network. When the sand slug is removed the old channel is exposed to the changed hydrological conditions of the catchment, and adjusts to the flashier flow regime by incising. This incision will also lead to incision of tributaries, particularly if those tributaries are graded to the elevation of the sand surface (as many are in Bryans and other creeks).

An important consequence of sand extraction can be bank erosion. Sand has typically filled one third to a half of the depth of channels in the Glenelg catchment. This sand supports the stream banks, reducing the incidence of bank slumps. Large extraction operations would drop the sand surface rapidly (over 1m in a decade in Pigeon Ponds and upper Bryans Creeks) and this can lead to slumping. By contrast, the slow natural fall in sand levels as a sand-slug passes, allows banks to vegetate and batter-back to a stable slope. The effect of sand extraction on bank erosion is greater in the smaller tributaries than in the Glenelg and Wannon Rivers.

i.ix The sand management strategy

There are three general types of deposit from which sand can be extracted in the Glenelg catchment. Extraction from each of these locations has specific consequences.

I. Extraction from major slugs in the Glenelg and Wannon Rivers (eg. at Casterton). These sites have continuous sheets of sand in the bed so extraction will lead to deepening above and below the extraction site. There will be limited bed and bank erosion following extraction because of the size of the channel and the volume of sand available. The major management issue is the supply of sand to downstream reaches, particularly reaches in which there are still ponds, and upstream progressing erosion that would remove a TJP and drain a wetland.

II. Extraction from the 'chains of slugs' reaches (eg. between Dergholm and the Wando Junction, or below the Wannon Junction). Extraction from these reaches will produce only local erosion of sand because the 'sluglettes' of sand are separated by deep pools. That is, there is not a continuous hydraulic connection between the extraction site and a large slug of sand.

III. Extraction from the lower ends of tributaries (eg. Pigeon Ponds Ck.). There are three issues with extraction in these sites. (a) A rapid fall of sand levels can trigger bank erosion. This problem is reduced by the widening of the channels. (b) Removing the sand exposes the channel bed and banks to erosion. (c) Extraction will lead to erosion of the TJPs and eventual draining of the upstream wetlands.

Thus the major negative impacts of sand extraction could be (a) to bring forward bed erosion, (b) to increase bank erosion, and (c) to accelerate the removal of wetlands behind TJPs. In summary, the sand extraction policy recommends the following:

i. Sand extraction from tributary streams should be a low priority, with the extraction rate restricted to the annual bedload transport rate (< about 3,000 m^3 per year).

ii. The priority extraction sites are from the Glenelg River itself.

iii. Extraction should take place at the downstream or central portion of a slug rather than at its upstream end.

iv. There are four priority extraction zones in the Glenelg River, and the annual extraction rate from each could exceed 20,000 m^3 per year and still be beneficial. There would not be any interaction between these extraction sites. The four sites are: the Glenelg River between Wando Junction and the Wannon River Junction (volume of stored sediment 400,000 m^3), in the vicinity of Myaring Bridge (300,000 m^3), Glenelg River at Harrow (up to 1,000,000 m^3), and at Burkes Bridge (200,000 m^3). Extraction at these sites would protect remaining deep pools, protect the Heritage River reach, and improve the biological and environmental values of the river at Casterton.

v. Sand extraction should be considered a major management tool in rehabilitating the Glenelg River. Government could consider enhancing this management role by taking the management benefits of sand extraction into account when negotiating royalty charges for extracted sand.

1. INTRODUCTION

The catchment of the Glenelg River has long had a reputation as one of the most severely eroded catchments in Victoria (Mitchell, 1990). Erosion of the catchment has occurred as rotational land-slumps, and as extensive gully networks. The land-slumps have not introduced much sediment into the stream network, but gullies have. As a result the bed of the Glenelg River and many of its tributaries have filled with sand. As we discuss below, some reaches of stream have lost over 80% of their former channel capacity.

Mitchell (1990) concluded that:

"The main problem affecting the environmental condition of rivers in the Glenelg Basin appears to be erosion of tributary streams causing sediment input to the Glenelg River and to the Wannon River below Bryans Creek."

It is worth noting that the main management issue is the transport and deposition of sand rather than of suspended sediment.

Similarly, the Glenelg Catchment Waterway Management Study (Ian Drummond and Associates, Erskine et al., 1992) (henceforth GCWMS) identified that siltation problems in the Glenelg and Wannon Rivers are directly related to gully and instream erosion processes in the tributary streams, as opposed to erosion in the main stream. In the Glenelg River the main sources of sand are Pigeon Ponds Creek, Chetwynd and Wando Rivers and the Wannon River. Sources of sand in the Wannon River are Bryans Creek (and its tributary the Koonong Wootong Creek) and Dwyers Creek (and its tributaries Henty and Miakite Creeks). Historical evidence indicates that sediment inputs are declining and that reworking of the sediment sinks in the major streams will commence.

Aggradation of the bed of the Glenelg River has been catastrophic for in-stream biological values, with the majority of the river's length now classified as being in 'poor' environmental condition (Mitchell, 1990) Of particular importance is the 65 km reach of the lower Glenelg that has been declared a Heritage River under the Heritage Rivers Act of 1992. This is the highest conservation status available for a Victorian River and implies that the river reach will be preserved from human impact. The integrity of this reach of river could be threatened by the large volumes of sand that are now moving down the river.

In order to avoid future catchment and waterway degradation the GCWMS proposed that in the short term:

i. well managed and monitored sand extraction should be initiated;

ii. gully erosion works should be constructed; and

iii. grade control structures should be constructed to prevent reworking of sediment sinks.

In the longer term:

i. waterways should be revegetated; and

ii. land management techniques should be improved.

Sand extraction for the building industry is potentially the most useful management tool in the Glenelg catchment. Western Victoria is dominated by basalt geology that does not produce sand, and coastal systems are dominated by carbonate sand that is not appropriate for building. Thus, the Glenelg River provides an ideal source of quartz sand for the building industry in Western Victoria. The Glenelg River presently provides sand to the towns of Portland, Hamilton, Casterton, Horsham and Mt Gambier (in SA). Through well managed sand extraction, there is the opportunity to not only improve the biological values of the Glenelg River and protect the Heritage River reach, but also to provide a scarce economic resource for the region.

Although the GCWMS highlighted the importance of using sand extraction as a tool in reducing future sedimentation problems, no information was given about volumes of sand stored in the channel, or guidelines for the volumes and locations that could be extracted. Neither did the study elaborate on the detailed local effects of extraction. Such information is essential for the development of a catchment wide sand extraction policy.

The key issues in managing sand in the Glenelg catchment are seen to be:

i. Identifying sources of sediments within the Glenelg Basin.

ii. Identifying the volumes of sediment stored throughout the catchment.

iii. Preventing the movement of a major slug into the Lower Glenelg River (classified as a Heritage River).

iv. Predicting the movement of sand and erosion throughout the catchment if there is no extraction (ie. a no intervention scenario).

v. Identifying the environmental problems associated with sand extraction in the Glenelg, and developing a management strategy that identifies where sand should be extracted from.

1.1 Aims of the report

The specific aims of this report are to:

i. describe the sand resources in the catchment

ii. describe the movement of sand through the catchment

iii. predict future movement of sand

iv. predict the effects of sand extraction

v. develop a sand extraction strategy for the catchment (how much sand should be removed, when, where, and how).

It should be stressed that this is the first whole-of-catchment sand management strategy to be developed in Victoria. It should also be stressed that this report is written primarily from the perspective of benefits to the riverine environment from sand extraction. It is not our brief to examine the economic viability of the sand extraction plan that is presented.

2. THE GLENELG CATCHMENT

The physiography of the Glenelg River basin has been described in detail by (Gibbons and Downes, 1964), and GCWMS (section C, by W.D. Erskine) and will not be repeated here, apart from the following general points.

The Glenelg River Basin is a 12,700 km^2 catchment in Victoria's south west (Figure 2.1). The topography of the catchment is quite varied taking in the rugged Grampians ranges, the Dundas and Merino tablelands, basalt plains around Hamilton, and the coastal plains and an estuarine lagoon at the mouth of the Glenelg River. The catchment contains some 2,400 km of streams which were classified by Mitchell (1990) on the basis of contributing catchment area as: 22% major streams, 14% tributaries and 64% minor streams. The mean annual flow of the basin is approximately 725 GL, which is approximately 3.3% of Victoria's total discharge.(Department of Water Resources Victoria, 1989)

2.1 General description of the natural morphology of the Glenelg River

This report is concerned with the 180 river kilometres of the Glenelg River between Rocklands Reservoir (above Balmoral) to the head of the estuary at Dartmoor. The river can be divided into four sections: Rocklands to Fulhams Bridge (30 km), to Killara Bridge (120 km), to Dartmoor (30 km), and then the estuarine Heritage River reach to the sea (65 km).

The Glenelg River, particularly between Rocklands Reservoir and Fulhams Bridge, is characterised by alternating anastomosing reaches separated by deep pools (Erskine, 1994). Anastomosing rivers have multiple branching channels separated by a floodplain. The pools separating the anabranching reaches are as much as three kilometres long and nine metres deep (McGuckin, Anderson et al., 1991). This morphology of multiple

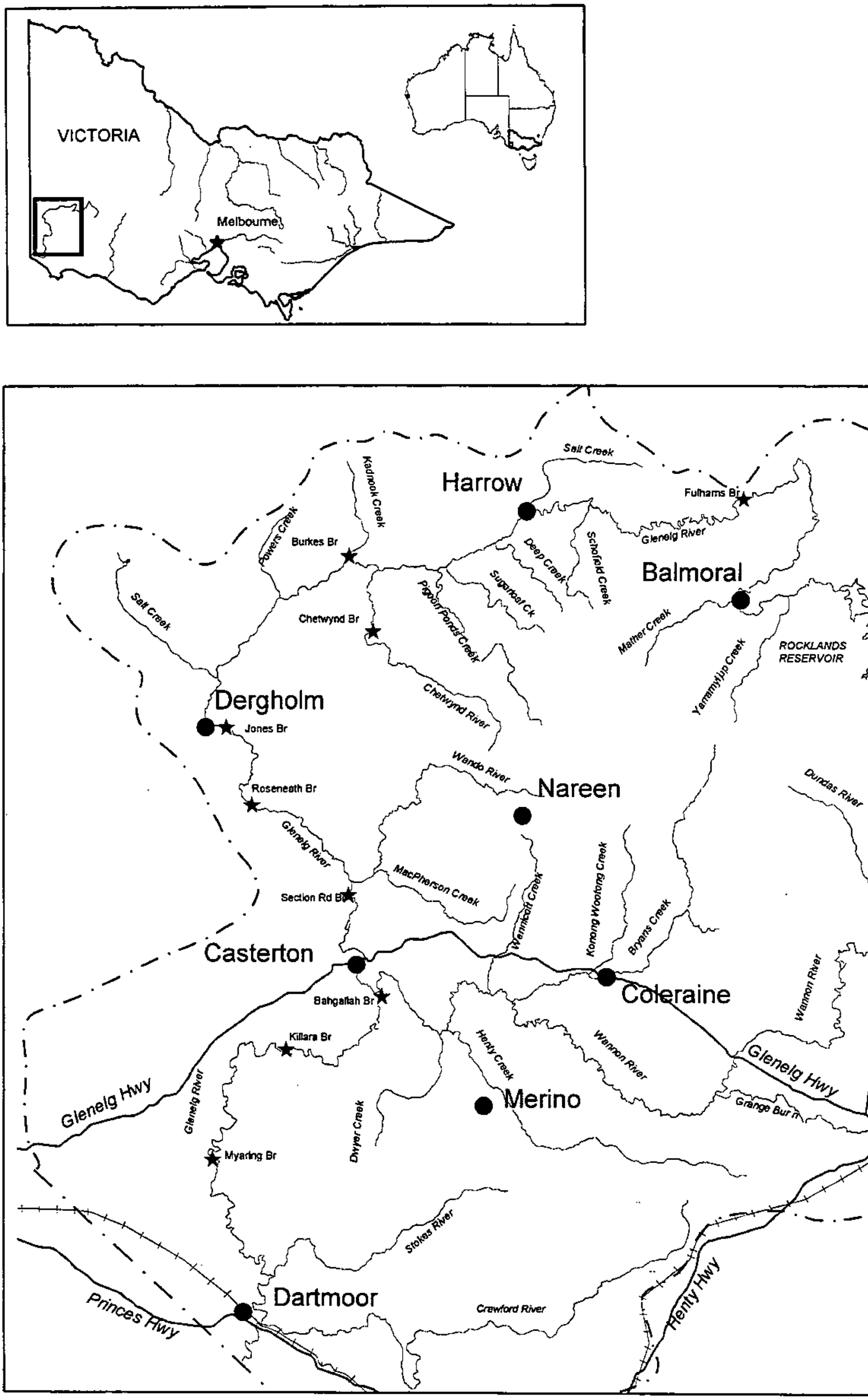


Figure 2.1 Location of the study catchment.

channels connected by deep pools is similar to the channel forms described from the arid Cooper Ck in the Lake Eyre Basin (Knighton and Nanson, 1994)). However, it is unique to find such a well developed example of this type of morphology in a humid stream system. There is no doubt that the morphology of the Glenelg River is unusual and important.

Below Fulhams Bridge the river ceases to anabranch and begins to meander, and the floodplain begins to widen as the river turns westward and follows the edge of the Dundas Tablelands. Under natural conditions the river still had unusually deep pools (up to 6m) for its whole length. Many five metre deep pools still remain along the Glenelg River.

In 1836, Major Mitchell crossed the Glenelg River somewhere downstream of Harrow and stated that: "the banks of this stream were thickly hung with bushes of the Mimosa ... the river was everywhere deep and full, on an average 120 feet (36m) wide and 12 feet (3.6m) deep". The river was deep enough for Mitchell to lose a bullock when crossing. On the 12th of August the party took to their boat in deep water, but within two miles the river divided into several channels that were overgrown with bushes. This description suggests that anastomosing reaches of channel existed below the present location of Fulhams Bridge.

The major tributaries of the river join from the left bank, flowing from the Dundas Tablelands. Along the westerly portion of its course these tributaries include Pigeon Ponds Creek and the Chetwynd River. Below the Chetwynd junction the Glenelg turns to the south, the floodplain narrows and the river takes a confined course. Again the major tributaries join from the left bank, the Wando River and its last major tributary, the Wannon River. At Killara Bridge the floodplain narrows again and the channel becomes confined within high banks until Dartmoor. Here the river is tidal, and has cut a gorge into limestone for the last 60 km before it reaches the sea at Nelson. The river below Dartmoor is part of the Nelson National Park and is the 'Heritage River' portion.

The anastomosing character of the Glenelg River was a morphology shared by its tributaries. There is strong evidence that most of the larger tributaries to the Glenelg River were originally 'chains-of-ponds'. That is, the streams were characterised by deep holes separated by densely vegetated zones. This morphology is typical of medium sized tributaries in SE Australia (Eyles, 1977). Thus, Pigeon Ponds Creek was originally named 'Pigeon Ponds' by Major Mitchell, and we also have Wando Vale Ponds. Erskine (1994) found considerable evidence that both the Wando River and Bryans Creek were chains-of-ponds. Finally, Wade's 1852 map of the Glenelg River labels many streamlines as being 'ponds', 'chains-of-ponds', or 'permanent ponds'.

An important characteristic of chains-of-ponds around SE Australia, is that almost all of them have been affected by catastrophic deepening and widening (Eyles, 1977; Bird, 1982; Bird, 1985). The trigger to erosion is usually related to disturbance of the channel floor, such as drains or cattle tracks. The streams of the Glenelg catchment are no exception to this pattern and have almost all been widened and deepened by erosion. By contrast, there is little evidence that the Glenelg River itself has suffered from much erosion of bed and banks. The erosion of the tributaries to the Glenelg is important for much of the following discussion.

2.2 Impacts on the Glenelg River since European settlement

The five most obvious human impacts on the Glenelg River and its tributaries since European settlement, have been: clearing of riparian vegetation, incision and erosion of tributary streams, sand aggradation, regulation of the river by Rocklands Reservoir, and desnagging of the Glenelg and Wannon Rivers. Most of the riparian frontage to the Glenelg River was cleared last century. However, good riparian Eucalypt forest still remains in some sections, particularly downstream of the Wannon Junction. Clearing of vegetation along tributaries last century, combined with stock trampling, probably led to the incision of many of the 'chains-of-ponds'. It was into these eroding channels that much of the sand from gully and catchment erosion has gone.

The other major impact on the river has been the operation of the Rocklands Reservoir. The reservoir was completed in 1953. With three times the average annual flow of the river, the dam can substantially influence both average flows and flood flows. We will discuss the impact of flow regulation in detail below. To summarise its impact, Rocklands diverts two thirds of the Glenelg's mean annual flow to the Wimmera-Avon Basin, for the Wimmera-Mallee Stock and Domestic system. Flow in the Glenelg is maintained at around 25Ml/d at Harrow. The frequency of floods has also been greatly reduced (Section 7.9).

Following the recommendations of a Parliamentary Public Works Committee (1957), a River Improvement Trust was constituted on the middle reaches of the Glenelg. The major task for the Trust was the removal of obstructions (snags) from the river so as to accelerate the downstream movement of sand and so reduce the severity of flooding. Surprisingly, the Public Works Committee did not consider the dramatic impact that Rocklands Reservoir would have upon flooding - far more than the small impact of desnagging. Nevertheless, in 1961 and 1962 the Trust carried-out a desnagging program along the Glenelg in the vicinity of Casterton, and in the lower Wannon. Further desnagging was carried-out by the Shire of Dundas in the Wannon River through the Murndal Estate in 1977-79 (GCWMS, 1992).

2.3 Sand sources and sinks

The GCWMS drew the following conclusions about sand contributions to the Glenelg River:

i. Catchment erosion and gullying was reported in the Glenelg catchment as early as 1853 in the much quoted 'Robertson' letter.

ii. Larger channels (such as Pigeon Ponds Creek , Bryans Creek, and Wando Vale Ponds) were transformed from chains-of-ponds to incising streams.

iii. Several early references note that by the 1930s, sand choked the lower reaches of Mather Creek, Pigeon Ponds Creek, Chetwynd River, and tributaries to the Wannon River (McIlroy, Brake et al., 1938; Strom, 1947; Blackburn and Leslie, 1949). Similarly, the bed of the Glenelg, as well as its floodplain, was partially infilled with sand.

iv. The major source of sand to the Glenelg River has been from gullying in the Dundas Tablelands, particularly from the Casterton and Dundas Land Systems (Gibbons and Downes, 1964).

v. Since the 1960s tributary catchments have been treated by the Soil Conservation Authority, and more recently by DNRE, and Landcare groups. As a result, the supply of sand to the upstream end of the tributaries has declined and the sand stored in the channels is now being eroded (Erskine 1994).

Our investigations in the catchment generally support all but the last of these conclusions, but the following report adds the detail required for the development of a management plan.

3. DISTRIBUTION OF SAND STORED IN THE GLENELG CATCHMENT

This section considers the sources of sand to the Glenelg River, and the distribution of that sand in stream channels. To assist with this work two surveys were made of the Glenelg River. One survey extends from one kilometre above Pigeon Ponds Creek for 23 km downstream, past the Chetwynd River confluence. The second survey covers the 10 km of river above Dartmoor at the downstream end of the study reach. In both reaches, cross-sections were surveyed every kilometre, bed samples were taken for grain size analysis, and the depth of sand in the bed was probed with a steel probe (that could be extended to five metres). In addition, many other cross-sections were roughly surveyed and probed across the catchment as part of the scour chain experiment, and as part of our general field inspections.

Erosion in the channel of the Glenelg River itself is not severe and could account for a maximum of 10% of the total sand stored in the bed (discussed below). Sand in the Glenelg River comes almost exclusively from gully and sheet erosion in tributaries draining the Ordovician granodiorite portions of the catchment (Gibbons and Downs, 1964). Granite catchments are unusual in having very efficient transmission of sand from the catchment to the trunk stream (Rutherfurd, 1996). Although other tributaries are eroded by gullies (eg. on the sedimentary lithologies) most of this sediment is stored in the catchment and does not reach the lower reaches of the tributaries. Thus, where a tributary drains granite areas, the downstream end of the stream has typically filled with sand.

Accelerated erosion of the Dundas Tablelands had begun by the 1850s (Mitchell, 1978), and there is a record of sand filling Schofield Creek, a right bank tributary above Harrow, as early as the 1870s. Aerial photographs from 1947 (*Adastra* aerial photographs, scale: 1:15,840) show that the sand had already filled the lower end of tributaries by that time. The distribution of sand shown in the 1946 photographs is little different from the pattern that we see today. Much of the sand possibly moved during the 1946 flood. The 1947 aerial photographs show many fresh sand-splays across the floodplain, suggesting that large volumes of sand were being transported in this flood. This also corresponds with recollections of many farmers along the river that this flood moved large volumes of sand.

Mr John Laidlaw of "Runnymeade" recollects that the first major movement of sand below the Wannon Junction occurred in the 1946 flood.

Strom (1947) described siltation in the Chetwynd River, Pigeon Ponds Ck, Wando Vale Ponds, and in the Wannon and Glenelg Rivers. He shows photographs of the delta of sand at the junction of Pigeon Ponds Creek and the Glenelg that differs little from the modern view (GCWMS, 1992). Similarly, a report by Scott and Furphy (1952) for the proposed Glenelg River Improvement District, described 'evidence of considerable siltation in the last fifty years' (p.4). Thus, the general distribution of sand that we see today in the Glenelg River and its tributaries was in place by the 1950s.

3.1 Controls on sand distribution

The distribution of sand in the Glenelg River is controlled by the sand supply from each tributary, the distance between tributary junctions, and the size of pools along the river. Where there is a large sand supply from a tributary there will be a large slug of sand extending below the tributary for tens of kilometres (Figure 3.1). Figure 3.2 shows the depth of sand in the Glenelg River for 35 river kilometres below Harrow Bridge. This plot shows that the depth of sand increases immediately below a junction with a tributary draining a granite catchment (Deep Ck, Pigeon Ponds Creek, Chetwynd River). The depth of sand increases to four to five metres, and gradually decreases to less than one metre within five to ten kilometres of the junction. Other similar slugs of sand are found in the Glenelg River below its junction with Yarramyljup Ck, Mather Ck, and the Wando River; as well as below the junction of Bryans Creek with the Wannon River. The largest of these slugs is that below the Wando River, which is an average of 2m deep and extends 20km down the Glenelg River to the Wannon Junction. Many smaller tributaries have formed a small fan of sand at the junction with the Glenelg or Wannon Rivers, but they have not produced discrete slugs. It is important to emphasise that these smaller tributaries are major sources of sand. For example, the largest single store of sand in the river occurs above Harrow, and this sand comes entirely from the many small left bank tributaries upstream of Harrow, of which Schofield Creek is the largest.

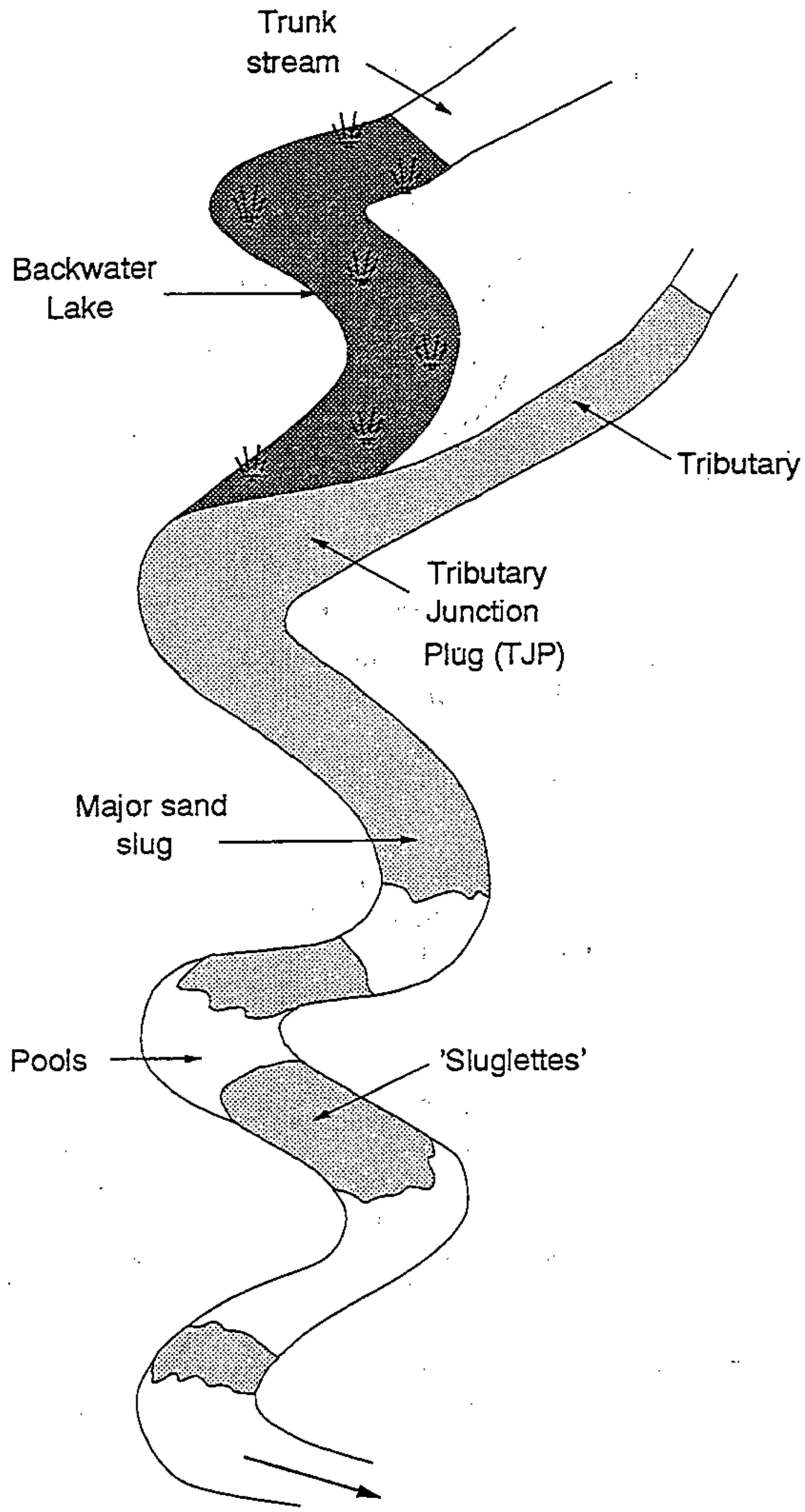


Figure 3.1: Schematic picture of the movement of sand from a tributary into the Glenelg River

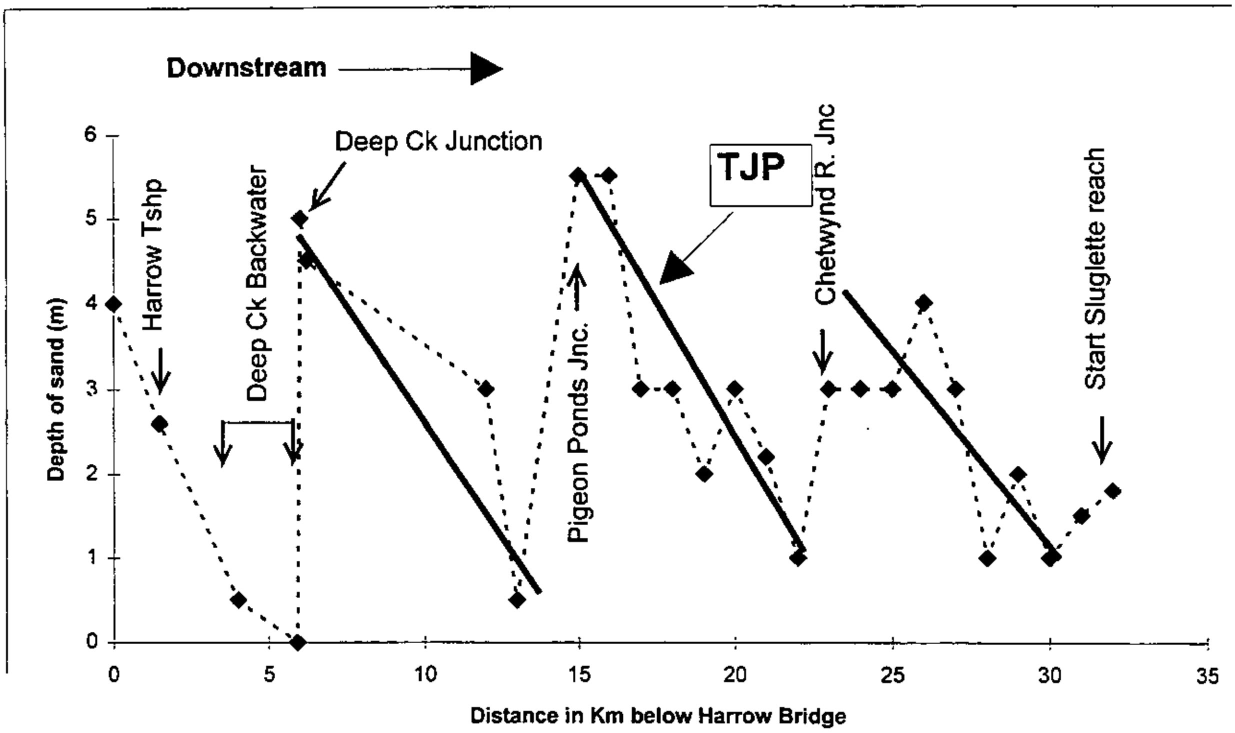


Figure 3.2: Maximum depth of sand in the Glenelg River for 33 km below Harrow Bridge (heavy lines are the tributary junction plugs)

Most of the sand slugs from the larger creeks have blocked the Glenelg River, producing backwater pools up to five kilometres in length (Figure 3.2). Because this sand has blocked the river we call these 'tributary junction plugs' (TJPs). TJPs have existed at the junction of the Glenelg with the following creeks since at least the 1940s: Yarramyljup Ck, Mathers Ck, Deep Ck, Pigeon Ponds Ck, and the Chetwynd River (Figures 3.2, 3.3). The backwater behind the Deep Creek TJP forms a lake and swamp that stretches for five kilometres upstream to Harrow. The Wannon River forms a similar lake three kilometres long above the Bryans Creek TJP.

Where tributary junctions are close together on the Glenelg River, such as the junctions of Pigeon Ponds Creek and the Chetwynd River, which are seven kilometres apart, the slugs have almost coalesced. Where junctions are far apart (eg. it is 64 km between the Chetwynd and Wando Rivers), the depth of sand declines and the sand slug gradually attenuates into smaller discrete 'chains-of-slugs' of 200m - 500m in length, separated by about the same distance of open channel where there is little sand. We have called these smaller slugs 'sluglettes'. Sluglettes have an amplitude of about 1.5 m, and the snouts of the slugs can be a well defined avalanche face, or an ill-defined zone. Sluglettes also appear below the junction of the Glenelg and the Wannon Rivers, and in the lower reaches of the Wannon River. The process by which these slugs develop is described in Section 3.3 below.

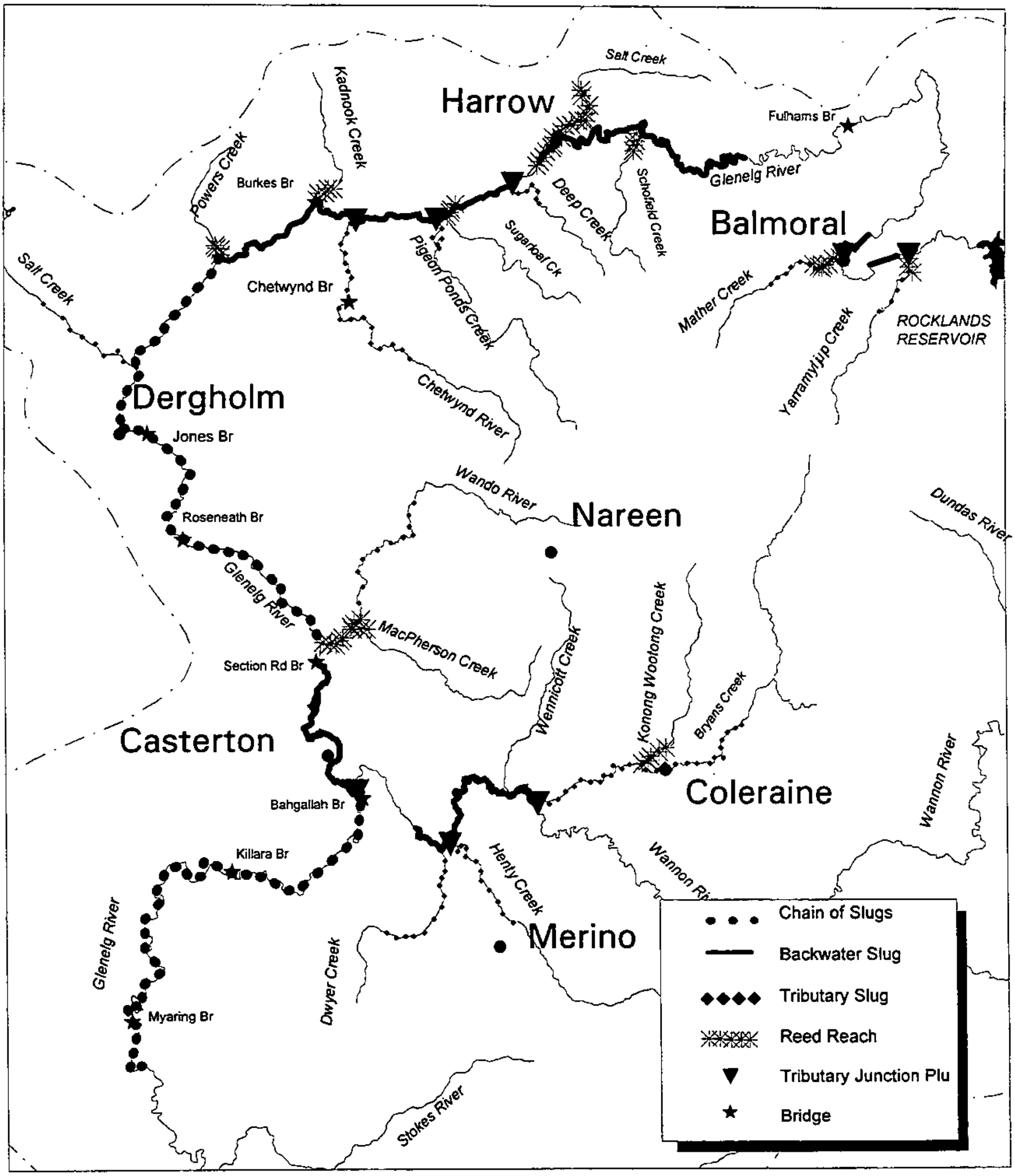


Figure 3.3. Controls on the distribution of sand in streams of the Glenelg catchment.

(See removable colour copy of this figure at the end of the report)

Movement of sand down the Glenelg River is limited by pools. We can divide the pools into two scales: pools that are large enough not to be drowned-out by flood flows, and pools that are drowned-out. The larger pools trap sand in the same way that sand is trapped in a lake or reservoir: as a prograding wedge of sand. As described above, the reach between Rocklands Reservoir and Fulham Bridge is characterised by pools that are up to nine metres deep and four kilometres long, and these large pools are not drowned-out by floods. The sand leaving Yarramyljup (Frenchmans) Creek and Mather Creek is entirely trapped in these large pools, and so does not move any further downstream. Similarly, the backwaters above the TJPs that dam the Glenelg River represent a constraint on the movement of sand. The most prominent of these is the wedge of sand deposited at Harrow into the backwater pool behind the Deep Creek TJP. Smaller pools represent temporary impediments to the migration of sand, and these will be discussed in more detail below.

Therefore, we can identify four distinct styles of sand deposition in the Glenelg Catchment.

i. Tributary bed deposits (stores of sand in the lower ends of tributary streams that drain granite catchments)

ii. Tributary junction plugs (slugs of sand deposited in the Glenelg and Wannon Rivers by tributaries)

iii. Deposits prograding into large natural pools, and into lakes dammed behind TJPs.(these may be the downstream end of another TJP)

iv. 'Chains' of discrete slugs (sluglettes) that develop at the downstream end of major slugs when there is a long distance between granite tributaries.

It is important to consider this pattern of deposition because it controls the way in which sand will be evacuated from the channel (discussed in Section 6 below), and provides a framework for understanding the impact of sand extraction operations.

Summary of Distribution of Sand in the Glenelg River

The dominant source of sand to the Glenelg River is granodiorite tributaries. Sand from each tributary forms a discrete slug of sand in the Glenelg River, often completely damming the trunk stream. Where tributaries are far apart, the slug from a single tributary attenuates into a series of smaller 'sluglettes'. This occurs between the Chetwynd and Wando River, and below the Wannon River junction. The movement of sand down the stream is constrained by the deep natural pools that capture all of the sand, particularly between Rocklands and Fulham Bridge, and also by the long pools behind the tributary junction plugs that dam the Glenelg and Wannon Rivers.

3.2 Origins of Tributary Junction Plugs

It is interesting to consider why the TJPs occur at all. We would have expected the trunk channels (the Glenelg and Wannon Rivers) to be able to transport all of the sand introduced to them by the smaller tributaries. As we demonstrate below, Rocklands Reservoir has dramatically reduced flood frequency and magnitude in the Glenelg River. This reduction in discharge is part of the explanation for the TJPs. The tributaries are not regulated, so their flood peaks are unchanged from the natural condition, and so can transport sand into the trunk channel. Such tributary fans of sediment have been reported from other regulated rivers (Lawson, 1925). However, regulation cannot be the only cause for the TJPs because they were already developed on the Glenelg River before Rocklands Reservoir was built. TJPs also occur in the unregulated Wannon River at the junction with Bryans Creek.

The explanation for pre-regulation peaks is probably a combination of rapid flood peaks in tributaries, combined with large sand loads. The tributary flood peak must precede the peak in the trunk by long enough to allow the TJP to be deposited. The backwater from the TJP is then sufficient to back-up the later flood in the trunk channel. Such a lag between the tributary and trunk peaks certainly occurs in the regulated river. For example, the Chetwynd River at Chetwynd peaks up to a week before the Glenelg at Fulham Bridge, even though Fulham Bridge is still 45 km from the confluence with the Chetwynd. Thus there is plenty of time to deposit a TJP before the Glenelg peaks. Such a gap may also have occurred pre-regulation because the anabranching form of the Glenelg would slow the flood peaks.

The practical importance of the timing of tributary peaks is that the TJPs are unlikely to be removed by flows in the Glenelg whilst there is still a large sand supply from the tributaries to replenish the TJP. This is discussed further in the section on future sand movement (Section 6).

The TJP at the junction of the Wannon and Glenelg Rivers requires a different explanation. Here the sand plug is actually in the Glenelg River upstream of the Wannon Junction, with deep water in both the Wannon and below the confluence. This can be explained by sediment transport capacity. The Glenelg River carries far more sand than the Wannon at this point. When the rivers meet, the combined flow is able to carry the sand that is delivered to it. Recall that floods in the Glenelg River are regulated by Rocklands, whilst there is no regulation of the Wannon. In addition, the Glenelg River usually peaks first at the junction, and this means that the later Wannon peak will back-up flow and sand above the junction.

3.3 Migration of Sluglettes

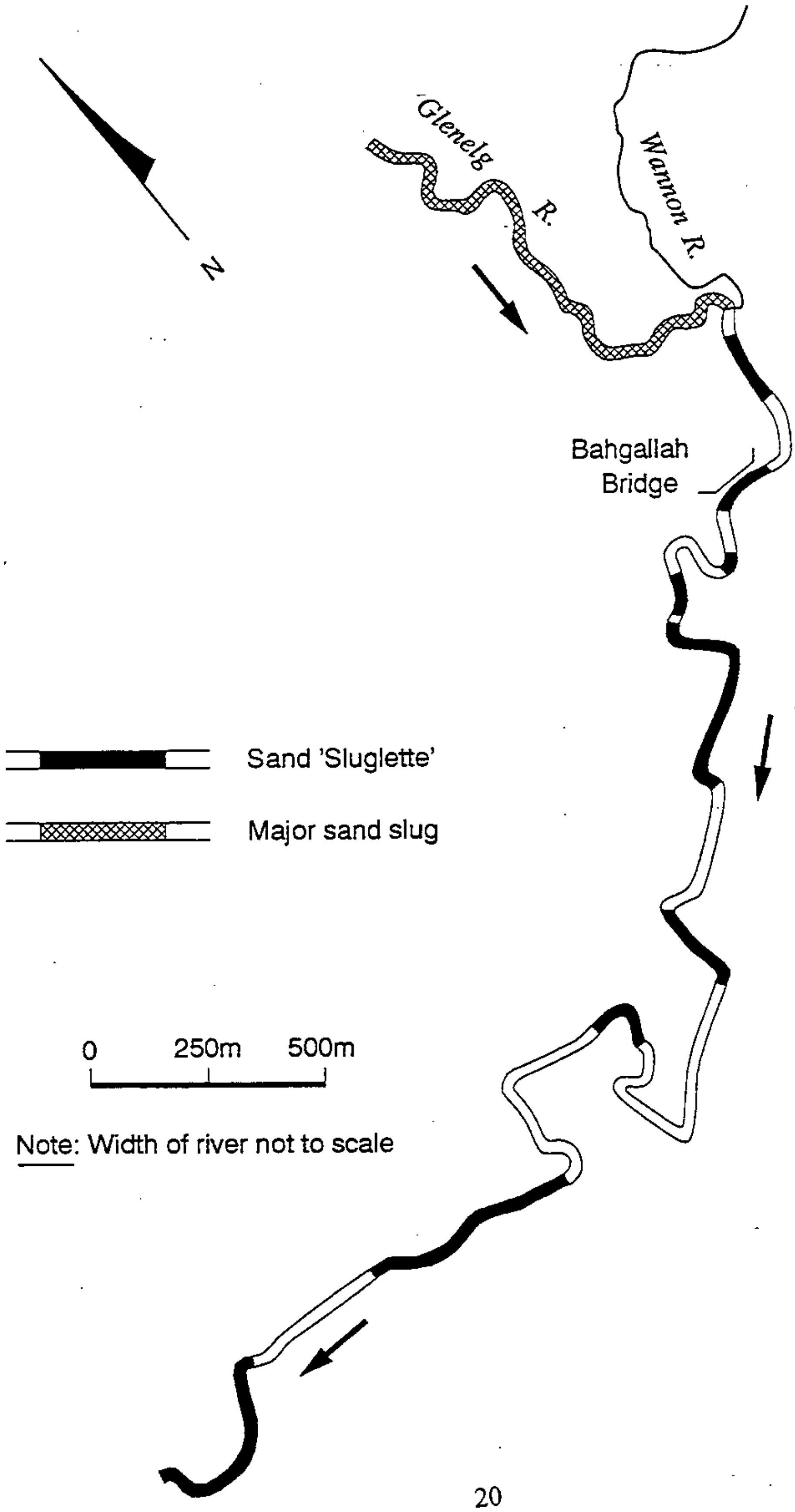
As described above, the major sand slugs break-up into small and discontinuous slugs of 200 to 500 m in length. These are the slugs that are migrating into the Heritage River, so it is worth considering how these forms evolve. Comparing the 1947 and 1991 aerial photographs shows that the individual sluglettes have been remarkably stable in their position over this 44 year period. For example, the five sluglettes shown in 3.4, directly below the Wannon Junction, have not changed their position over that period. The original bed of the Glenelg River consisted of pools and riffles, with the pools sometimes being up to 5m deeper than the riffles. Field inspection of sluglettes shows that they are deposited on riffles, with their snouts lying at the upstream end of a pool. At low water (when inspections were made) the snout of the sluglettes were prograding into the pools, often with a distinct avalanche face.

The following is a hypothesis of how sand moves through these pools. At low flows, sand is deposited in the deep pool as a prograding wedge. At high flows the reduced roughness of the pool produces a 'velocity reversal' in which the pool becomes a zone of increased velocity and sediment transport (Gilbert, 1914; Lane and Borland, 1954; Keller, 1971; Keller and Florsheim, 1993). Sand deposited in the pool is flushed out. On the falling limb of the hydrograph, sand is again deposited at the upstream end of the pool and on the riffle between pools. For this reason the sluglettes of sand have remained in the same location since the 1940s. Scour chain results (Section 7.2.3) suggest that only the top 0.5m or so of the slug is mobilised in a flood. This suggests that the bulk of the sand is stored on the riffle, which means that the sluglette is not being continuously replaced with new sand.

The sluglettes migrate downstream by progressively aggrading successive riffles. We observed this after the flood of 1995 when progressively smaller deposits of sand were deposited on riffles downstream of the 'End -slug'. The End-slug. Is the final well defined sluglette in the Glenelg River (Figure 3.3).

The 'velocity reversal' hypothesis for the formation of sluglettes implies that pools could become filled with sand if the period between floods is so long that long periods of

Figure 3.4: A typical chain of 'sluglettes' below the Junction of the Glenelg and Wannon Rivers (taken from 1991 aerial photographs)



average flows gradually fill the hole with sand. Once the pool was filled with sand the velocity reversal mechanism could no longer function. It appears, however, that even the impact of Rocklands upon flood frequency has not been sufficient to convert the sluglettes into a flat sheet of sand.

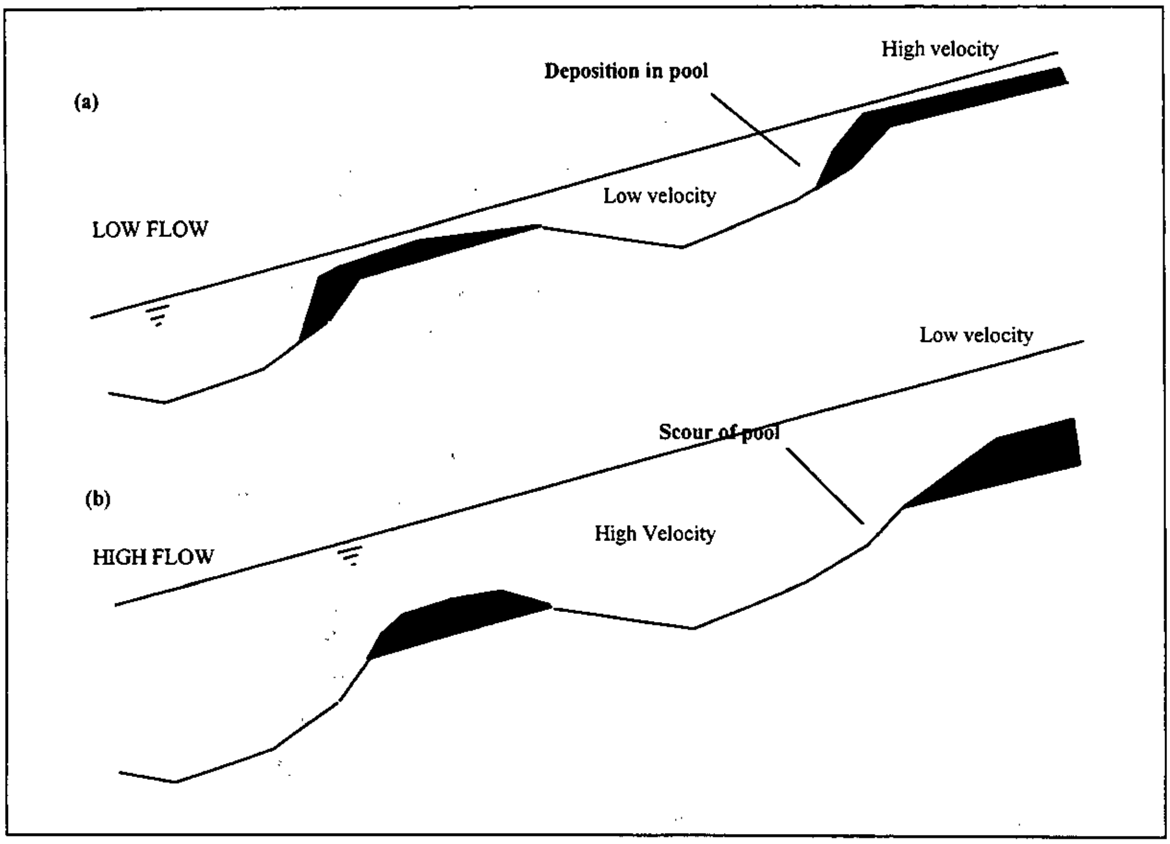


Figure 3.5: Sluglettes prograding into pools at low flows (a) are scoured out of the pools by a velocity reversal at high flows (b).

Summary of Slug Migration

The tributary junction plugs are deposited, partly because Rocklands Reservoir has removed many of the flood peaks from the river, but predominantly because the hydrograph in the tributaries peaks much earlier than that in the trunk stream. The backwater effect of the plug, once it is established, limits the opportunities for its removal. Thus the TJPs will now only be removed by a reduction in sand transport in the tributary stream. The sluglettes at the downstream end of the major slugs are stable bedforms. We hypothesise that the slugs are deposited on riffles and are maintained in their position by the velocity reversal mechanism that occurs at high flows.

4. VOLUMES OF SAND IN STORAGE

Now that we have described the distribution of sand in the Glenelg River and its tributaries we must estimate the volume of sand in storage.

4.1 Method

The volume of sand in storage in the Glenelg River was estimated with a sand probe. The steel probe could be extended to seven metres in length. The depth of sand was probed at cross-sections all over the catchment in association with the scour chain program (described below). It was easy to differentiate the sand from underlying clay at most sites. The bed was most intensively probed for the 20 km of cross-section survey completed below Pigeon Ponds Creek , and the 10 km of survey above Dartmoor. Sand estimates in Bryans Creek were made from surveys of the creek completed for the Shire of Coleraine in 1984 and 1991. Estimates of sand volume were made by dividing the streams into reaches, and extrapolating channel dimensions and sand volumes surveyed at cross-sections in those reaches.

In order to estimate the upper and lower bound figures for sand volumes, we used the range of widths and depths found in the intensive probing done in the detailed cross-section surveys. The standard deviation of sand width and depth for the Glenelg and its tributaries was used to provide a sensitivity analysis of sand volumes. Thus, the maximum estimated figure is derived by using the upper limits of the surveyed width and depth of sand (ie. the upper standard deviation of each from the surveys). An example of the sensitivity analysis is shown in Table 4.1. Finally, in those reaches where sand is deposited as 'chains of slugs' (eg. below the Wannon Junction), we have halved the total sand volume estimate for the reach because slugs only occupy about half of the channel length. This probably leads to an underestimate of volumes in these reaches.

4.2 Estimated Volumes

We estimate that there is between 4 and 8 million cubic metres of sand stored in the Glenelg catchment (Figure 4.1 and Table 4.1). The extreme upper bound estimate is 11.2 million m^3, whilst the extreme lower bound estimate is 2.6 million m^3. Approximately

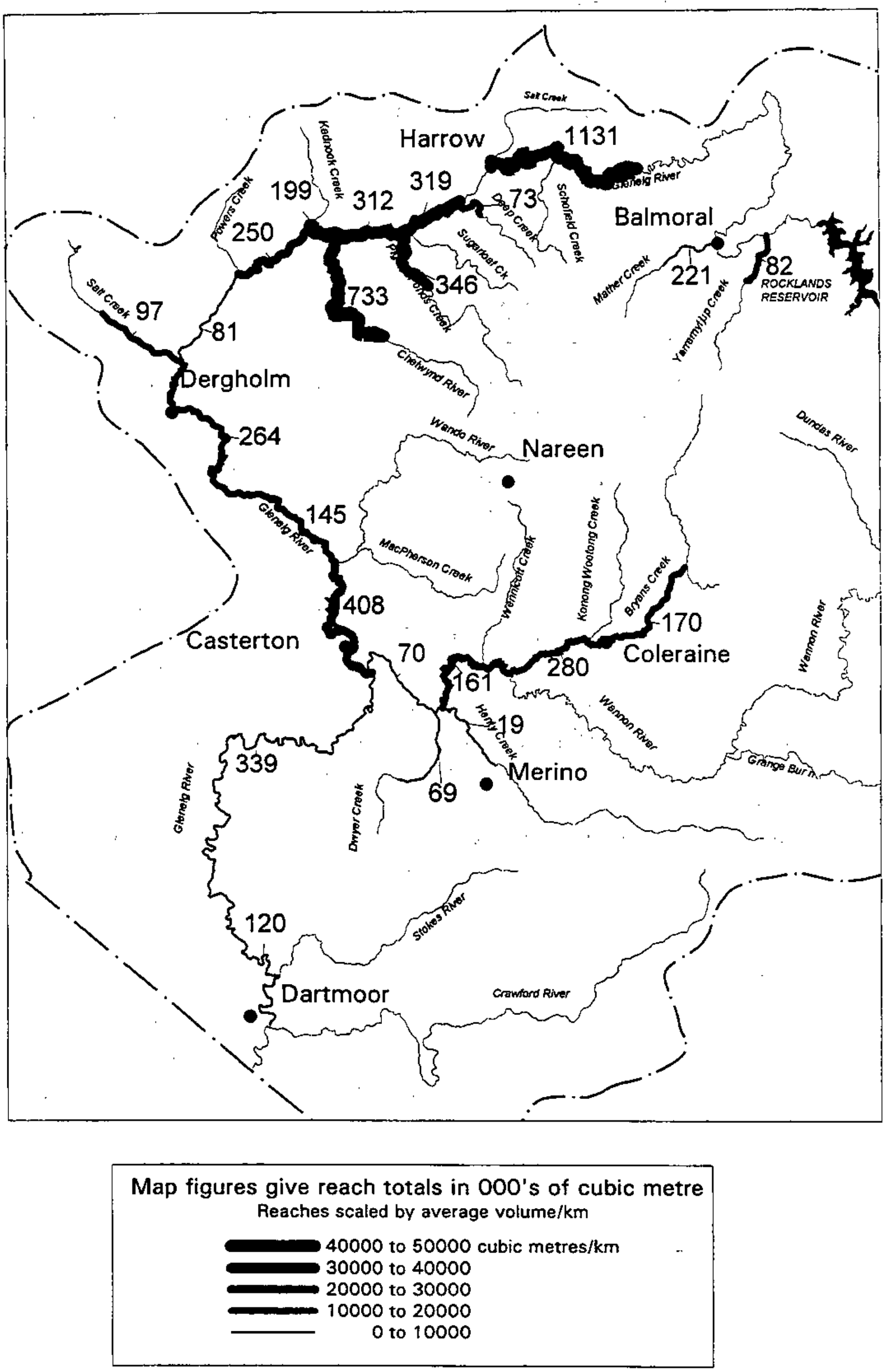


Figure 4.1 Volumes of sand stored in the major streams of the Glenelg catchment.

Table 4.1: Estimated sediment volumes stored in the streams of the Glenelg Catchment

Sediment Sink	Length of Glenelg (m)	Length Tribs. (m)	Stream Width Top (m)	Coeff. var.	Bottom (m)	Coeff. var.	Sand Depth (m)	Coeff. of var.	Area (m2)	Average Volume in Storage (m3)	Average Volume in Storage (m3/km)	Minimum Volume in Storage (m3)	Maximum Volume in Storage (m3)
Yarramyljup Crk4		5740	12.0	0.5	12.0	0.2	1.2	0.5	14.4	82,656	14,400	34,457	145,547
Mathers Crk4		7390	25.0	0.5	25.0	0.2	1.2	0.5	30.0	221,700	30,000	92,420	390,385
Glenelg R (above Pecks Rd to Harrow)2	25500		25.1	0.4	24.0	0.4	1.8	0.5	44.2	1,126,845	44,190	333,818	2,314,495
Deep Crk2		4100	10.0	0.5	10.0	0.2	1.8	0.5	18.0	73,800	18,000	30,765	129,952
Glenelg R (Deep Crk to Pigeon Ponds Crk)2	7210		25.1	0.4	24.0	0.4	1.8	0.5	44.2	318,610	44,190	94,385	654,412
Pigeon Ponds Crk4		5000	26.2	0.5	25.0	0.2	1.6	0.5	41.0	204,800	40,960	83,374	352,174
Glenelg R (Pigeon Ponds Crk to Chetwynd R)2	7050		25.1	0.4	24.0	0.4	1.8	0.5	44.2	311,540	44,190	92,291	639,890
Chetwynd R5		17400	19.5	0.2	15.0	0.3	2.0	0.2	34.5	600,300	34,500	295,948	810,640
Glenelg R (Chetwynd R to Burkes Bridge)2	4500		25.1	0.4	24.0	0.4	1.8	0.5	44.2	198,855	44,190	58,909	408,440
Glenelg R (Burkes Bridge to Powers Crk)2	10300		25.1	0.4	24.0	0.4	1.0	0.5	24.6	252,865	24,550	74,909	519,375
Glenelg R (Powers Crk to Salt Crk)1,2	11700		20.0	0.4	24.0	0.4	0.7	0.5	15.4	90,090	7,700	29,782	206,489
Salt Crk5		9720	20.0	0.2	20.0	0.3	0.5	0.2	10.0	97,200	10,000	55,108	150,947
Glenelg R (Salt Creek to Red Cap Crk)1,2	23400		25.1	0.4	24.0	0.4	1.0	0.5	24.6	287,235	12,275	85,091	589,969
Glenelg R (Red Cap Crk to Wando R)1,2	14300		25.1	0.4	24.0	0.4	0.9	0.5	22.1	157,979	11,048	46,800	324,483
Glenelg R (Wando R to Wannon R)2	20100		25.1	0.4	20.0	0.4	0.9	0.5	20.3	407,930	20,295	109,636	760,153
Glenelg R (Wannon J. to 'End Slug')1,3	57500		17.0	0.1	17.0	0.1	0.7	0.5	11.9	342,125	5,950	302,798	577,687
Glenelg R (End slug to Dartmoor)7	28200									120,000	4,255	120,000	120,000
Bryan Ck (Robsons Rd to Coleraine)5,6		13040		0.2		0.3	0.3	0.2		300,000	23,006	300,000	300,000
Bryan Ck (Coleraine to Wannon Jnc)5		13030	12.0	0.2	12.0	0.3	0.3	0.2	12.0	156,360	12,000	24,378	66,775
Wannon R (Bryan Ck to Henty Jnc)2		16100	10.0	0.4	10.0	0.4	0.4	0.5	10.0	161,000	10,000	21,711	150,528
Wannon R. (Henty Jnc to Glenelg R)2		14000	10.0	0.4	10.0	0.4	0.4	0.5	5.0	70,000	5,000	18,879	130,894
Henty Ck (u's of Wannon)5		9850	5.0	0.2	5.0	0.3	0.3	0.2	2.0	19,700	2,000	7,679	21,033
Dwyer Ck (U's of Wannon)5		9970	7.0	0.2	7.0	0.3	0.3	0.2	7.0	69,790	7,000	10,881	29,805
									Total	**5,671,379**		**2,324,019**	**9,794,072**

Notes:
1. Volume in sluglette reaches multiplied by 0.5 because sluglettes don't occupy whole channel
2. Coefficients of variation for Upper Glenelg R. survey applied to this reach
3. Coefficients of variation for Lower Glenelg R. survey applied to this reach
4. Coefficients of variation for Pigeon Ponds Ck. survey applied to this reach
5. Coefficients of variation for Chetwynd R. survey applied to this reach
6. Minimum estimate of volume (taken from Bryans Ck survey, 1984).
7. Estimate of volume from Dartmoor survey made for this study.

half of the sand is stored from below Fulhams Bridge to Burkes Bridge in the northern section of the catchment. According to these estimates, the Wannon system at present stores only about 15% of the total sand in the catchment. Surprisingly, the highly sinuous Harrow reach probably stores the most sand, and this sand is isolated from the rest of the river by the long lake above the Deep Creek TJP. Another large store of sand is in the Chetwynd River (about 700,000 m^3, or over 40,000 m^3/km). The reach of the Glenelg between the Wando junction and Casterton stores over 400,000 m^3 of sand, but at less than 30,000 m^3/km. The storage per unit length is also greatest in the Harrow reach (around 50,000 m^3/km), but storage averages about 10-20,000 m^3/km for most of the stream network.

In some reaches we have probably under-estimated the volume of sand because we used the variation in depth found in the surveys to characterise the variation in each reach. Last century, there were many deep holes in the bed of the Glenelg River . These still exist below Rocklands Reservoir, where they have been measured at up to 8.5m deep (McGuckin, Anderson et al., 1991). Similarly, at Harrow there is a local anecdote about a man who was drowned in the river in the 1930s, and his body was found in a hole that was 27 feet (8.2m) deep. Further downstream, about 10 km above Casterton, Boral Pty. Ltd. is extracting sand from a similar deep hole in the bed. Thus, large volumes of sand could be stored in many deep holes along the channel, increasing the estimated volume in storage.

The total figure for sand stored in the tributary streams is probably an overestimate (ie. true value is probably toward the lower bound figure), because the cross-sections were often extrapolated from the deepest sand probe. In reality the store of sand in the tributary beds can be strongly asymmetric, meaning that the deepest point of sand occupies only a small proportion of the cross-section. This is certainly shown by detailed probing on Bryans and Pigeon Ponds Creeks.

4.3 Proportion of channel filled

It is important to know the volumes of sand in the Glenelg river so that we can estimate how much extraction would be required to have an impact on the sand storage. However, in terms of the impact of the sand on flooding and on ecological values, a better measure of the impact of sand is the proportion (or percentage) of the channel cross-section that is occupied by the sand. The percentage of the bankfull cross-section that is occupied by sand tends to be highest in the tributaries, and generally declines downstream on the Glenelg. At the junctions of the major tributaries with the Glenelg River, the tributary Junction plug typically occupies over 70% of the original cross-section area (Figure 4.2). The Glenelg between Harrow and the Chetwynd River junction has lost over half of its original area. At Casterton, in the middle portion of the river, this percentage falls to 20-30% as the cross-section gets larger. For example, the TJP in the Glenelg River above the Wannon Junction, occupies about 25% of the Glenelg's channel. In the lower Glenelg, at Dartmoor, sand occupies only 10% of

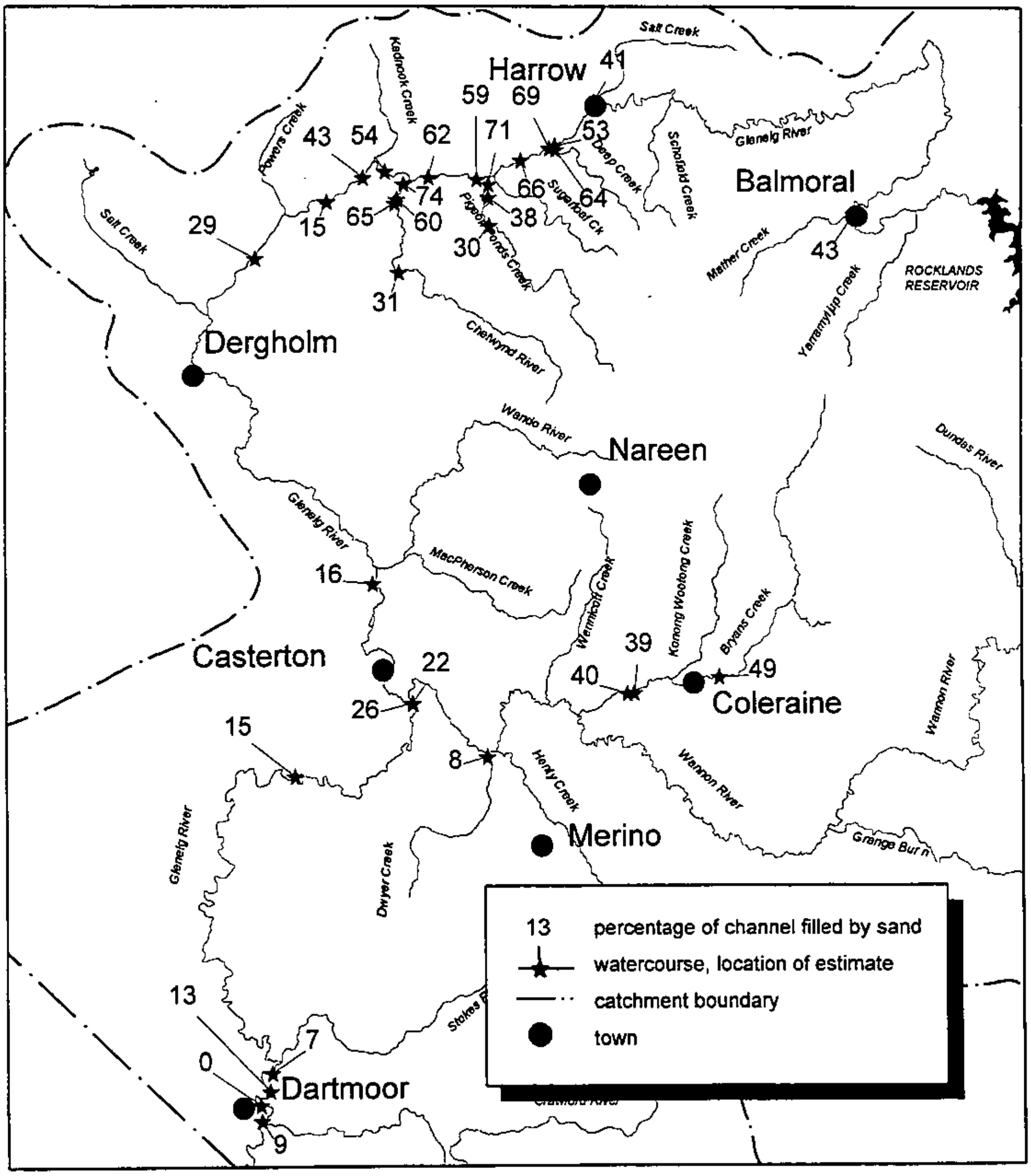


Figure 4·2 Percentage of bankfull channel cross-section filled by sand in major streams of the Glenelg catchment.

channel capacity, and this may be close to the natural, pre-European volume of sand. Sand fills 40 to 50% of Bryans Creek in the lower aggraded reaches.

Storage of sand in the Glenelg and its tributaries

There are about six million cubic metres of sand in the major storage zones in the Glenelg catchment. The bulk of the sand is stored in the northern section of the catchment between Fulhams Bridge and Burkes Bridge. The average depth of sand in the Glenelg is about one metre. Sand occupies about 60% of the Glenelg's cross-section in the upper reaches, 20% at Casterton, and 10% in the lower reaches. This represents between 10,000 and 50,000 m^3 of sand per kilometre of channel.

5. MANAGEMENT IMPLICATIONS OF SAND IN THE GLENELG RIVER

Following is a list of the damage done by sand slugs.

i. Produces an almost sterile stream (reduced biological values) (reduced habitat, increased water temperatures, unstable substrate)

ii. Reduced channel capacity and increased nuisance flooding.

iii. Reduced aesthetic and recreational values of the stream (dramatically decreased fishing and swimming opportunities).

iv. Compromised stock (cattle) management by providing easy access across streams. The result is that the river no longer represents a well defined property boundary.

The only positive aspect of the sand is the opportunity for sand extraction.

The effect of sand upon nuisance flooding and stream ecology require further discussion.

5.1 Sand and flooding

One of the major concerns about slugs of sand occupying stream channels is the increase in flooding associated with the lost channel capacity. There is no question that channel capacity in the lower reaches of some of the tributaries is dramatically reduced (eg. Pigeon Ponds Creek). However, on a catchment wide scale, it is interesting to investigate the magnitude of sand upon flooding. We investigated this question by using a rainfall runoff model (RAFTS). This model routes runoff from storms of a given size (recurrence interval) through a channel network. We were not able to set-up a model of the Glenelg catchment (a large task) but we have an existing model already setup for the Acheron catchment (400 km^2) within the Goulburn catchment. This model can be used to test the general impact of filling a stream channel with sand.

The full set-up of the Acheron model is being reported elsewhere, and we will only summarise the system here. The catchment model includes surveyed cross-sections and realistic precipitation and runoff parameters. We are confident that the results are crudely indicative of the magnitude of effect. The model was run with original cross-section dimensions, and the run was then repeated with half of the entire channel network filled with sand (ie. halved the depth of all cross-sections). Importantly, the roughness of the channel was also reduced, by 0.01, because a uniform sand bed is hydraulically smoother than the original channel. In the model, roughness varies from 0.06 to 0.02 depending on the reach.

The flood discharge, time to peak, and flood stage, for 2 year to 100 year floods, were little affected by filling the channel with sand. The reduced cross-section tends to force more flow out onto the floodplain which slows the flood wave through the catchment. At the same time, the reduced roughness increases the flow velocity in the channel. These effects counter-balance each other, producing little overall effect.

This exercise is only intended to suggest that the impact of a sand slugs on floods may not be as important as many may at first assume. It is also important to recall four other points in regard to flooding in the Glenelg catchment. First, Rocklands reservoir has already dramatically reduced flood frequency in the river (see Section 7.9). Second, flooding at one point is a product of upstream processes. This means that sand slugs upstream could even reduce flooding by forcing more water onto the floodplain. Third, many tributary channels, such as the Chetwynd River and Bryans Creek, have dramatically increased their channel dimensions over the last century, so flood frequency is already much reduced along these streams. Finally, the aggradation of the bed of the Glenelg and its tributaries is balanced by overbank deposition of sand on the floodplain. In some cases the elevation of the banks has been raised at least as much as the elevation of the bed (eg. upstream of Casterton). Thus, the modelling exercise, combined with these other effects, suggests that the reputed impact of sand slugs upon flood frequency may be overstated.

5.2 Ecological impacts

Converting a narrow and deep channel, with regular pools, into a featureless sheet of sand, has disastrous ecological consequences (Alexander and Hanson, 1986). On the Pranjip-Creighton Creek system in Victoria the migration of a slug of sand through the creek has not only destroyed habitat, but it has also led to a change in seasonal diversity (O'Connor and Lake, 1994). Because the sandy substrate is more mobile than the original bed, it is scoured every winter. This produces large seasonal declines in macro-invertebrate species richness and populations. In addition, the water temperature increases in the shallower water over sand-slugs.

On the Glenelg River and its tributaries, the most important impact of the sand is assumed to be the loss of pools, and a major decline in the diversity of habitat and substrate size.

6. FUTURE SAND MOVEMENT: NO INTERVENTION

Future sand movement involves two issues. First the volume of sand available for transport, and second the capacity of the stream to transport the sand.

We have defined the approximate volume of sand in the Glenelg River and its tributaries at the present time. Future sources of sand to the Glenelg River could come from sheet erosion of the catchment, gully extension and widening, erosion of the banks of the lower reaches of the tributaries, erosion of the sand stored in the bed of tributaries, and erosion of the banks of the Glenelg River itself. We will discuss the major futures sources of sand in the system.

6.1 Future sources of sand

6.1.1 Sheet erosion of the catchment

The consensus amongst land managers is that sheet erosion of the surface of the Glenelg catchment has reduced substantially since the 1940s (Marker, 1976). This is due to several factors. The droughts and rabbit plagues of the 1940s have given way to better climate and reduced rabbit numbers. In addition, the efforts of the SCA have encouraged better land management (reviewed in GCWMS, p.C34). For example, the percentage of each landholding that is planted to improved pasture has increased from about 50% to about 70% between 1962 and 1987 (Australian Bureau of Statistics data for statistical divisions covering the Glenelg catchment). It is reasonable to expect that the supply of sediment from the catchment surface to the Glenelg and its tributaries will be less than the supply that in the first half of this century.

6.1.2 Continuing erosion of gullies

The GCWMS, Erskine (1994) , and Marker (1976) concluded that sediment yield to the Glenelg River has declined over the last 30 years as catchment and gully erosion has declined. This is, in part, due to soil conservation works completed since the 1950s. These have included 467km of gully fencing, 300 silt traps, and nearly 8,000 m of gullies battered up to 1980 (Anon, undated). Not all of the catchment has been treated by conservation works. Even in those catchments that have not been treated the amount of gully erosion has been limited. This was shown in the catchment of Pigeon Ponds Creek, which has not been treated with soil conservation works. We mapped all of the gully networks in the 150 km^2 catchment from 1991 colour aerial photographs (scale 1:26,000). Changes in the gully network were identified over a 47 year gap by comparing the 1991 map with the 1947 *Adastra* aerial photographs (scale: 1:15,840). Although only planform changes could be identified, it was clear that there had been very little change in the extent of the gully networks over this 47 year period. This is not to say that there has not been sediment released by gully wall erosion (ie. widening). Erosion of gully walls can contribute half as much sediment as erosion of the gully floor (Blong, 1982; Blong, 1984; Crouch, 1987), and field inspection in the catchment showed that many gullies still have unstable channel walls.

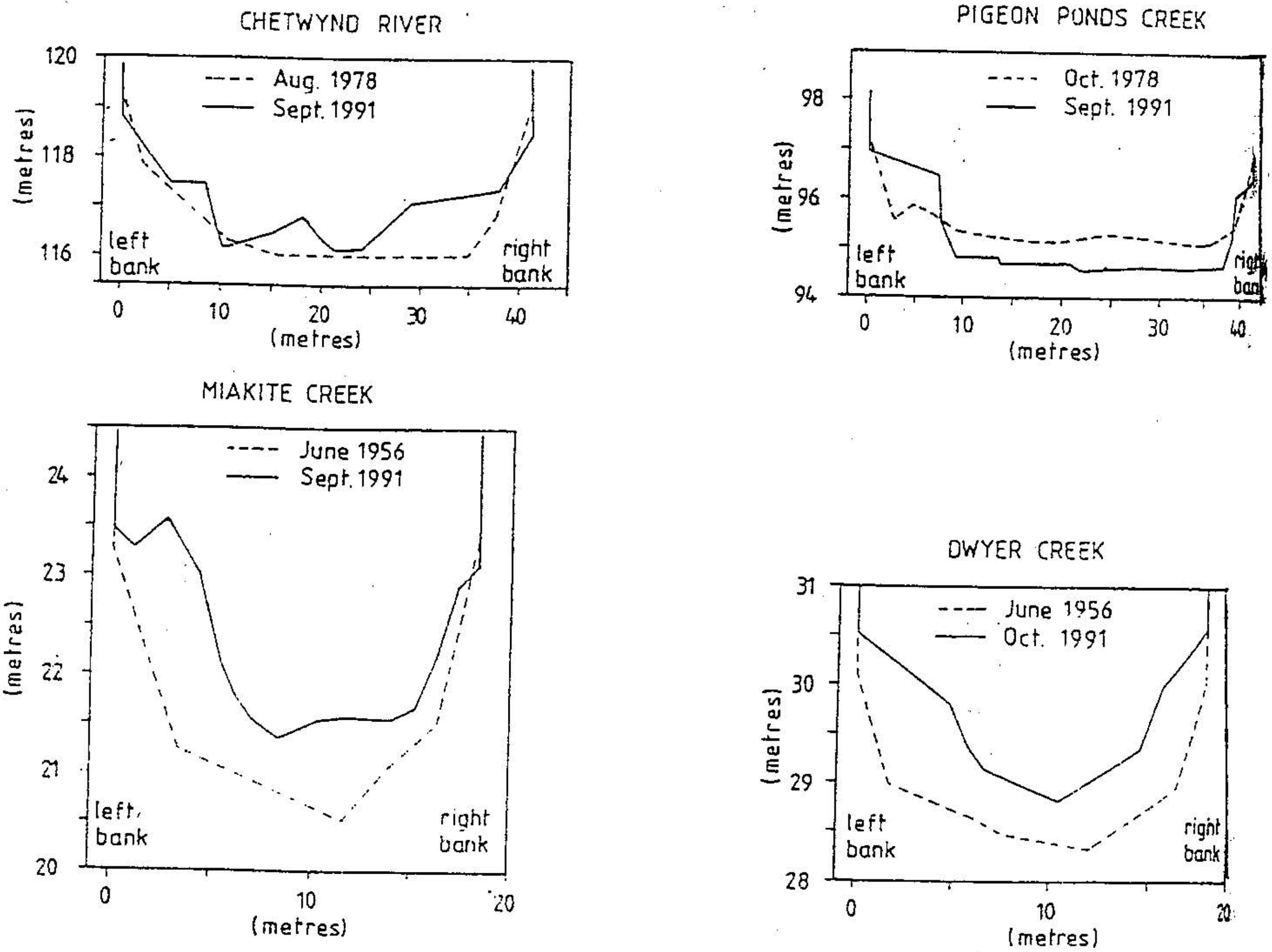
6.1.3 Erosion of sand stored in the tributary channels

The major source of sand to the Glenelg River in the future will be from sand stored in the bed of tributaries, and from the large deposits in the downstream reaches of the tributaries. This sand is moving through the tributaries as a wave, and these waves will continue to provide sand to the lower tributary reaches for many decades. The movement of a slug of sand as a wave has been described in many studies (Gilbert, 1917; Pickup, Higgins et al., 1983; Knighton, 1987; James, 1991; Erskine, 1994; Nicholas, Ashworth et al., 1995). Like a flow hydrograph, the sand wave has a rising and falling limb that reflects the depth of sand in the bed. Erskine (1994) suggests that the sand slugs in those tributary catchments that have been treated by the SCA have already passed their peak and are now on the falling limb of the wave because the SCA works have cut-off the sand supply to the channel. Evidence for this is the bed degradation occurring at bridge sections.

There is no doubt that degradation has occurred in some stream channels, but it is difficult, with existing information, to conclude that the major reason for the degradation is treatment of the catchment. The four streams that are unequivocally experiencing a fall in bed elevation are the Wando River, Wando Vale Ponds, Pigeon Ponds Creek, and Bryans Creek (Figure 6.1). The Wando River was channelised and desnagged as one of the first activities of the Glenelg River Improvement Trust in the early 1960s. Farmers on the Wando River suggested that the desnagging and straightening of the Wando River and Wando Vale Ponds produced immediate erosion of the bed. Today the Wando River requires grade control structures to control the incision of the bed.

Both Pigeon Ponds Creek and Bryans Creek are degrading their beds because of commercial sand extraction. As we discuss below, over 400,000 m^3 of sand has been extracted from Bryan Creek since the 1950s, and this has led to a drop in bed elevation. One quarter of this extraction occurred before 1970. Although, the absence of sand stores in the bed of Bryan Creek and its tributaries suggest that the SCA works have succeeded in reducing sand loads, the explanation for the falling bed level is also closely associated with sand extraction. Changes in Bryan Creek will be discussed in more detail in Section 8.4 below.

As with Bryans Creek, extraction from Pigeon Ponds Creek has contributed to bed degradation at the Chetwynd-Moree Road Bridge. Between 1978 and 1991 the bed fell by about 0.5m below the road bridge (Figure 6.2). Extrapolating the 0.5m fall in bed level across the four cross-sections that we surveyed on Pigeon Ponds Creek (Appendix 1) suggests



Wannon River

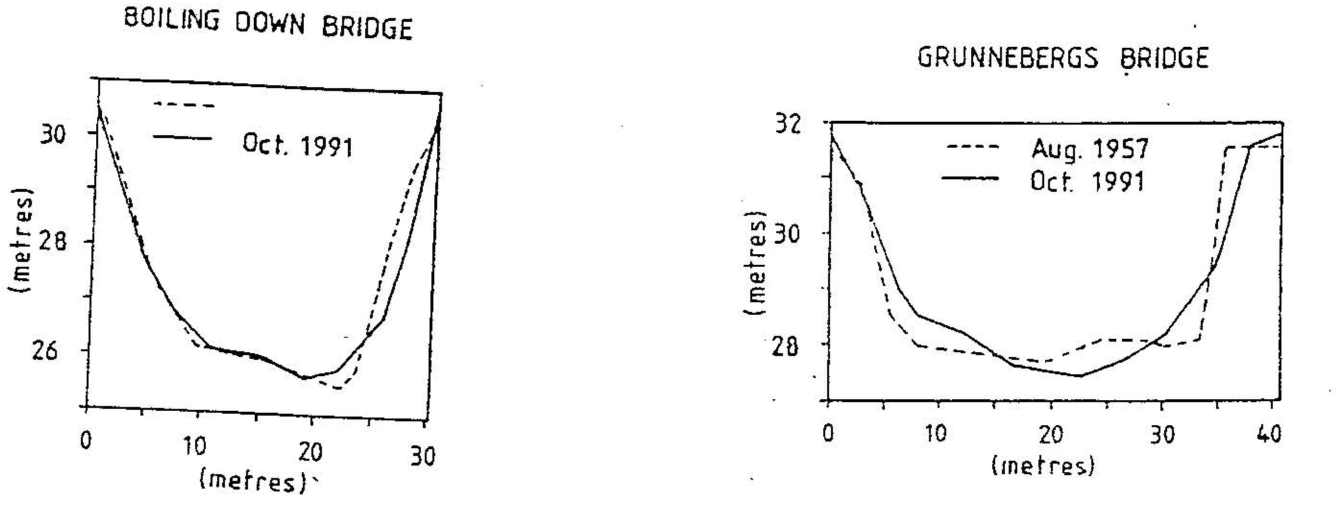


Figure 6.1: A comparison of historical cross-sections at bridges around the Glenelg and Wannon catchments (taken from the Glenelg Catchment Waterways Management Study, 1992, pages c30 & c40).

that about 50,000 m^3 of sand has been lost in the vicinity of the extraction. Official records of sand extraction (discussed in Section 10.1) suggest that about 30,000 m^3 of sand has been extracted from Pigeon Ponds Creek between 1985 and 1993. Therefore, given the uncertainties in the cross-section measurements, and the probable underestimation of extraction volumes, it is reasonable to conclude that most of the fall in bed elevation in lower Pigeon Ponds Creek is due to sand extraction. Thus, whilst soil conservation works may well be affecting some streams, the three cases of bed degradation cited by Erskine (1994) are probably best explained by local factors: channelisation in the Wando River catchment, and artificial sand extraction in Bryans and Pigeon Ponds Creeks.

In other creeks the bed is either stable, or is continuing to aggrade. Bridge surveys in the GCWMS indicate that the Chetwynd River at Flacks Bridge has aggraded close to a metre in parts since 1978. This corroborates the suggestion by Mr Fisher of the property "Chetwynd South" that the bed of the Chetwynd River, upstream of Chetwynd township, has aggraded by "four to five feet (1.2-1.5m) since 1965". Both Miakite Creek at Paschendale, and Dwyers Creek at the Casterton-Portland Road are continuing to aggrade their channels (Figure 6.2).

Even though we cannot conclude that the peak of the sand waves has passed through the tributaries to the Glenelg and Wannon Rivers, we can conclude that the contribution of sand to those sand slugs is declining. In other words, the sand that is presently in storage in the lower reaches of tributary streams is the major store of sand in the catchment - there is not some enormous slug of sand still moving through the upper catchment. This can be shown with the example of Pigeon Ponds Creek.

We showed above that the gully networks in the headwaters of Pigeon Ponds Creek are now stabilised. Although there is sand stored throughout the catchment in the bed of the streams, most of the sand in the Pigeon Ponds Creek system is now stored in the last four kilometres of its channel. This is shown in the surveyed cross-sections (Appendix 1). These show that the depth of sand decreases from about 4m at one kilometre from the mouth, to about 1m at kilometres four and five. More importantly, the volume of sand per metre of channel is 90 to 100 m^3 in the lower three kilometres of channel, falling to less than 10 m^3 at kilometres four and five. There is about 25 km of channel between the last of our cross-section surveys and the township of Pigeon Ponds. This is the extent of channel that appears, from 1991 aerial photographs, to have active sand in the bed. Inspection of this reach suggests that the channel bed consists of steep reaches, with a granite bed, interspersed with flatter reaches with a sandy bed. . The sandy reaches have about the same volume of sand as our cross-sections at kilometres 4 and 5: typically sand stores 10 - 15m wide and 0.5 - 1m deep. A realistic estimate of the volume of sand in this 25 km reach (assuming half of the length of 12m wide channel is filled to 0.75m) is about 112,000 m^3 . This is about half of the 210,000 m^3 of sand stored in the lower four kilometres of channel. Thus, sand will continue to be supplied to lower Pigeon Ponds Creek from the stores of sand remaining in the bed of the creek in its middle reaches, but the major store of sand in the catchment is stored in 4000m of channel above the confluence with the Glenelg River. It is reasonable to assume that the same situation applies in creeks throughout the catchment.

6.1.4 Reeds

In several creeks an obvious trend is the invasion of the lower reaches by reeds. Since 1949 vegetation, particularly reed species (*Phragmites* and *Typha*), have become established throughout the catchment in depositional zones. For example, in 1947 the bed of the lower reach of Mather Creek was a broad, bare sheet of sand. By 1991 this sheet of sand had been invaded by trees. The sand had migrated to the junction of the Glenelg River by 1991, but in common with other creeks, the lower one to two hundred metres of creek above the junction is now choked with reeds. Salt Creek, and most of the small creeks joining the Glenelg below Harrow, have similarly had their mouths choked with reeds. Elsewhere in the catchment, reeds are also important: in Koonong Wootong Ck, Wando Vale Ponds, and in the Wando River. We would argue that the invasion of the channel floor by reeds is an indication of declining rates of sand transport since the 1940s. However, it is not only those streams that have had soil conservation works that have been invaded by reeds, it is many catchments. Thus the presence of reeds does suggest declining sand transport rates across the catchment.

Summary of Future sources of sand to the Glenelg River

Catchment and gully erosion has released waves of sand that are moving through the tributaries of the Glenelg River. There is no doubt that the major period of catchment and gully erosion has passed in the Glenelg catchment, and that soil conservation activities have contributed to the reduced erosion rate. However, there is, as yet, no strong evidence that the active stores of sand in the lower reaches of streams are now responding to that catchment treatment by eroding (ie. that the peak of the wave of sand has passed). Local degradation of the lower reaches of some streams is explained by local activities (sand extraction and channelisation), and the lower reaches of streams appear now to be either aggrading or stable. In other words, the sand waves in the lower tributaries are still on their rising limb, or close to their peaks. Nevertheless, the major store of sand in catchments is now located in the lower few kilometres of tributary streams, and there are no large reserves of sand moving through stream networks toward the Glenelg River. Invasion of many stream beds by reeds suggests an overall decline in the rate of sand transport The next section shows that not all of the sand presently stored in the tributaries and in the Glenelg River will be available for transport.

6.2 Long-term storage of sand in the Glenelg and its tributaries

Recall that we are concerned here with the rate at which sand will move through the Glenelg and its tributaries into the Heritage River reach. We are also concerned with the distribution and total volume of sand in the system in order to judge the effectiveness of various management strategies. It is important to note that the volume of sand that we identified as being stored in the channel bed is not an indication of the volume that is available to move through the stream system and into the Heritage River. This is because a proportion of this sand will be stored indefinitely and will not be available for transport. Areas of storage are: floodplains, channel benches, and in 'abandoned thalwegs'.

6.2.1 Floodplain storage

A large volume of sand and silt eroded from the catchment of the Glenelg River has been deposited on floodplains. Such deposition is described in several of the early records of tributary erosion: for example, on the flats of the Wando Vale Ponds (Parliamentary Public Works Committee, 1959), and Pigeon Ponds Creek (Strom, 1947). This sediment can be seen along the top of the banks of the Glenelg River where it forms a one to two metre buff-coloured, sandy-loam deposit. Assuming a thickness of 1m and a width of 20m, the overbank deposits along the Glenelg probably represent a minimum volume of about three million m^3. This is about half of the estimated volume of sand stored in the bed. The overbank flow of August 1995 deposited drapes of fine sand on the levees indicating that deposition on the floodplain is continuing. These deposits had a median particle size of about 0.3 mm (maximum of 0.5mm) compared with a median particle size of about 1.5 mm for the bed sediments.

Particle size distribution of sand in the bed of the Glenelg River suggests that about 20% of the bed material is less than 0.3mm diameter. Thus, 20% is the maximum proportion of the bedload that could be deposited overbank. It is more likely that the volume would be considerably less than this figure.

6.2.2 In-channel Benches

Long reaches of the Glenelg River and its tributaries are characterised by flat sheets of mobile sand. It is unusual for stream beds to maintain this form for two reasons. First, any curvature in the channel leads to preferential erosion of one side of the deposit, producing incision. Second, the wide, shallow flow invites colonisation by vegetation, usually reeds. The result is that wide sheets of sand will eventually develop a narrower channel, both by preferential erosion, and by deposition amongst the colonising vegetation.

There are several streams where benches are forming, particularly with invasion by reeds. An examples is in the middle and lower reaches of the Wando River in which the river now takes a narrow path through reed covered benches. Eventually the benches may accrete high enough above the flow to be colonised by terrestrial vegetation. The sand stored in such stable benches will not be available for transport down the river. In the Wando Vale Ponds, up to half of the original sand volume stored in the bed has been stabilised in reed covered benches. This is suggested by comparing 1944 and 1991 photographs of the creek reproduced in GCWMS (p.C35), and by field inspection.

Bryans Ck is another example of a creek that has developed benches. Grass has colonised the point bars of the channel in the reach of Bryans Creek upstream of Coleraine. Despite most of the sand in the channel being evacuated by commercial extraction, the grassed portions of the channel have remained stable.

Thus, we suggest that a large proportion of the sand that is presently stored in the channels of the catchment will be locked-up in vegetated benches, and will not be available for transport. We have not seen many examples of benches forming in the Glenelg River itself, but they are forming in the over-wide sand sheets that have formed in the lower reaches of tributary streams. Examples are, Pigeon Ponds Ck, Mathers Ck, parts of the Chetwynd River, and Bryans Creek. In these examples it is possible to estimate the volume of sand that would be stored in benches. This can be done by estimating what the original width of the channel would have been before the arrival of the sand slug. This is made more difficult because these streams were all incising before the arrival of the sand. Nevertheless, an estimate can be made from the channel dimensions upstream of the over-widened reaches. For example, on Pigeon Ponds Creek the channel immediately above the over-wide reach is about 15m to 20m wide. This compares with a width of 25m to 30m downstream. Thus, we could assume that a bench of about 10m width could develop along this creek. How much sand would such a bench store? This depends very much upon the morphology of the cross-section. If the sand store is rectangular, then a 10m bench would store perhaps one third of the sand. However, investigating this question led us to the observation that much larger volumes could be stored in benches and point bars because of 'abandoned thalwegs'.

6.2.3 Storage in abandoned thalwegs

The focus of sand transport in a channel is the outer bank of the channel (concave bank) where velocities and shear stresses are highest. It is usually assumed that the major store of sand also occurs at the present thalweg of a channel, at the outside bend. This is usually true in the Glenelg River where the introduction of sand has produced little channel change. However, it is not true of the tributary streams that have been continually changing their morphology over historical time, even with the introduction of sand. Although the sand often protects the channel bed from incision (discussed below), it is common for channels to widen when they have a sudden increase in sand load. This is because, for the same discharge, sand is more efficiently transported by a wide shallow channel than by a narrow deep one.

"At any given discharge Q and gradient S an alluvial river can transport a bed load of a given mean grain size at a greater rate the shallower the flow" (Bagnold, 1977, p.322).

For example, Mathers Creek, Pigeon Ponds Creek, Chetwynd River, and Bryans Creek have all widened their channels and experienced active meander migration over the last 30 - 40 years. Landholders describe all of these streams as being much narrower and deeper before

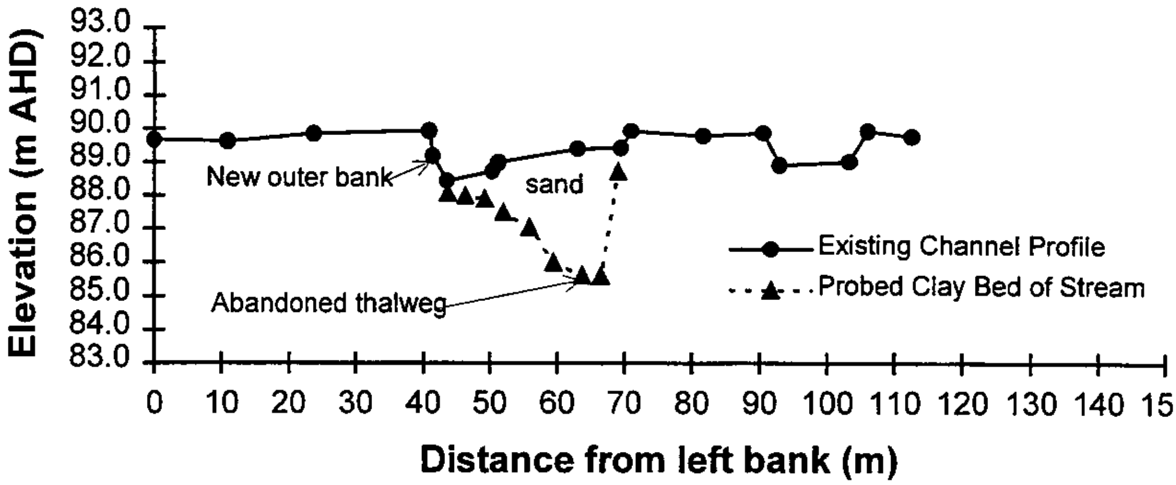


Figure 6.2: Cross-section of the Glenelg River showing an abandoned thalweg (cross-section is about 3km upstream of the Chetwynd River junction, surveyed Sept 1994).

the arrival of the sand. There are the common stories about boys on horses riding under bridges that are now 0.5m above the broad sand bed. The important result of the widening of these channels is that the largest depths of sand in the cross-section of these creeks is not found in the thalweg, but beneath the point bar. That is, the channel went through the following progression (Figure 6.2 & 6.4).

i. The original chain-of-ponds, or small channel, deepened and widened.

ii. The bed of the incising channel was aggraded by a wave of sand

iii. The channel widened in response to the increased sand load, but the widening took place within 0.5m of the surface of the sand (ie, the maximum depth of sand transport) rather than at the former thalweg level.

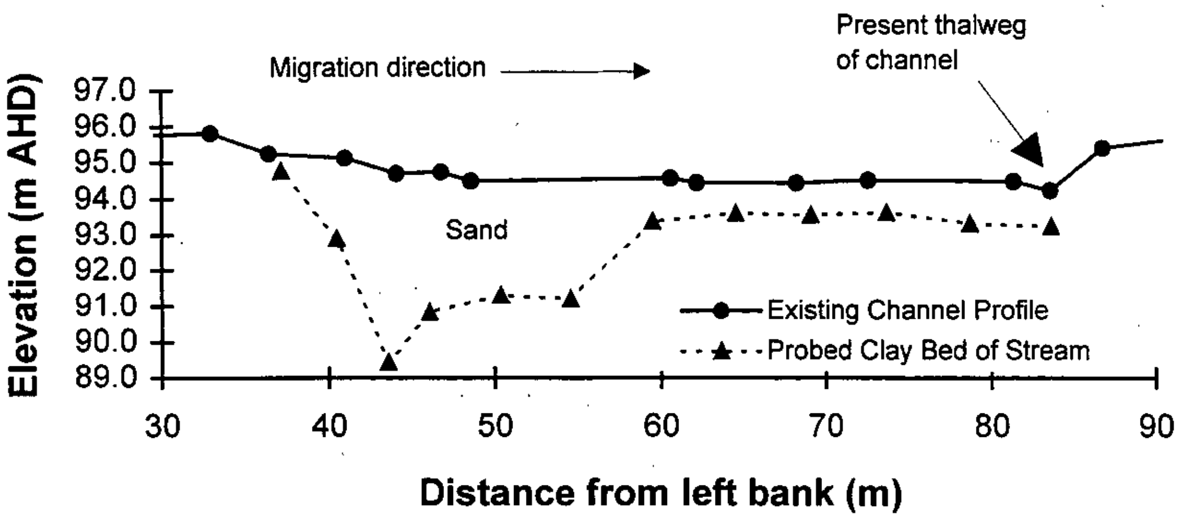


Figure 6.3: Cross-section surveyed across Pigeon Ponds Creek 1km from the Glenelg Junction. Eroding outer bank is on the right side, sand store is on the left.

One implication of this channel development is that the original thalweg of the channel is abandoned as the outer bank of the channel migrates away, leaving the deepest stores of sand beneath the point bar. These stores of sand are often invaded and stabilised by vegetation. The result is that a large proportion of the sand remains in storage and will not be mobilised unless there is direct extraction, or deepening of the new thalweg. Sand stored in point bars will remain in storage for many decades, particularly if they are stabilised by vegetation. Thus, the widening response of the channel to a sudden influx of sand effectively stores a large proportion of the sand.

Thus, assuming that the channel maintains its existing sinuosity, and that the point bars are stabilised by vegetation, then a large proportion (say 50%) of the stored sand will not be readily available for transport. This means that it will take much less time for the active sand to evacuate the channel, and there will be much less sand moving through the system (ie. a greater proportion in long-term storage). It is important to note that this morphology does not develop so strongly at the inflection points, where the sub-sand profile is flat.

We estimate that at least half of the sand stored in the lower reaches of tributary streams will be stored in vegetated bars and benches. These tributary stores represent about one third of the total volume of sand in storage in the major streams of the catchment . More important than the relative proportion of sand in the tributaries is the eventual impact of reduced sand supply from the tributaries. It is likely that sand supply from the tributaries will run out more quickly than we originally anticipated. This means that the TJPs will begin to erode more rapidly.

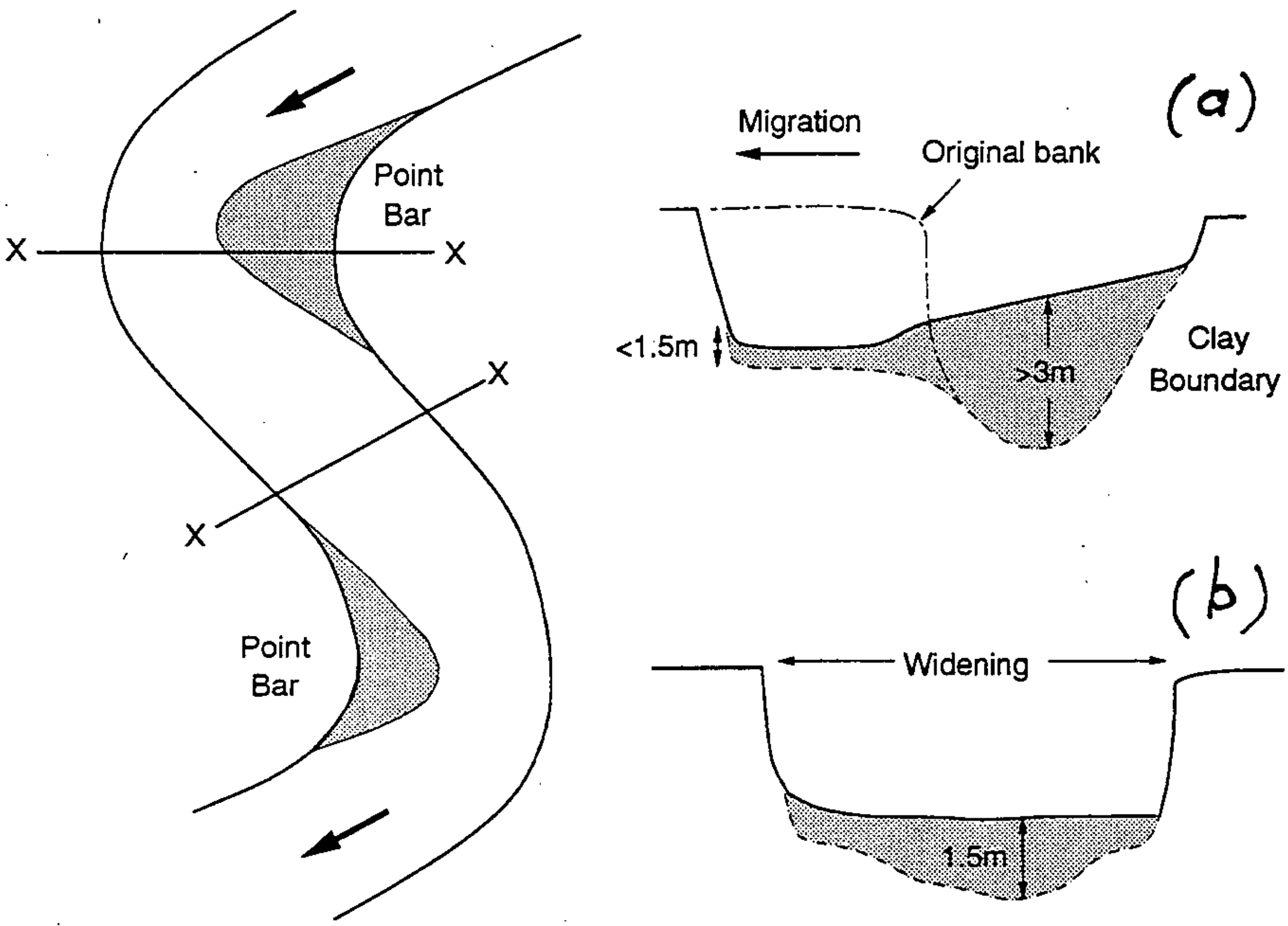


Figure 6.4: Schematic figure of an 'abandoned thalweg' (stippled area is sand). (a) Original boundary of incised stream (dotted line) that has been filled with sand, after which it has migrated laterally, abandoning the deep thalweg of sand as a point bar. (b) Widening of the cross-section at the channel inflection point.

The eventual development of benches in the Glenelg will reduce sand movement in this river. As we discuss in the management section, limiting stock grazing in the streams will encourage vegetation to grow which will stabilise the sand into benches.

Summary of long term storage of sand in the stream network

Of the volume of sand now stored in the Glenelg River and its tributaries, less than two-thirds will be available for downstream transport over the coming decades. The balance of the sand will be stored in benches and bars that will be stabilised by vegetation. In some cases the widening of the tributaries has meant that the majority of sand is now stored in abandoned thalwegs beneath point bars. Another proportion of the sand will be stored on the floodplain of the river.

7. RATES OF SAND TRANSPORT IN THE GLENELG RIVER

In the previous section we discussed the distribution and volumes of sand stored in the Glenelg River and its tributaries. We also discussed the future sources of sand to the Glenelg River and its tributaries, and the main zones of sand storage. In this next section we discuss the *capacity* of the Glenelg River to transport the sand delivered to it. It is important to have an estimate of the rate of sand transport in order to predict how long it will take for the stored sand to move downstream. We conclude that rates of bedload transport are lower than has previously been thought. This is in part because of regulation of the river flow by Rocklands Reservoir.

7.1 Predicting sand movement by extrapolating past rates of movement

7.1.1 Historical rates of sand movement

There is little historical reference to the rate at which sand moves through the river. Anecdotal evidence suggests that the upper Glenelg and its tributaries filled very rapidly with sand. Several landholders have suggested that the main phase of gullying, and the aggradation of the tributaries. occurred within decades. There is no doubt that the main phase of aggradation occurred before the 1940s.

Comparison of the 1947 and 1991 aerial photographs indicates surprisingly little change in the aerial extent of the sand in the Glenelg or its tributaries, although this cannot tell us much about changes in the depth of sand. The major changes in the photos are the stabilisation of fans of sediment debouching from gullies and small tributaries, and the invasion of tributary junctions, and some benches, by vegetation (reeds and grass). As mentioned above, even the small sluglettes that occupy long reaches of the channel have changed their position little over the last 40 years.

7.1.2 Migration of the most downstream end of the sand

The most downstream slug of sand (the 'end-slug') has now reached a point 28 kilometres above Dartmoor. Unfortunately we have no 1940s photographs of this lower reach of river to identify the rate at which the slugs are moving, and the scale of the 1960s photographs is too large to identify the slugs.

Strom (1947) states that "at the Killara Bridge, 10 miles SW of Casterton and about 20 miles downstream by river, the bed does not appear to be badly sanded, and there is still ample waterway" (p.5). However, the accompanying photographs in the report show that Strom visited the site during a period of quite high flow that would cover even the present sand slugs in this portion of the river. The later report by Scott and Furphy (1952) described the same section of river in these terms: "Above Killara bridge ... there is at least 3 feet of sand in the river bed; but below Killara Bridge there is deep water. The toe of the sand bank can be seen moving downstream and is now about 50 feet below Killara Bridge" (p.8). We cannot accept this observation as evidence that Killara Bridge was the most downstream extent of sand in 1952. It is quite possible that the authors of the 1952 report were simply seeing the snout of a sluglette. The same sluglette can be seen today, but there is a large volume of sand further downstream. Nevertheless, this observation provides a maximum rate for sand transport. That is, we know that the end-slug is now thirty four kilometres below Killara Bridge, suggesting a migration rate of 800 m per year since 1952. Following the flood of 1995 we observed that new sluglettes were being deposited in the bed up to four kilometres below the end slug. However, it would take several such events to deposit fully formed sluglettes (ie. 1-5m deep).

The migration of the end slug provides some crude measure of sand transport rates. Assuming a migration rate of 800m per year, a 20m wide channel, and an average sand depth of 1.5m, , and that the sand occupies half of the channel length, then the migration of the end slug represents an annual sand volume of 12,000m ^{3}. This number is a maximum rate because of the uncertainty of whether the sluglettes existed below Killara Bridge before the 1940s.

There has been surprisingly little change in the aerial distribution of sand in the Glenelg catchment since 1947. But this does not tell us what changes there have been in the elevation of the bed over this time. Aggradation and degradation of the river bed tells us about the movement of slugs of sand, and rates of bedload transport. Bedload in sandy channels moves as bedforms of various types. If there is little change in elevation in the bed through a year then it implies that bedload transport rates are low. The next section investigates changes in bed elevation.

Figure 7.1: Former Casterton gauge site. Note the regular cross-section, vegetated banks, and flat sand floor.

7.2 Evidence of sand transport from changes in bed elevation

Information about changes in bed elevation comes from specific gauge records, repeat cross-section surveys, and scour chains.

7.2.1 Specific Gauge records

There are four uncontrolled gauges in the catchment: on the Glenelg River at Fulhams Bridge, Casterton and Dartmoor, and on the Wannon River at Henty. Because the gauges have no controls (eg. a rock bar or weir that controls water levels) the stage discharge relationship must be rechecked every month or so. All three stations are located at regular cross-sections with flat sand beds, and with resistant, grassed banks (Figure 7.1). Therefore, we interpret all variations in the stage discharge relationship as changes in bed level. A graph showing changes in stage (water level) over time for a given discharge is called a stage discharge curve (Figure 7.2a-d). If the curve fluctuates wildly then it can be interpreted that the bed level is changing often and bedload transport is occurring.

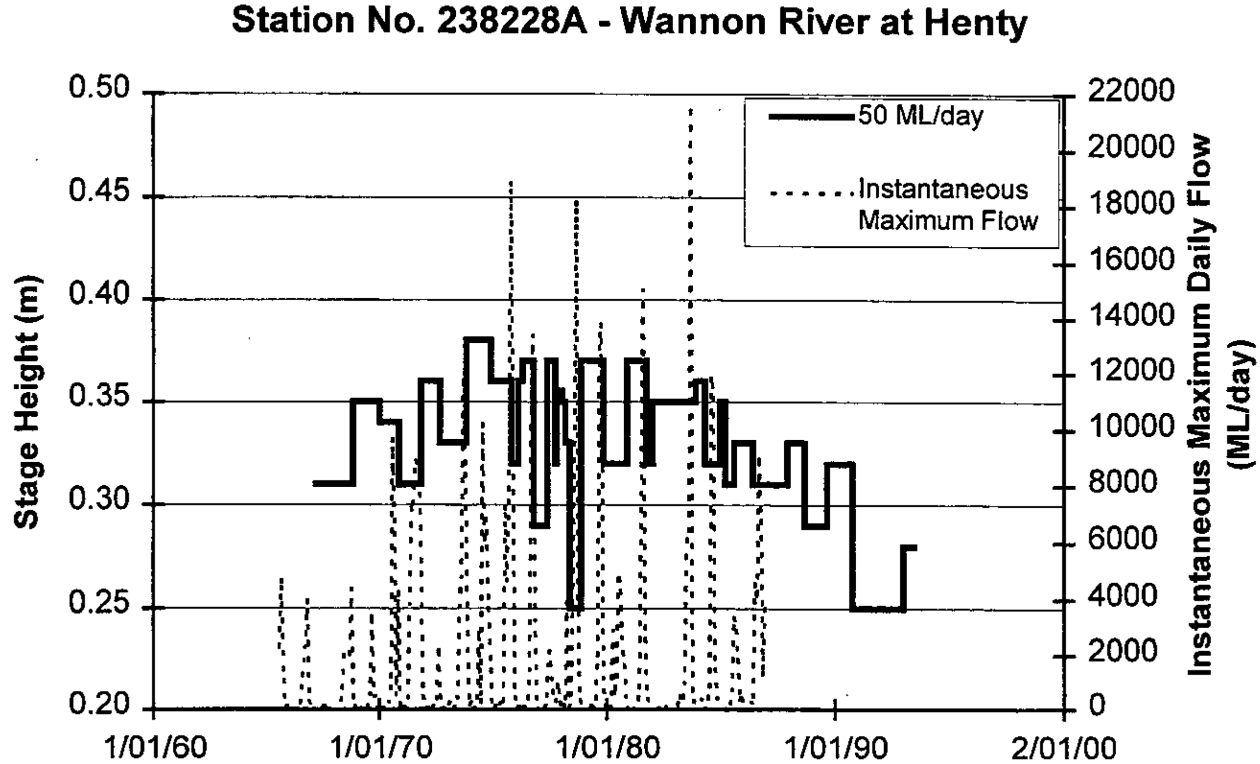


Figure 7.2a: Specific gauge record for the Wannon River at Henty, 1968 to 1991

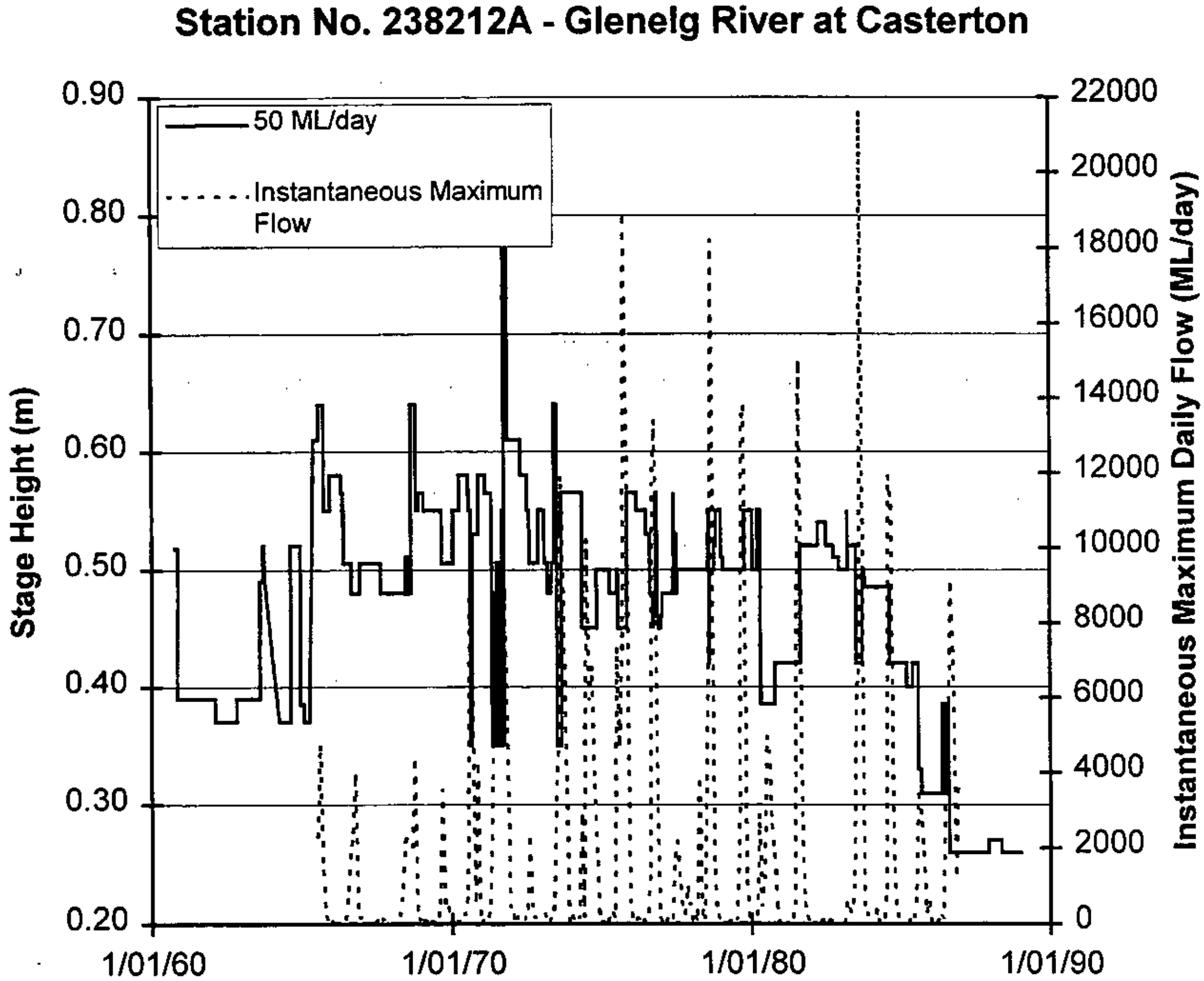


Figure 7.2b: Specific gauge record for low summer discharge (50 Ml/d) for the Glenelg River at Casterton, 1960 to 1988, compared with instantaneous maximum monthly discharge.

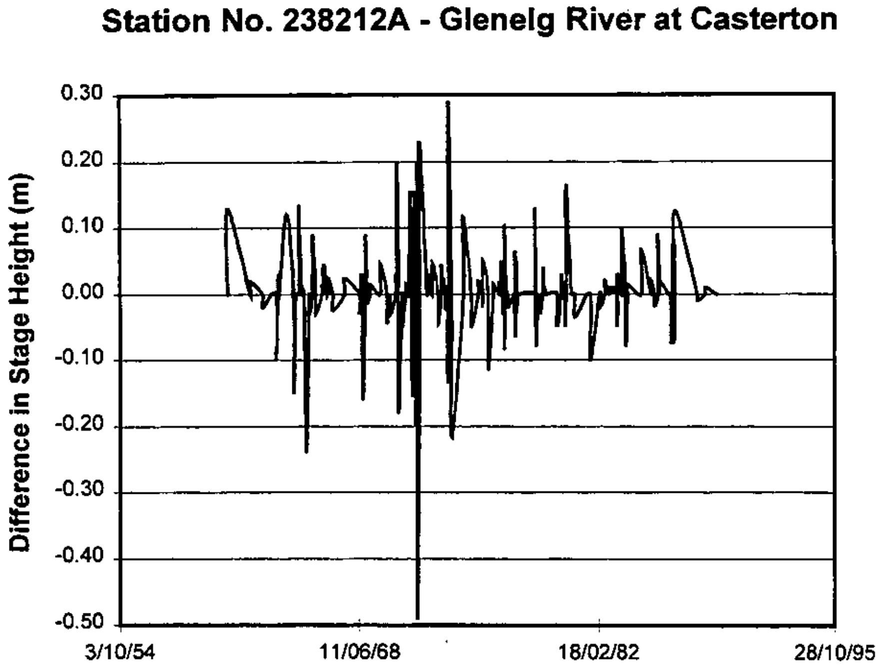


Figure 7.2c: Difference between successive stage readings for a discharge of 50 Ml/d at the Casterton gauge between 1960 and 1988.

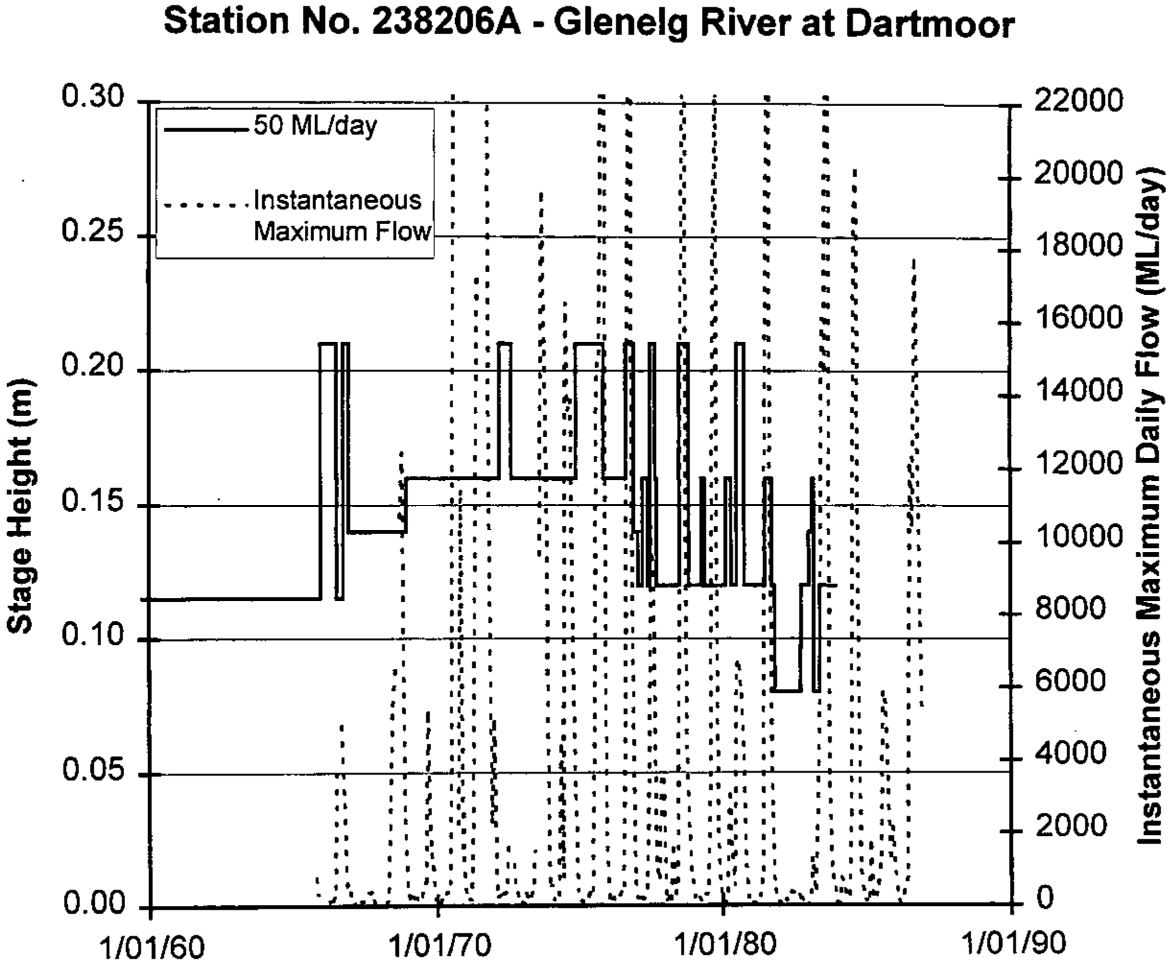


Figure 7.2d: Specific gauge record for the Glenelg River at Dartmoor for a discharge of 50 Ml/d for the years 1960 to 1988.

All three of the specific gauge records show a slight fall in the specific gauge since about 1980. The Wannon record suggests a fall in the bed of 5-10cm since about 1984, as does the Dartmoor record since 1980. The Casterton gauge showed about a 20cm fall from 1980 to 1990. These subtle falls in the gauge may reflect low flows through the 1980s, or they may reflect a general, but slow, trend to falling bed levels.

The most important information provided by the specific gauge records is evidence of the general stability of the river bed over time. Both the Wannon and Casterton SGRs show very little movement of the bed (0.1m and less than 0.08m respectively) whether the rating was taken before or after a major flood. Ratings of the cross-sections are taken at reasonably random points in time, often during quite high discharges, so it is our contention that this is a good record of low bedload movement over the last 30 years. The greatest change in the specific gauge is a single scour of about 0.5m at the Casterton gauge, although the average change from season to season is less than 0.2m. This means that the sand bed of the river is not being scoured to its clay bed in each flood. At most the bed is scouring tens of centimetres.

The evidence of the specific gauge record is supported by a series of regular cross-sections. As part of the 1976 investigation into the feasibility of a weir at Casterton, the SR&WSC resurveyed the full cross-section at Casterton for six separate months (July to September 1976 and January to March 1977). The original cross-sections are lost, but O'Keefe (1978) describes the results: "The average bed elevation rose and fell between limits of 0.15 - 0.2 metres from month to month". This is the same variation displayed by the longer record of the specific gauge. The envelope curve of cross-sections shown in O'Keefe (1978) shows that the total change in the cross-section was less than 0.5m over this period. This small change in the average bed depth is important because two of these cross-sections were surveyed during the floods of August and September 1976. This supports the conclusion from the specific gauge record: that even large floods do not appear to cause major scouring of the bed.

The small variation in the Glenelg River suggests that, over time, sand may be moving through the gauge as dunes or in suspension, but over more than 25 years there has been no movement of the bulk of the sand in the reach - it has been in storage. Sand moves into a reach, moves across the top of the sand slug as a dune, then out of the reach. The sand stored in the bed will only move when the tail of the sand slug reaches the site.

7.2.2 Scour Chains

Estimates of minimum sand transport rates can be made by inserting scour chains into the channel bed. A scour chain is a length of chain inserted vertically into the ground. A known number of links is left exposed on the surface, the sand bed scours and the chain falls down. Subsequent deposition will cover the chain again. Thus, when the chain is dug-up, the length of horizontal chain (minus the original exposed length) shows the depth of initial scour, and the depth of sand over the chain reflects the depth of subsequent fill.

With the assistance of the Glenelg Waterways team we deployed 34 scour chains (1 to 2m in length) at 20 sites across the Glenelg catchment. Eighteen of the chains were located in the Glenelg River, seven in tributaries to the Glenelg River, two in the Wannon River, and eight in tributaries of the Wannon, particularly Bryans Creek. The chains were deployed in July 1994, but there were no significant flows until a minor flood occurred in August 1995. The chains were recovered in late 1995, and early 1996 (after between 524 and 650 days).

Scour chains deployed	Scour chains recovered	Chains confirmed lost*	Failed to recover chain at correct site	Failed to find the correct site	Removed by vandals	No attempt made to recover chains
34	12	5	5	7	1	4

Table 10.2: Statistics on recovery of scour chains in the Glenelg catchment (* ie. the entire chain was certainly lost by erosion of the bed)

Just over one third of the chains were recovered. There were four reasons for the poor recovery rate:

i. It was remarkably difficult to recover the chains in wet sand. We could only dig about 0.75 metres in the wet sand, although we could feel around a further 0.75m with our arms. At five of the sites we were not sure if we could not find the chain because of deep scouring, or because we were looking in the wrong place. A metal detector was not successful at finding the chains.

ii. Because the chains were deployed by several different people, the detailed deployment sheets were not always filled in precisely. After 18 months it was often difficult to find the precise chain site. In some cases cattle had knocked over the star-pickets marking the sites.

iii. Five of the chains were completely removed when tributary fans were eroded away.

iv. One 2m chain was dug up and removed by an enthusiastic fossicker

7.2.3 Results of the Scour Chain Experiment

When they were recovered, the scour chains recorded cut and fill with a precision of about 5cm. In general the scour chains confirmed the specific gauge results: the depth of cut and fill in the Glenelg River and its tributaries is on the order of tens of centimetres during a minor flood (bankfull) event. Unfortunately, the chains were deployed before we had the specific gauge record. Future chains should be located at the Casterton gauge to compare scour around the chain with changes in the specific gauge record.

In the Glenelg River itself, cut and fill was on the order of 40 cm. At Harrow, in the backwater of the Deep Creek TJP, the cut and fill was less than 20 cm, suggesting that the backwater does limit sand transport. Further downstream above the Wando Junction the bed cut 10 cm and filled 40 cm. Similarly, at the End Slug the bed cut 32 cm and filled 45 cm. These results confirm that the entire bed of the Glenelg River is not mobilised during flood events, only the top half metre or less.

Bed level changes were also small in the tributaries. Deep Ck recorded negligible change, either in its bed, or the surface of the TJP below the junction. By contrast, the fan of sand that was blocking the Glenelg River at the mouth of Pigeon Ponds Creek was completely removed, taking four two-metre scour chains with it. It is possible that the erosion of the fan was related to sand extraction in this creek. The Chetwynd River recorded scour and fill of 20cm at Chetwynd South (above the Chetwynd-Moree road bridge) in a sand depth of up to four metres. The depth of scour increased to half metre in a narrow section of the Chetwynd above the Chetwynd Junction road bridge.

The scour chain record from the Wannon system is poor. No chains were recovered from Bryans Creek because the sites could not be relocated from the field sheets. Only the chains on Dwyers Creek, just above the Wannon Junction showed scour and fill of only around 10 cm. By contrast, the small fan of sand at the mouth of the Henty River was completely removed by the flood.

To conclude, the scour chains confirm the following points:

i. the depth of cut-and-fill in a minor flood in the Glenelg River is less than half-a-metre.

ii. sand slugs in the tributary streams also experience limited scour

iii. erosion rates in the backwater of a TJP are low

iv. the fan of sand from Pigeon Ponds Creek was completely removed in the 1995 flood event.

7.3 Estimating Rates of Sediment transport

Changes in bed elevation, or slug migration, are not a direct measure of sand transport rates. We attempted to measure sand transport directly with a Helley-Smith bedload sampler during the August 1995 flood. However, by the time that we got to the Glenelg River, the flood wave had passed, and we could only sample bedload at a discharge of about 200 Ml/d. At this discharge there was negligible bedload transport at Casterton. Therefore, we estimate annual sand transport by using bedload transport equations, and by estimating bedload transport as a proportion of the suspended load. These estimates of sand transport can then be used to estimate the rate at which sand can be expected to move into the Heritage River, and the rate at which extracted sand would be replenished.

7.3.1 Earlier estimates of bedload transport

Bedload transport rates in the Glenelg River were first estimated as part of an evaluation of a proposed weir at Casterton (O'Keefe, 1978). As part of this study, suspended load was measured at Casterton on 26 occasions between August 1976 and August 1977, and the corresponding bedload was estimated using the Schoklitsch equation. By developing a combined suspended and bedload rating curve against discharge O'Keefe was able to estimate the average daily sediment load by integrating through a flow duration curve. This work suggested an average daily total load of 1150 tonnes, or an annual load of 420,000 tonnes. This is equivalent to the total store of sand in the bed of the Glenelg River between the Wando River and the Wannon River junction. It is likely that this is a substantial over-estimate of the total load because O'Keefe probably overestimated the bedload transport rate.

Bedload is "normally less than 10% of the total solids load, although in non-alluvial mountain streams it may reach 70%" (Richards, 1982, p.106). The 10% figure is often quoted in text-books, but the proportion may be higher on the Glenelg River. In alluvial rivers a rule-of-thumb is that the more similar the bedload and suspended load in particle size, the higher the bedload as a proportion of the total load. Deposits of sediment on the floodplain of the Glenelg River have a median diameter of 0.3mm, which is quite close to the median for the bed material of between 0.7 to 1mm. This suggests that the bedload on the Glenelg River should make up a large proportion of the load. Lane and Borland (1951) estimate that bedload in a stream like the Glenelg, with a sand bed, and a suspended sediment concentration less than 1000 mg/l, could be between 25% and 100% of the suspended load. The true percentage is unlikely to be at the high end of this range (ie. 100%) because the suspended sediment concentration on the Glenelg does increase to several thousand mg/l at high flows. Thus we would predict that bedload would be at most 50% of the suspended load. By contrast, the Schoklitsch equation, as applied by O'Keefe, suggests that bedload is between 20 and 80 greater than the measured suspended load. This difference is highly improbable.

Using O'Keefe's suspended sediment data for 1976 we can use the 25% - 100% approximations to estimate the bedload transport rate. We did this by using a logarithmic relationship between discharge and the suspended sediment data (Figure 7.3), estimating the bedload for a series of discharges, then integrating the area under the flow duration curve for that set of discharges. Figure 7.4 shows that, from this limited data-set, the majority of suspended load (and by implication, bedload) is transported at flows below bankfull (ie. 6 - 7,000 Ml/d). Very little bedload is transported either by large floods, or by flows of less than 2,000 Ml/d.

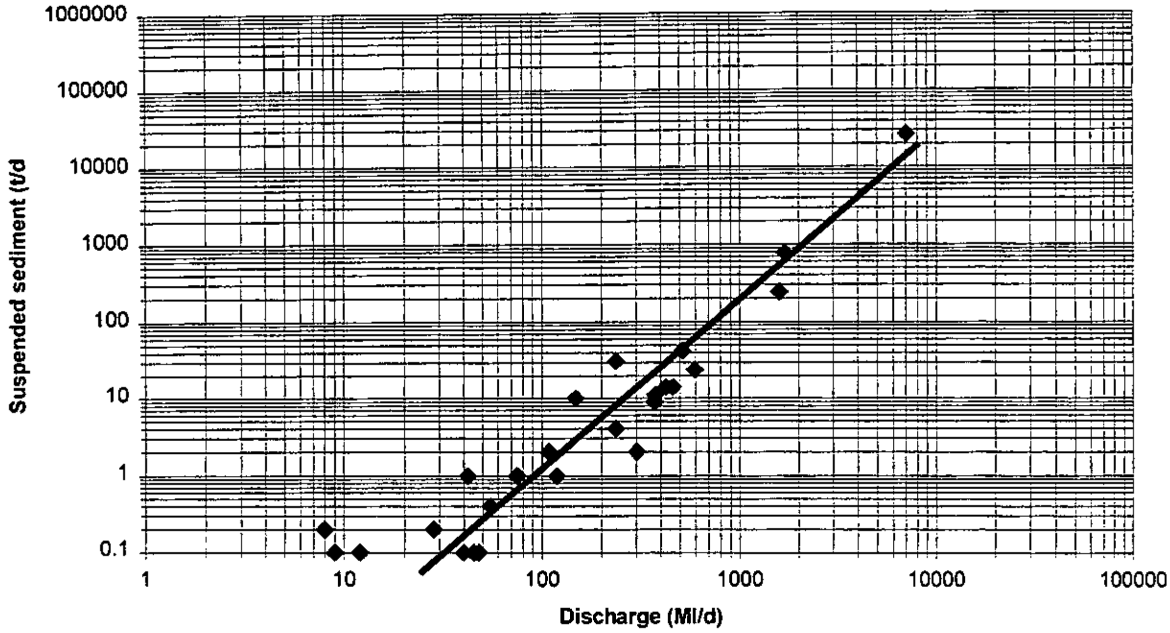


Figure 7.3: Suspended sediment rating curve for the Glenelg River at Casterton for the period 8/76 to 8/77 (from data in O'Keefe, 1978).

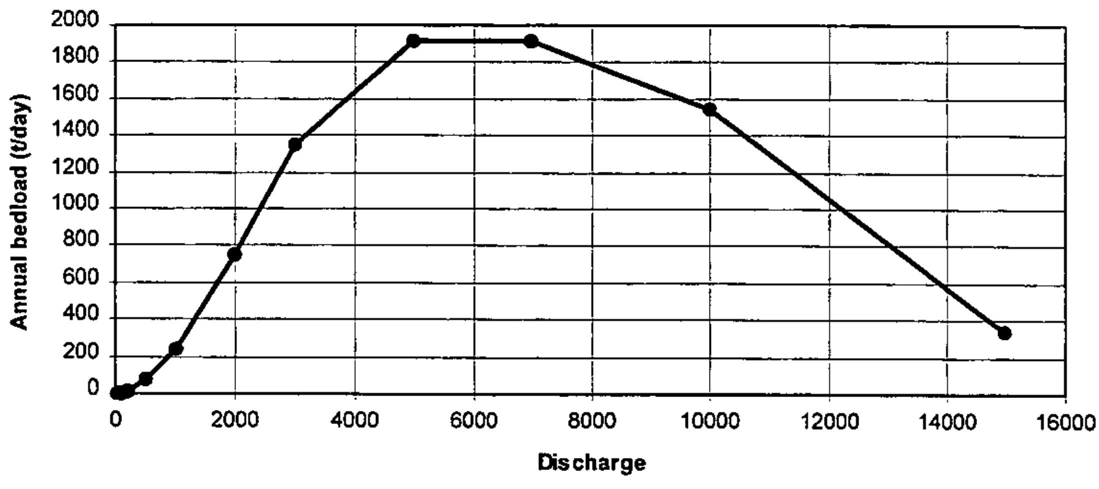


Figure 7.4: Estimated bedload volume (expressed as 10% of suspended load) transported annually by various discharges on the Glenelg River at Casterton (extrapolated from relationship in Figure 7.3 and flow duration curve in O'Keefe, 1978)

If we assume that bedload is 50% of suspended load, then this suggests an average annual bedload transport of about 44,000 tonnes, or 27,500m^3. It is likely that the true bedload lies somewhere between 25% (13,750 m^3) and 100% (55,000 m^3) of the suspended load, which is nearly an order of magnitude smaller than O'Keefe's estimates with the Schocklitsch equation. Uncertainties in this estimate relate to the long term validity of the suspended sediment rating curve (it was only measured for one year), extrapolation of the rating curve to higher discharges, and the methods used to measure the suspended load. Nevertheless, the results suggest order-of magnitude figures for bedload. The figure can be compared with other bedload estimates from equations.

7.3.2 Estimating bedload with Colby's method

O'Keefe used the Schoklitsch bedload transport equation to estimate bedload in the Glenelg River. He does not provide his data, so it is not clear why the results overestimated the load. The Schoklitsh equation "should not be applied to sand bed streams which carry considerable bed sediment in suspension" (ASCE. 1971, p.526). Probably the most appropriate bedload estimation technique for the Glenelg River is that of Colby (1964). Colby's empirical relationships were derived from sand-bedded streams with negligible suspended sediment concentrations, and as such are very appropriate for the Glenelg River. The bed-material discharge per unit width is given as a function of mean flow velocity, water depth, median sediment size, water temperature and concentration of fine sediment. These variables encompass effects on sediment transport due to stream power and shear stress, and could be defined for a series of discharges from O'Keefe's data combined with gauging information at Casterton.

The derived flow duration data (Figure 7.4) suggests that most sediment load is transported at a discharge of about 7000 Ml/d. Using this discharge (depth 3m, velocity 0.78 m/s, width 35m) yields a bedload transport rate of about 1,200 tonnes per day. This figure is less than the value of 2000 tonnes per day estimated if it is assumed that bedload is 10% of suspended load (Figure 7.4). Similarly, a larger flood of 15,000 Ml/d would transport 3000 t/d according to Colby's method, and 10,000 t/d if it was 10% of the suspended load. Thus, using Colby's method predicts a smaller annual bedload (on the order of 20,000 t/yr, 12,500 m^3/yr) than that predicted by taking a proportion of the suspended load.

7.3.3 Bedload transport rates in the tributaries

We do not have much information about bedload transport rates in the tributaries. However, we can make some crude estimates of rates on the basis of sand extraction volumes (discussed below in Section 10.1). For example, in Bryans Creek, repeat cross-section surveys of the bed downstream of the Coleraine Bridge (11.5km of channel) show that the bed is degrading (see Figure 11.1 in Section 11.1). Of particular interest is the degradation of 20 to 30 cm below the Hilgay Lane Ford. At the time of the surveys (1989 to 1993) Hilgay

Ford was the only site where extraction was permitted on the creek. We know that the extraction rate from the site was less than 2,000 m^3 for each of the four years. Importantly, because the extraction took place below the ford, the extraction did not produce upstream progressing degradation that would have refilled the extraction hole. Instead the supply of sand to the extraction site reflects the sand supply from upstream. Because the bed below the extraction site degraded between 1989 and 93, this implies that the extractors were removing at least the volume of sand that was being delivered to the site. Thus, we conclude that the annual bedload transport rate of lower Bryans Creek must be less than about 2000 m^3 per year.

Similarly, there is evidence that the recent sand extraction rate from the bottom end of Pigeon Ponds Creek has exceeded the supply of sand from the stream. In 1994 the fan of sand into the Glenelg River was completely removed, which suggests that extraction exceeded the background transport rate. Furthermore, the volume of bed degradation occurring at the Chetwynd-Morree Road Bridge corresponds to about the total volume of sand extracted. This means that sand supply from upstream is not filling the bed as fast as the extraction is removing the sand. The extraction rate below the Chetwynd-Moree Road bridge before 1991 was as high as 4,000 m^3 per year, suggesting that the background bedload must be considerably less than this volume.

7.3.4 Summary of the Bedload Transport Rate

Several lines of evidence confirm that sand is moving through the Glenelg River system at a rate of between 10,000 m^3 and 30,000 m^3 per year. Bed scour is limited to tens of centimetres. The bedload transport evidence is summarised in Table 10.8. The presumption with the following is that little new sand is being delivered to the river from the catchment.

Lines of Evidence	Conclusions
Direct measurement of bedload	There is negligible sand transport at discharges below 200 Ml/d
Migration of the End-slug	Anecdotal evidence and field observation suggests that the front of the sand sluglette is migrating down the lower Glenelg River at a maximum of 800m per year. This represents an annual load of about 12,000 m^3
Estimating bedload as a proportion of suspended load	Bedload transport = 14,000 m^3 to 55,000 m^3 (most probably around 30,000 m^3). Most bedload is transported by medium sized flows of around 7000 Ml/d
Colby (1964) bedload method	Less than 20,000 m^3 per year

Specific gauge records for three gauges	The bed of the river has changed little over 30 years. Cut and fill is restricted to 10 to 20 cm.
Scour chains	A minor flood led to cut and fill of tens of centimetres in both the Glenelg River and its tributaries.
Bedload transport rate of tributary streams	Sand extraction rates of 2,000 and 4,000 m^3 per year exceed the background sand transport rates of Bryans and Pigeon Ponds Creeks respectively.

Table 10.8: Summary of evidence concerning bedload transport in the Glenelg River and its tributaries

These are some implications of these estimates of bedload transport in the Glenelg River system.

1. An earlier estimate of bedload transport at Casterton (>300,000 tonnes per year, >190,000 m^3 per year) (O'Keefe, 1978) probably over-estimated the bedload transport rate by nearly an order of magnitude.

2. Based on three independent techniques, an annual bedload transport rate of about 20,000 m^3 seems a reasonable working estimate for the Glenelg River at Casterton. The rate may be slightly higher below the Wannon junction.

3. The limited sand transport in the river is supported by the modest changes in the channel bed over time as shown by specific gauge records, scour chains, and repeat surveys.

4. Given the large store of sand in the bed of the Glenelg River and its tributaries, it will take many decades (over a century) to remove all of the sand at present transport rates. For example, the sand slug from the Wando River, that now lies between Section Road Bridge and the Wannon Junction, has a volume of about 400,000 m^3. At an estimated transport rate of 20,000 m^3 per year it will take 20 years to remove this sand. In reality it may take much longer because some sand is also reaching this slug from upstream. By 'remove the sand' we mean that the sand will be eroded from the upstream end of the slug at the Wando River, and will be delivered to the Wannon Junction where it will move progressively across the top of the sluglettes.

5. The limited evidence about sand transport from the major tributaries (eg. Pigeon Ponds and Bryans Creeks) suggests that they each transport a few thousand m^3 of sand each year at the most.

6. Extrapolating past migration rates, the sluglettes will reach the Heritage River at Dartmoor in about 35 years. After this time between 12,000 m^3 and 20,000 m^3 of bedload sand will enter the Heritage River each year. The estuary is a sand sink. That is, little of the sand

will be transported to the coast, instead the sand delivered to the estuary will remain in storage.

7. Artificial sand extraction rates would need to be more than about 20,000 m^3 per year to have an appreciable impact on the sand stored in the Glenelg River.

7.4 Controls on Sand Transport Rates: Flow Regulation by Rocklands Reservoir

We have demonstrated that bedload transport in the Glenelg River is modest in comparison with the volume of sand in storage. We have also shown that sand transport is dominated by flood events. Part of the explanation for the modest sand transport rate in the river could be the impact of Rocklands Reservoir on the flow regime.

The Glenelg River is regulated from the Rocklands reservoir (closed 1953). Two thirds of the Glenelg's mean annual flow is diverted to the Wimmera-Avon Basin for the Wimmera-Mallee Stock and Domestic system. Thus, a diversion canal takes flow from Rocklands to Toolondo Reservoir, reducing the mean annual discharge below Rocklands from 71,500 Ml for the pre-dam period (1944-51) to 22,200 Ml for the post-dam period (1954-81) (GCWMS, 1992). On average, releases to the Glenelg from Rocklands are 25 Ml/d when water is not being diverted, falling to 10 Ml/d when flow is being diverted during the irrigation season. The lower flow during the irrigation season is because leakage from the diversion canal provides the balance of water required to provide 25 Ml/d at Harrow (Godoy, 1996).

Rocklands reservoir has a capacity of 348,000 Ml, and the average annual inflow to the reservoir is 110,000 Ml. Thus the reservoir can hold three times the annual flow. This means that the reservoir can affect major floods as well as average flows. This is shown by comparing the natural inflows to Rocklands with the spills (ie. floods over the spillway) that would have occurred between 1903 and 1991 if the dam had been in position all of that time (Figure 7.5).

We know that the 1946 flood was responsible for the movement of large volumes of sand. This flood had a monthly discharge of about 70,000 Ml (Figure 7.5). This, of course, does not tell us much about the instantaneous discharge. Nevertheless, in the absence of Rocklands, since 1953, there would have been at least nine floods with monthly flows of similar magnitude to the 1946 event. With regulation by Rocklands, the dam has only spilled six times since 1953, and only the 1956 spill exceeded the size of the 1946 monthly flow at Rocklands. Thus, at the upstream end of the study area, Rocklands has removed the flood flows that would have transported large volumes of sand. The impact of Rocklands remains considerable at Casterton. As is demonstrated below, the remaining flows in the Glenelg do not transport large volumes of sand.

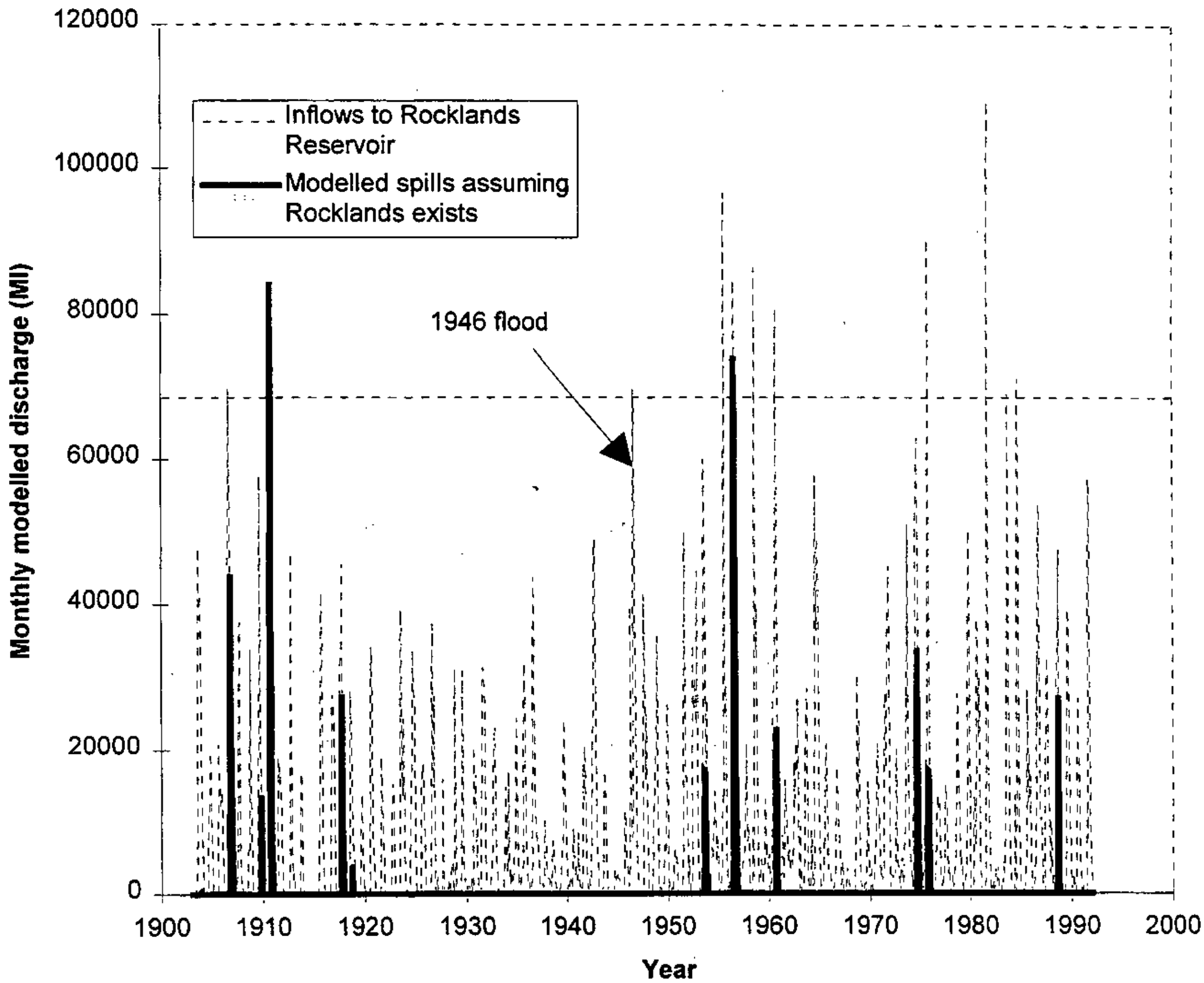


Figure 7.5: Comparison of natural monthly inflows to Rocklands Reservoir with the spills from the reservoir (ie. overtopping of the reservoir) that would have occurred if the dam was in place. The dam was closed in 1953, so numbers before this date are hypothetical, numbers after are the true spills. (Source: modelled with the REALM model by Mr John Martin of Wimmera-Mallee Rural Water Authority).

Summary of bedload transport

The bed of the Glenelg River and its tributaries are not scoured out at high flows. Scour depths tend to be on the order of tens of centimetres. Most sand is transported at flows below bankfull rather than by large floods. Four independent methods suggest that the annual bedload transport rate in the Glenelg River is on the order of tens of thousands of cubic metres, rather than the hundreds of thousands of cubic metres estimated in O'Keefe (1978). We are suggesting a working estimate of 20,000 m^3 *per year at Casterton. At this rate, it will take hundreds of years to remove the sand stored in the stream channel. There is little question that the sand transport rate would be considerably higher above the Wannon Junction, without the regulating effect of Rocklands dam. Movement of sand out of the stream network is the subject of the next section.*

8. PREDICTING THE FUTURE MOVEMENT OF SAND IN THE GLENELG RIVER AND ITS TRIBUTARIES WITH NO INTERVENTION

We have now described the distribution of sand stored in the Glenelg River stream network, the volume of sand, the future sources, and the rate at which the sand is moving. This section brings this information together to describe the pattern and rate of future sand movement through the stream network in the absence of any intervention.

To summarise: the major source of sand to the Glenelg and Wannon Rivers is from tributaries draining granite catchments. Sand from the tributaries forms discrete slugs in the Glenelg River. These slugs often dam the river. The slugs attenuate downstream, gradually giving way to a succession of small sluglettes. The major future source of sand to the large slugs is from sand stored in the downstream end of tributaries, because little sand is now being contributed from the catchment. There are about six million cubic metres of sand stored in the Glenelg and its tributaries. Sand is moving through the stream network at a slow rate, with only tens of thousands of metres per year being removed by bedload transport.

We will predict the sequence of changes that are likely to take place, over the coming decades, to the sand stores in four reaches: Rocklands to Harrow, Harrow to the Wando Junction, Wando Junction to Dartmoor, and the Wannon system.

8.1 Rocklands to Harrow

Sand supply from Yarramyljup and Mathers Creeks is declining, and the channel beds are being stabilised by vegetation. All of the sand that enters the Glenelg River from these tributaries will be stored in the deep pools that occur immediately downstream of the mouths. Almost no sand from either of these streams will continue downstream. For example, if we assume that Mathers Ck carries 10% of the annual load of the Glenelg River at Casterton (a great overestimate) (say 2000 m^3 per year), then this would enter the four kilometre long pool about 2.5 km downstream of the junction. The pool is about 20m wide and over 3m deep. The sand would prograde into the pool as a wedge, at a rate of 33m per year. At this rate the pool would take 120 years to fill. In fact, the total length of the sand wedge at the top of the pool, resulting from at least 20 years of sand inputs from Mathers Creek, is only about 30m. Thus, sand from these large tributaries will not threaten the lower Glenelg River as a whole, but it may eventually threaten the biologically valuable pools.

The large slug of sand deposited in the 25 river kilometres of the Glenelg between Pecks Rd and Harrow (over 1 million m^3 of sand) is trapped behind the Deep Creek tributary junction plug (TJP). Scour chain measurements (above) have confirmed that the sand transport rate at Harrow, in the backwater of the lake, is negligible. There is unlikely to be any substantial change in the bed elevation at Harrow until the Deep Ck TJP is removed.

8.2 Harrow to the Wando Junction

This reach of river includes the three major TJPs from Pigeon Ponds Creek, Deep Ck and the Chetwynd River. We predict the following changes.

i. The major tributary streams in this reach will erode their stores of sand over several decades, beginning at the upstream end. This process has begun in Pigeon Ponds and Bryans Creek (on the Wannon) because of sand extraction, but it will begin in a few decades in the other creeks. Storage of sand in benches and in abandoned thalwegs will hasten the removal of sand from the tributaries. The eroded sand will be deposited in the Glenelg River.

ii. As sediment supply from the tributaries declines the upstream end of the TJPs in the Glenelg River will erode. The effect of a decrease in sand supply from the tributaries is shown by the examples of the Wando River (described below) and Pigeon Ponds Creek. Sand extraction in Pigeon Ponds Creek intercepted the sand moving through the creek and starved the TJP of sand. As a result, the fan of sand at the mouth of the creek, that had been in position since the 1940s, was removed by a minor flood.

iii. With a decrease in sand supply from the tributaries, the three major slugs of sand in this reach of the Glenelg River will begin to erode. They will be eroded both by flow from the tributaries that no longer carry large sand loads, and by the Glenelg River itself. The total load of sand being transported downstream from the slugs will not change, but the slug will begin to attenuate. That is, the depth of sand in the slug is presently deepest at the upstream end immediately below the junction. Over time the deepest point of sand will migrate downstream, getting lower as it travels. This is the classic 'sand wave' model described in many studies.

iv. Gilbert in his classic paper on hydraulic mining debris in California, suggested that sediment that is episodically introduced into a channel ..."is analogous to a flood of water in its mode of progression through a river channel. It travels in a wave"...(Gilbert, 1917). Thus the bed of the river will rise and then fall as the wave passes. Gilbert observed that both the amplitude of sediment waves, and their velocity, decline as the wave moves downstream. This model of sediment movement has been observed in many streams (Pickup, Higgins et al., 1983; Madej and Ozaki, in press). For a single slug of given size, the rate of sediment transport declines downstream because the rate of bedload transport declines with small decreases in slope. The amplitude (depth) of the slug also decreases downstream because the sediment is 'sorted' as it migrates, with finer sediment moving further. This dispersion is described by Pickup (Pickup, Higgins et al., 1983). A good example of the process may be the slug of sand that has originated from the Wando River. The sand supply from the Wando River was suddenly increased and exhausted by the channelisation and desnagging work of the 1960s. The large slug of sand below the mouth of the Wando River described in the report to the Glenelg Shire by Scott and Furphy (1952), is gone, and the upstream end of the sand slug is now located below Section Road Bridge, about 1.5 km downstream. This upstream end of the slug is eroding, as shown by the bed armour developing on the surface in this reach. The armour is formed of gravels from local bank erosion. We have seen no other major examples of armouring in the catchment. Thus the slug of sand has attenuated once the upstream source of sand was removed. The same pattern will probably occur in the Deep Ck, Pigeon Ponds Creek, and Chetwynd TJPs.

v. The backwater from the present sand slugs (eg. the lake above the Deep Ck TJP) will remain for many decades even when the sand supply from the tributaries ceases. However, with the erosion of the upstream end of the sand slugs, and the downstream migration of the slug, the backwater will get shorter (as the depth of the sand slug decreases) and will move downstream. In addition, the river is likely to begin to cut a deeper, migrating channel through the sand slug. This has certainly occurred below the Wando Junction. This deeper channel will drop the level of the backwater further. To give an example of this process, the Deep Creek TJP will begin to erode when the sand supply from the creek decreases. If the Wando River is a typical example, the upstream end of the sand slug could migrate more than a kilometre downstream, and the bed would fall at least 0.5m in the process. The stream could also cut a meandering channel up to 1m deep into the present flat sheet of sand. The result of this is that the backwater lake would be displaced downstream, and would become shallower, and thus shorter. The Glenelg River in this reach has a slope of about 0.001, meaning the bed falls by about 1m for every kilometre along the river. Thus, if we assume that the lake surface is horizontal, then movement of the Deep Ck slug one kilometre downstream, combined with a 1.5 m fall in the bed depth, would decrease the maximum depth of the lake from 4m to 2.5m, and reduce its length from 4km to 2.5km. In reality the decrease in the lake area would be greater than this because the depth of sand decreases rapidly below the junction of Deep Creek.

vi. The downstream migration of the lake, and fall in water level, would also increase sand transport from the sand slug at Harrow as the backwater moved downstream

vii. Eventually the stretch of river between Deep Creek and Burkes Bridge will be a flat sheet of sand an average of 1 to 1.5m deep. This sheet will continue to prograde downstream, gradually filling up the pools between the chains of sluglettes that lie between Burkes Bridge and the Wando Junction.

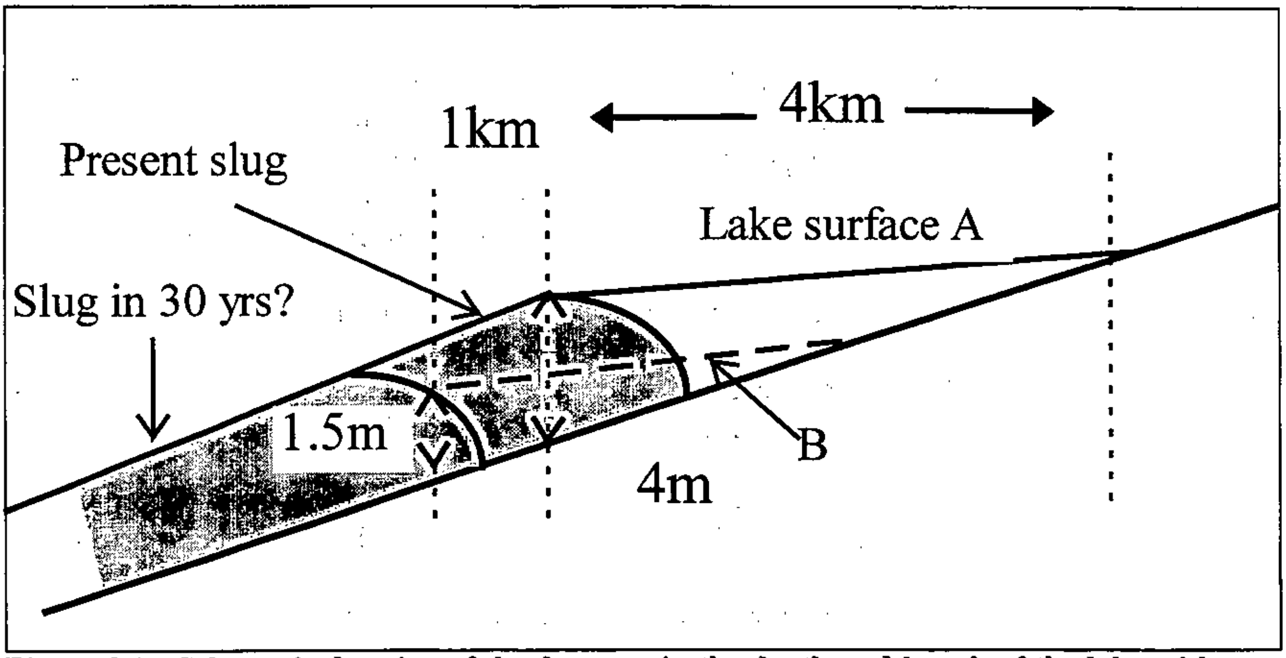


Figure 8.1: Schematic drawing of the decrease in the depth and length of the lake with downstream migration of the slug over the next 30 years.

There are about three million cubic metres of sand stored in the channel system between Pecks Road (downstream of Fulhams Bridge) and the Wando Junction. Of this volume, a maximum of about two million cubic metres will not be stored in benches and abandoned thalwegs, and will be available for transport through to Casterton.

8.3 Wando Junction to Dartmoor

Between the junctions of the Wando and Wannon Rivers with the Glenelg is a large slug of sand (the Casterton slug) that originated from the Wando River and its tributaries. As discussed above, there is little sand being delivered to the upstream end of this slug. The Wando River was the primary source, but it has now stabilised. Most of the new sand reaching the slug comes from the Glenelg River upstream, as sand moves through the sluglettes. Because the supply of sand to the Casterton slug has declined, the upstream end of the slug has begun to erode. The upstream end has already moved some 1500 m downstream of its position in the 1950s. This slow movement suggests that the sand slug will take many decades to move through the reach. The slight fall (about 10cm) shown in the specific gauge record since the 1980s (Section 7.2.1) does suggest that the sand wave may be entering its falling stage.

Invasion of the bed by reeds will accelerate the stabilisation of this reach, and lead to the development of benches in the channel. Narrowing of the channel by benches could reduce the volume of sand stored in the reach to around 200,000 m^3. If the sand supply from upstream were reduced, then natural sand transport rates could remove this volume of sand in under ten years. Artificial extraction could increase this rate.

8.4 The Wannon System

By far the major supply of sand to the Wannon River comes from Bryans Creek, although some sand is delivered from Dwyer and Henty Creeks. Bryans Creek has delivered about 200,000 m3 of sand to the Wannon, and this sand has blocked the river (producing a backwater lake), and is migrating slowly down the river. The front of the sand slug has certainly reached the Grunnebergs Bridge, about 9 km below the Bryans Ck junction, where sand depths are over three metres. Eight kilometres further downstream at Boiling Down Bridge, the depth of sand has fallen to only 1.5 metres, and sand depth progressively declines over the next 15 or so river kilometres to the Glenelg Junction. There are few obvious stores of sand in the Wannon River above the Glenelg Junction. Thus, the slug has migrated about half of the distance from Bryans Creek to the Glenelg River in perhaps 50 years. The depth of sand remains constant, implying that the slug is not actively eroding (ie. that it had passed its peak). This is confirmed by cross-sections surveyed in 1957 and 1991 at both Grunnebergs and Boiling Down Bridges (GCWMS, 1992, figure 5). There is almost no change in the elevation of the bed over this 34 year period suggesting that the sand slug in the Wannon is still being supplied with sand from Bryans Creek.

If the sand supply from Bryans Creek declined, then the Wannon slug will begin to slowly degrade as it moves downstream (ie. it will get shallower). The stability of the bed of Bryans Creek below Coleraine (GCWMS, 1992) suggests that Bryans Creek has not yet begun to actively degrade. This means that it will be many decades before Bryans Creek stops supplying sand to the Wannon, and so before the sand slug in the Wannon begins to degrade.

To conclude: first, the Wannon is not a major source of sand to the Glenelg River, and it will be many decades before the slug of sand from Bryans Creek reaches the Glenelg River.

Second, the lake dammed behind the Bryans Creek TJP will also be preserved for many decades.

In terms of managing sand in the Glenelg River over say the next 30 to 40 years, the Wannon can probably be ignored. However, when the slug of sand from the Wannon does reach the Glenelg River it will contribute perhaps 200,000 m^3 of sand over several decades.

8.5 Wannon Junction to Dartmoor

The Glenelg River above the Wannon Junction is filled with a slug of sand that terminates in an avalanche face at the junction. Because of the increase in discharge from the Wannon River, the continuous slug of sand in the Glenelg River spreads-out into a chain of sluglettes. Thee sand and water supply to the sluglette reach is unlikley to change over the coming 30-40 years. Thus the sluglettes are expected to remain in their present positions, with the lowermost slug (the End Slug) migrating at less than 1 km per year.

Reducing sand supply to the sluglette reach below the Wannon Junction (say by extracting sand from the Casterton Reach upstream), is unlikely to reduce the rate at which sand migrates toward Dartmoor. This is because the deficit in sand at the Wannon-Glenelg Junction would be made up with erosion of the sluglettes below the Wannon Junction. That is, the reach between Wannon Junction and Dartmoor would begin to operate as a long sand slug, with the downstream sand supply being maintained by erosion of the upstream end of the slug. The only way to reduce the rate of sand transport toward Dartmoor is to intercept sand near the End-slug, that is, at the downstream end of the reach.

If the upstream sand supply were cutoff, then the 300,000 m^3 of sand stored between the Wannon and the End-slug, would take 3 to 4 decades to move through the reach (ie. to be eroded from the upstream end and deposited at the downstream end) , and about a further ten or 15 years to reach Dartmoor. This rate assumes that there is little long-term storage of sand in this reach. This is probably a reasonable assumption. The channel through this reach is confined between high terraces and there is little opportunity for sand to be stored in benches.

Summary of future changes to the sand if there is no intervention

Sand stored in the streams of the Glenelg catchment are stored in slugs that occupy the downstream end of tributaries, and the beds of the Wannon and Glenelg Rivers below the tributaries. A reduction in the supply of sand to the upstream end of the slug will not reduce the export of sand from the downstream end, instead the sand deficit will be made up from erosion of the upstream end of the slug. Thus the slug will move downstream, getting lower and longer as it moves. The rate of slug migration will decline as it migrates because the slope decreases. The slugs in the lower end of tributaries will erode from the upstream end first, maintaining the existing sand supply to the slugs in the trunk streams. Within a few decades the tributary supply of sand will decline, and the upstream end of the trunk slugs will begin to migrate downstream. We make the following points:

The backwater lakes behind the TJPs will move downstream progressively with the slug in the trunk stream, getting progressively shorter and shallower over the decades. They will probably be drained entirely when the sand in the TJPs reaches a depth of less than 1.5m or so.

The movement of sand through the 'chain-of-sluglette' reaches between Burkes Bridge and the Wando Junction, and between the Wannon Junction and the End-slug, will not be affected by changes in the TJPs for many decades, because the TJPs will maintain their sand supply at the downstream end. This means that the rate of sand entering the Heritage River reach can only be reduced by intercepting sand at the End-slug itself.

At present sand transport rates it will be perhaps 30 years before the sluglettes will reach Dartmoor, and another century or more before the major stores of sand have evacuated the river system. The Wannon will not be contributing significant quantities of sand to the Glenelg River for several decades.

9. MANAGEMENT OPTIONS FOR SAND IN THE GLENELG RIVER

Managing sand in the Glenelg River involves removing sand from the river, locking the sand up so that it cannot move further down the system, or deliberately moving the sand downstream to another location. There are five management options.

i. Do nothing (the changes that would occur with no intervention were discussed in the last section and will not be discussed further here)

ii. Influence sand transport using regulated flows from Rocklands Reservoir.

iii. Channelise and desnag the river

iv. Artificially extract and remove the sand

v. Build weirs to artificially trap the sand

Management options for the Glenelg River depend upon the management aims. For example, it may not be desirable to hasten the movement of sand downstream if the management aim is to protect the Heritage River. These issues are discussed in Section 12. In this section we simply discuss the potential of different management activities to influence sand transport or storage

9.1 Managing sand through flow regulation from Rocklands Reservoir

Depending upon the chosen sand strategy, sand transport could be influenced by regulated flows from Rocklands Reservoir. For example, proposed improvements in the Wimmera-Mallee stock and domestic system could lead to an extra 7,000 Ml of water per year being available from Rocklands (see general discussion in Mitchell, et al., 1996). Release of this water could influence sand transport. However, the capacity of Rocklands to influence flow is limited by the size of the outlet structures. The maximum volume that can be released from Rocklands is about 1000 Ml/d (5-600 Ml/d from the wall and another 4-500 Ml/d from the channel at Twelve Mile). Over the last decade, this flow has only been exceeded for 4% of the time at Fulhams Bridge gauge. Downstream at Casterton, a flow of 1000 Ml/d is exceeded about 17% of the time. At Fulhams Bridge, the flow exceeded 1000 Ml/d on 19 occasions between 1985 and 1995. The river usually stays above 1000 M/d for 3 to 5 days, but it can stay high for weeks. On one occasion it stayed above 1000 Ml/d for 27 days, and another for 43 days. Thus, a flow of 1000 Ml/d for several days would be typical of the annual flood in the river.

Because the flow release from Rocklands is limited to 1000 Ml/d, then it appears that Rocklands can not increase sand transport significantly. Flows of 1000 Ml/d day are already common, and we have seen above that flows of this magnitude carry only a modest volume of sand. Most sand transport occurs at higher flows of around 7,000 Ml/d. These flows originate from rainfall in the tributaries below Rocklands and so are not regulated.

One effect that Rocklands could have is to fill the pools of water between the sluglettes in the 'chain-of-sluglette' reaches. This process is described more fully in Mitchell et al. (1996). Long periods of above average flow could lead to the more rapid progradation of sluglettes into pools. If the pool is filled sufficiently, then the velocity reversal process will be restricted, and the pool will not be cleaned-out. Since the pools between sluglettes are the major habitat left in the Glenelg River, long periods of above average flow should be discouraged.

In general, regulation of flow from Rocklands Reservoir provides limited opportunities to alter rates of sand transport because of the limited volume of water that it can release.

9.2 Effects of desnagging on sand transport

Following the recommendations of a Parliamentary Public Works Committee (1959), a River Improvement Trust was constituted on the middle reaches of the Glenelg River. The major tasks for the Trust was to decrease flooding on the river. Sand and snags were seen to be the major causes of flooding and so their plans were, first, to carry out soil conservation works in the catchment to avoid further siltation of the river; and second, to remove obstructions (snags) from the river so as to accelerate the downstream movement of sand and so reduce the severity of flooding. This followed from the conclusion of Strom (1947):

> *"The improvement of the carrying capacity of the river channel appears to offer the most practicable way of relieving the flooding problem, pending the effectiveness of soil conservation .... Such improvement may take the form of removal of logs, snags, etc. lying in the bed .. or it appears possible to make one or two cuts in special localities. ... It is considered that, if the velocity of riverflows could be increased by clearing and/or shortening the channel, this would help to transport some of the accumulated sand and so further relieve ... [the flooding position at Casterton]" (p.3).*

Surprisingly, the Public Works Committee did not consider the dramatic impact that Rocklands Reservoir would have upon flooding - far more than the small impact of desnagging. Nevertheless, in 1961 and 62 the Trust carried-out a desnagging program along the Glenelg River, approximately from the Wando junction nearly to Dartmoor, and in the lower Wannon River. There was also a large river improvement program in the Wando River (including excavation of channels at the mouth of the Wando, and from Satimer Bridge to Wando Vale Bridge, to shorten the river's course; and desnagging of the river between Wando Vale Ponds and the Glenelg junction[Camp Scott Furphy, 1992 #1276]. Further desnagging was carried-out by the Shire of Dundas in the Wannon River through the Murndal Estate in 1977-79 (GCWMS, 1992).

Attempts to evaluate the effective of desnagging upon flow velocities have suggested modest improvements in flow velocity (Gippel, O'Neill et al., 1992). Certainly the effect is not measurable in a large river if the snags occupy less than 10% of the cross-section area (Gippel, O'Neill et al., 1992). The effectiveness of the desnagging on the Glenelg and Wannon Rivers has not been rigorously established. Garlick and Stewart (1986) reported that the desnagging increased flow velocity from 0.45 m/s to 0.54 m/s (20%) at the Sandford Gauge. They do not state how this value was established, or for which discharge. Nevertheless, if it were true, then the Colby bedload function suggests that this would produce a 33% increase in the sand transport rate (based on a 7,000 Ml/d flow at the Casterton gauge). Farmers living on the desnagged sections of river suggest that the rate of sand transport has increased since the desnagging, but this has not been verified. Since desnagging tends to increase flow velocities at low flows more than high flows, the effect of the desnagging may have been to fill-up the pools between sluglettes more quickly. The desnagging would also have led to a sudden pulse of sand as the sand stored behind log-dams was released.

The effect of the channelisation was much more profound on the Wando River. There is a dramatic contrast between the river in the 1950s (a flat sheet of sand) and the modern river, in which there is little sand storage, and an actively eroding clay bed. Farmers living along the Wando River suggest that the sand was evacuated quickly after the channelisation works were completed.

To conclude, desnagging may have increased the rate of sand transport in the treated reaches of the Glenelg and Wannon Rivers, although the increase is likely to have been modest. For example, it is unlikely to have doubled the transport rate. Channelisation was much more effective on the Wando River. Predictably, channelisation works are more effective on small, steep streams than large ones. There are limited opportunities for completing more desnagging works on the Glenelg River, but there is some opportunity on the Chetwynd River. However, channelisation and desnagging are no longer considered appropriate management activities in most Victorian streams.

Summary of regulation and channelisation as management options

1. *Flow regulation by Rocklands Reservoir provides limited potential to manage sand transport rates in the Glenelg River. This is mostly because the storage can only release flow at about 1000 Ml/d which transports little sand..*

2. *Desnagging and channelisation in the 1960s and 70s led to a great increase in sand transport from the Wando River, and possibly a slight increase in transport in the Glenelg and Wannon Rivers. It is unlikely that such techniques offer much potential today for managing sand in the catchment.*

3. *The major sand management technique on the Glenelg River artificial sand extraction. This is the subject of the next section.*

10. ARTIFICIAL SAND EXTRACTION IN THE GLENELG CATCHMENT

Artificial sand extraction is the most important management option available to influence the distribution of sand in the Glenelg River catchment. The management plans of the 1950s discussed direct sand extraction as a management option, but were uncertain where to dump the sand. Since that time, commercial sand extraction has become an important industry on the Glenelg River. There is a shortage of good quality siliceous sand in western Victoria and eastern South Australia because the sand supply is dominated by carbonate sands that are not good for construction work. Thus, sand extracted from the Glenelg and its tributaries supplies sand to Horsham, Mt Gambier and Portland. There is potential to use commercial extraction as a useful tool in managing the sand in the Glenelg catchment.

The following sections describe:

i. the history and past volumes of sand extracted from the catchment

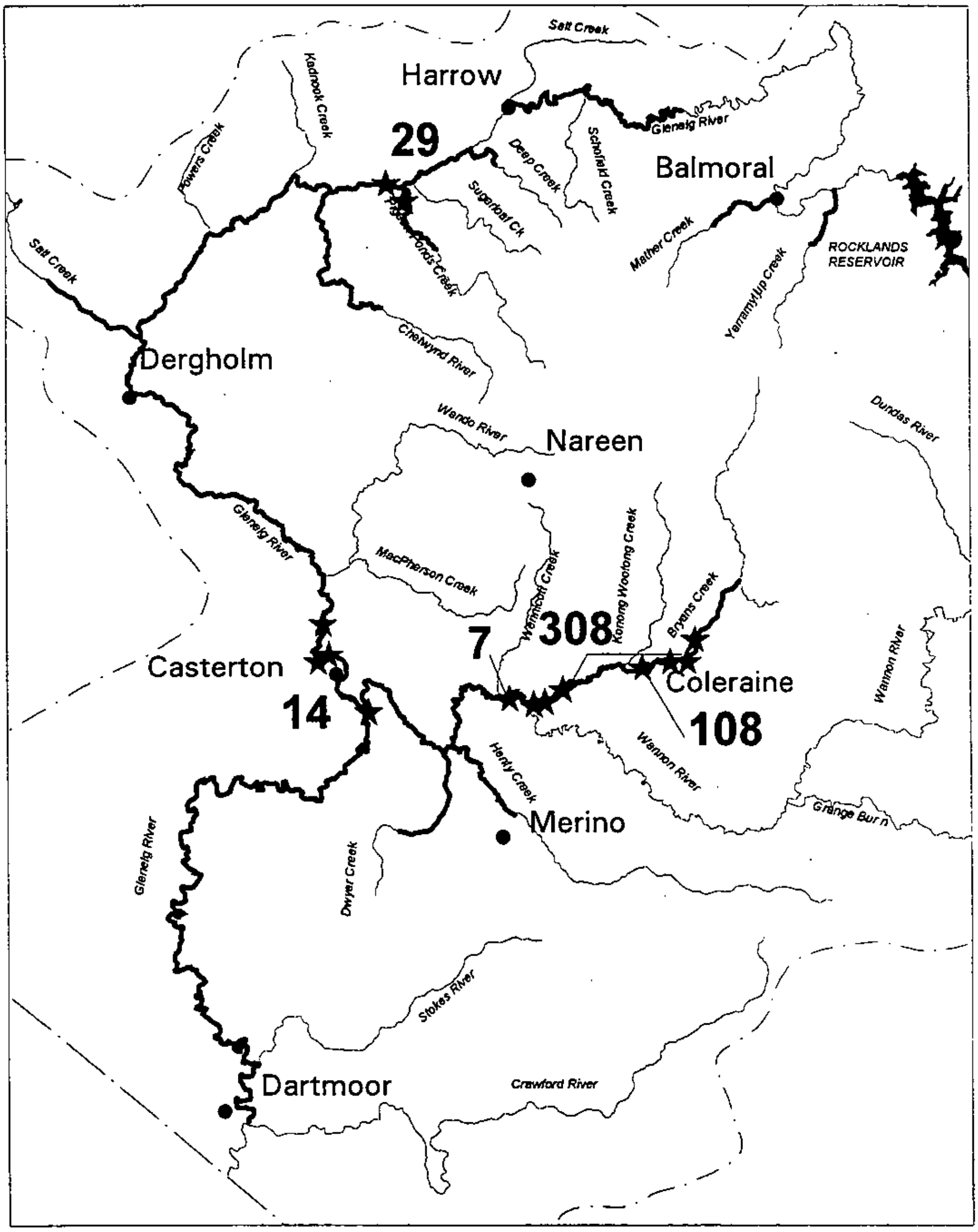
ii. the effect of sand extraction upon bed, bank and tributary erosion

iii. benefits and limits to managing sand in the Glenelg catchment with artificial sand extraction.

10.1 History and volumes of extraction

All sand extraction from the bed and banks of streams must be licensed by the Victorian government. Thus, volumes of sand extracted from the Glenelg catchment were estimated from the Department of Natural Resources and Environment (DNRE) extraction licence files (held in the Horsham office of DNRE, and in archive at Hamilton DNRE). Royalties have been paid to the government for about 470,000 cubic metres of sand since 1956 (Figure 10.1). The great majority of this extraction (about 415,000 m^3, or 88%) has taken place in Bryans Creek, with most of the extraction being used for construction of the Portland smelter. The peak rate of extraction in this creek was 50,000 m^3 per year. Figure 10.5 shows that extraction is also active in Pigeon Ponds Creek, in the Glenelg River at Casterton and in the Wannon River. These figures are likely to be a minimum for two reasons. First, much extraction goes unreported; and second, most of the extraction volumes are based on estimates made by the extractors themselves.

The volume of sand extracted from the Glenelg and its tributaries is about eight percent of the estimated volume of sand estimated to be stored in the stream network (Table 10.1). This volume is well within the error bars of the estimates. Exceptions to this conclusion are Bryans Creek, in which nearly half of the total sand volume has been extracted, and Pigeon Ponds Creek, in which about 15% of the sand has been removed.



▬	Sediment Reach
★	Extraction Site
Note:	Figures on map are in 000's of cubic metres. Figures sourced from sand extraction licensing files of the Department of Natural Resources and Environment, Hamilton and Horsham offices. Total extraction = 470 000 cubic metres.

Figure 10.1. Sand extraction volumes from the Glenelg River and its tributaries between 1965 and 1995.

Figure 10.2: Summary of sand extraction from Glenelg River Basin
1956 to 1993

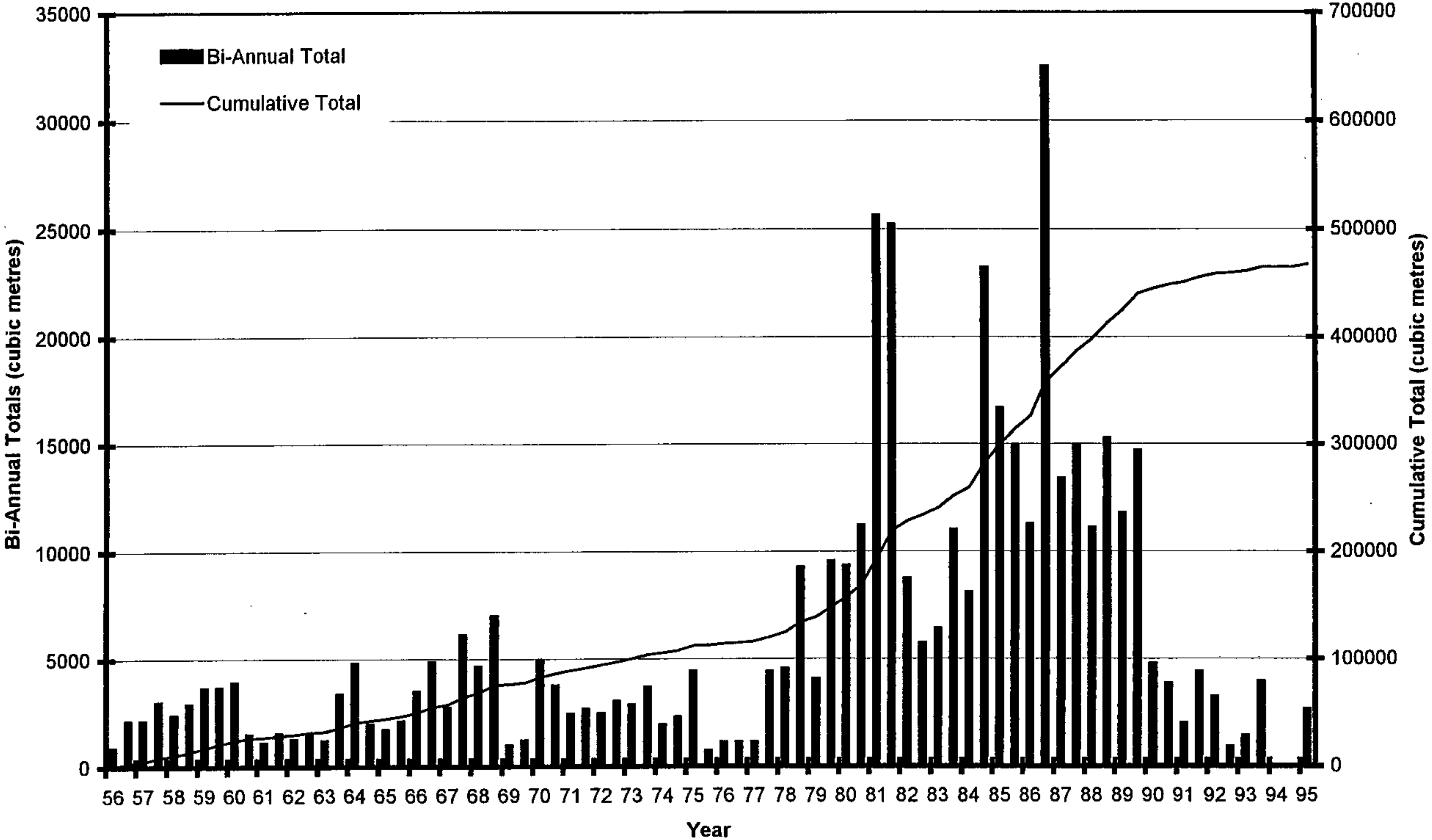


Figure 10.3: Summary of sand extraction from Glenelg River

1983 to 1994

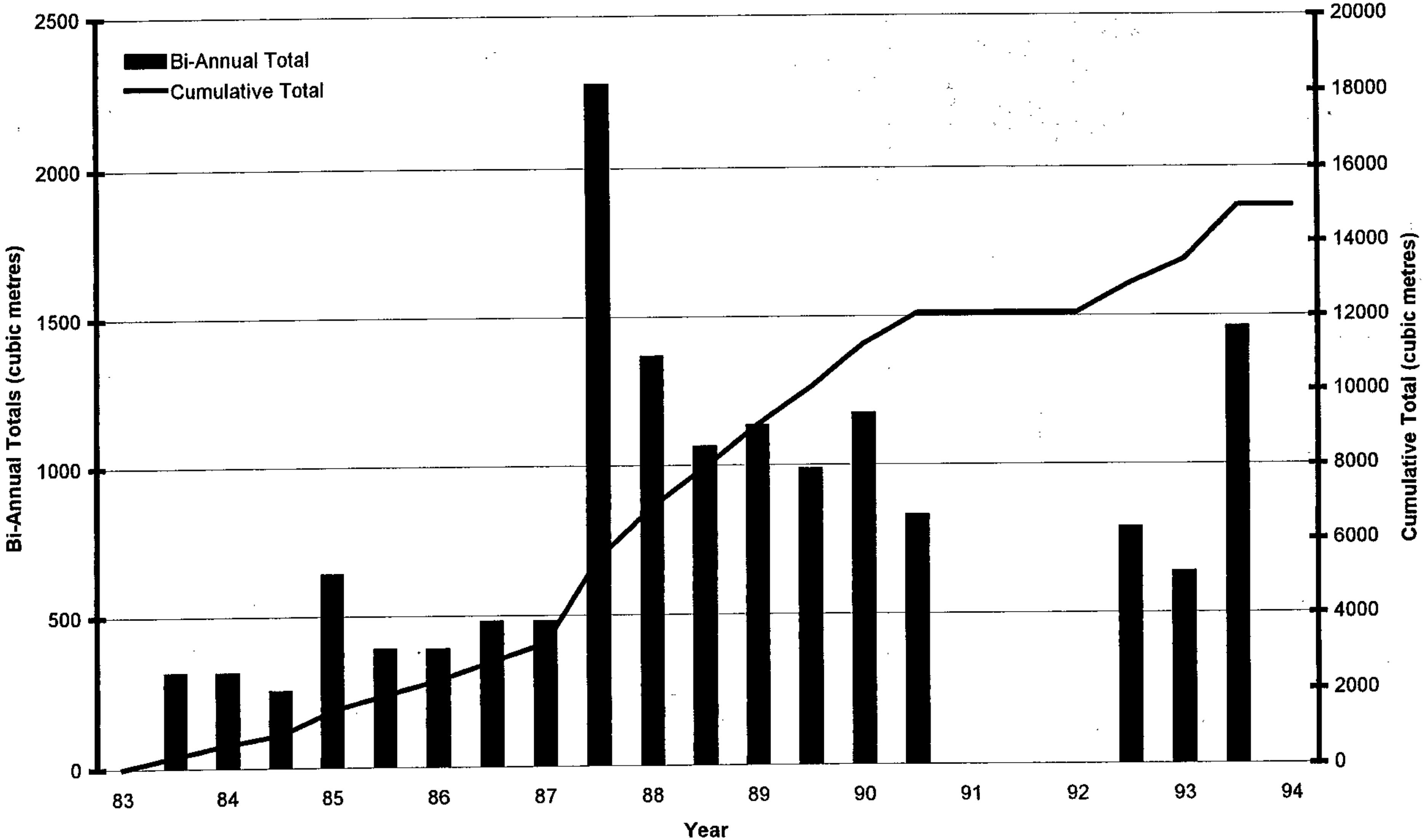


Figure 10.4: Summary of sand extraction from Bryans Creek

1956 to 1993

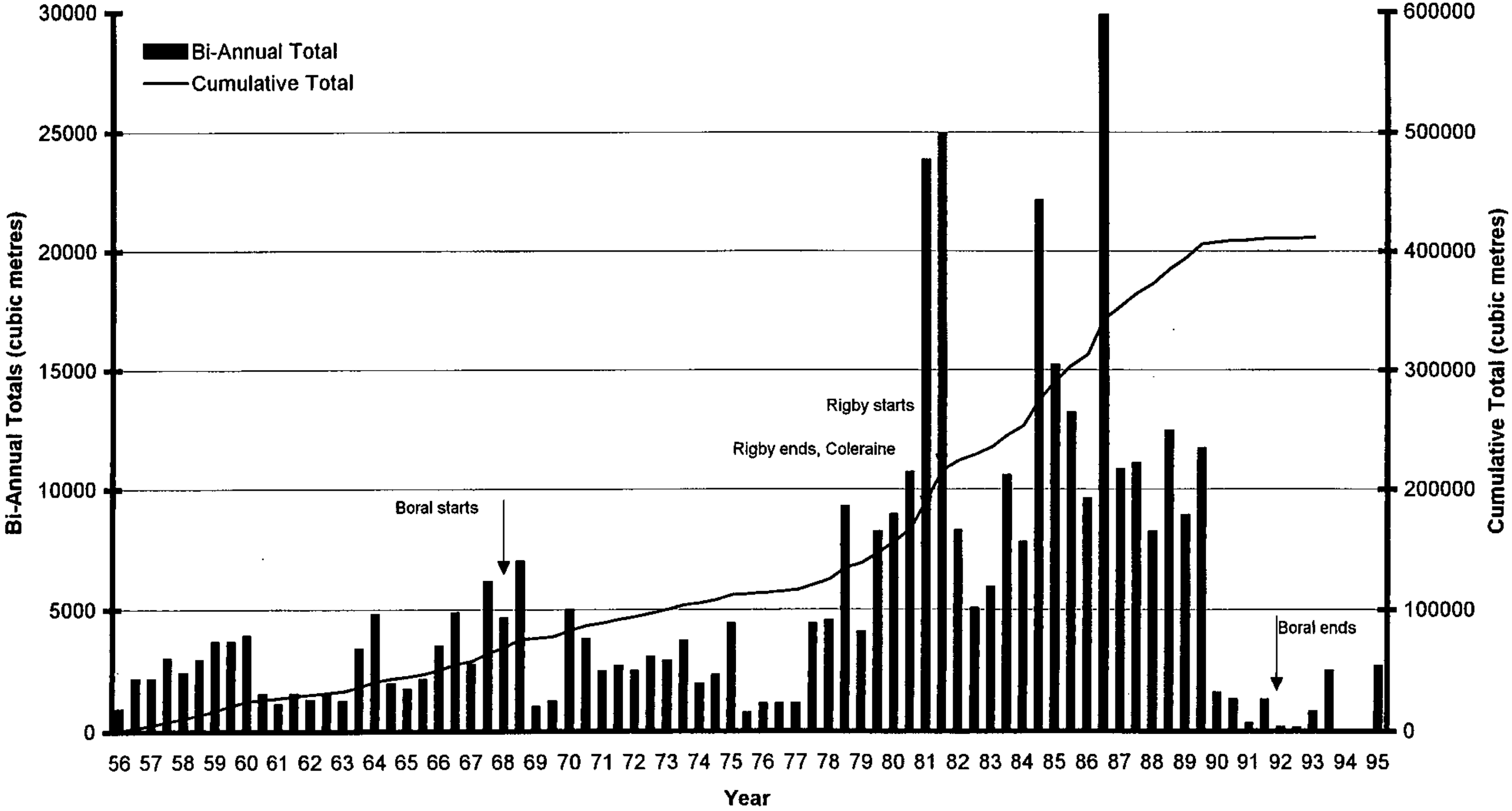


Figure 10.5: Summary of sand extraction from Pigeon Ponds Creek

1984 to 1992

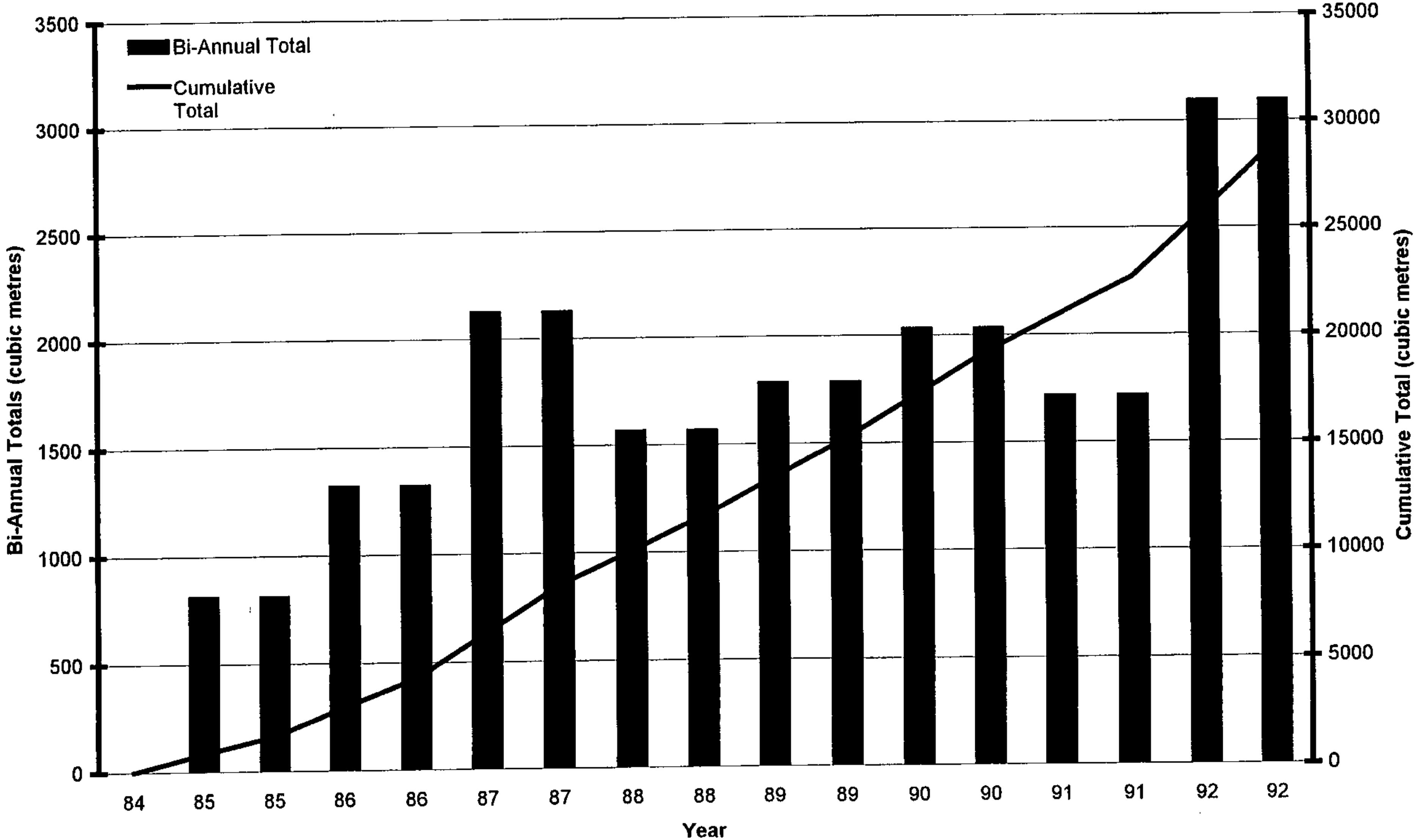


Table 10.1: Percentage of total volume of sand in a given reach that has been extracted

Reach	Storage Volume in cubic metres ('000)	Extraction Volume ('000 m^3)	Percentage of storage Extracted
Bryans Ck	170 (Minimum) (above Coleraine) 280 (below Coleraine)	415	**48***
Glenelg River (above Casterton)	408	20	**5**
Wannon River	156	7	**4**
Pigeon Ponds Creek	210	30	**15**

(Note: * The great bulk of sand extraction from Bryans Ck has occurred above Coleraine, thus probably three quarters of the sand has been removed from Bryans Ck above Coleraine).

The annual extraction rate from the Glenelg River at Casterton is always less than 1500 m^3, which is between 5% and 15% of the total annual sand transport rate estimated at Casterton (10,000 to 30,000 m^3/yr). Thus, based on these tentative sediment transport estimates, the sand extraction rate in the Glenelg certainly does not exceed the annual sand transport rate, let alone influence the volume of sand in storage.

Summary of extraction volumes

Sand extraction in the Glenelg river system has removed much less than 10% of the total sand in storage in the catchment, but nearly 90% of that extraction has been from Bryans Creek. The sand extraction rate at Casterton is probably below the background sand transport rate and will have to increase to more than 20,000 m^3 per year from the Glenelg River before it will influence the volume of sand stored in the catchment.

10.2 Benefits of sand extraction

The expected benefits of artificial sand extraction are reduced flooding, improved environmental values, and improved recreational values. These benefits have to be weighed against some possible problems associated with extraction. The most important of these is bed, bank and tributary erosion, but other problems include development of saline pools. We will discuss the benefits and then the problems.

10.2.1 Reduced Flooding

The major sand slugs in the Glenelg and its tributaries typically occupy about 40-50% of the cross-sectional area of the channel, but they can occupy up to 75%. Reducing flooding has been one of the major arguments put forward for extraction in Bryans Creek. The Coleraine City Council strongly encouraged extraction close to the city because of perceived benefits in reduced flooding. Casterton could also benefit from increased channel capacity. Indeed, the major activity of the Glenelg River Improvement Trust has been the desnagging of the Glenelg River in order to reduce flood stages. The flood analysis in Section 5.1 suggests that the overall impact of sand aggradation is not simple. We can conclude that local sand extraction could have a small local effect on the stage and duration of small floods, such as the one or two year nuisance flood, but it is very unlikely to influence major floods.

10.2.2 Environmental and Recreational Benefits of sand extraction

Converting a narrow and deep channel with regular deep pools and shallow crossings, into a featureless sand sheet, has disastrous ecological consequences, as shown on the Seven Creeks system in NE Victoria (O'Connor and Lake, 1994). There would be undoubted ecological benefits in removing the sand from the Glenelg and Wannon Rivers, and perhaps somewhat less benefit in the smaller streams. However, the environmental benefits may also yield economic dividends. A recent analysis of the economic costs and benefits of various river management works in Victoria (Read Sturgess & Associates, 1992) used sand extraction on the Glenelg River as a case study. The study concluded that removing sand from the stream would reduce flooding which would in turn produce about half-a-million dollars in extended life for roads and bridges. By far the greatest benefit, however, was expected to come from the value of improved recreational fishing in the river ($1.82 M). The high value of this activity produced the strongest benefit-cost ratio of any of the river management activities considered in the Read-Sturgess report (Table 10.2). Note that the development of salt-stratified pools in the cleared channel may jeopardise the ecological recovery of the Glenelg River.

Type of channel change to be treated	**Cost of works**	**Total Benefit**	**Are works justified ?**	**Detailed Benefits**			
				Bridges	Roads	Agric-ulture	Recreation
Tributary siltation	$0.55m	$2m	Yes	$1m		$1.15m	
Tributary erosion	$0.39m	$0.23m	No	$0.2m		$.03m	
Channel avulsion	$0.57m	$0.1m	No	$1.67m	$0.12m	$1.8m	
River siltation (Glenelg)	**?**	**>$2.2m**	**Prob-ably**	**$0.18m**			**$2.04m**
River bank erosion	$1m	$2.18m	Yes	$0.51m	$.27m	$0.04m	$1.82m

Table 10.2: Cost benefit estimates for various types of river channel change (summarised from case studies in Read Sturgess & Associates (1992)) (m = millions).

If commercial sand extraction were to be used as a tool for managing sand in the catchment, where should it be encouraged, and what controls should be placed on the industry? There have been many problems associated with extraction of sand from stream channels around the world, particularly with bed erosion and bank collapse (Williams, 1980; Erskine, Geary et al., 1985; MacDonald, 1988; Cotton and Ottozawa-Chatupron, 1990; Erskine, 1990; DWR, 1992; Kondolf and Swanson, 1993). In the next section we discuss the implications of sand extraction for bed and bank erosion rates, and for tributary incision.

11. THE INFLUENCE OF SAND EXTRACTION ON CHANNEL EROSION

There are three impacts of sand extraction upon erosion in the Glenelg River.

i. Bank collapse triggered by the increase in height of the stream banks

ii. Bank scour that occurs when the raw banks of a channel are exposed by a fall in sand levels.

iii. Up and downstream bed erosion

We will discuss each of these issues.

11.1 Bank collapse triggered by the increase in height of the stream banks following extraction

One of the major erosion processes on the banks of the Glenelg River and its tributaries is bank slumping. This occurs as rotational failures, or as slab type failures that topple outward. Many variables control bank failure processes (Thorne, 1982), but one of the most important is bank height. Over the last century, bank heights on the Glenelg River have increased with overbank deposition, and on the tributaries through stream incision. The influx of sand into stream channels has reduced the incidence of bank failures because the sand reduces the depth of the channel and hence the height of the banks. In some cases the sand has halved the bank height. Rapid artificial extraction of sand from a stream can lead to a rapid fall in the level of sand, and so a rapid increase in the height of the banks, leading to failure. Slower extraction may allow the banks to batter-back and stabilise.

Bank slumping in the Glenelg River appears to be most common in the lower reaches, particularly between Casterton and Killara Bridge. Further upstream we have not seen much slumping, even in the reaches that have little sand (eg. Burkes Bridge to the Wando River). On average, removing the sand from, say, the Casterton reach would increase the height of the steep outer (concave) bank by perhaps 1m (20 - 25%). This could be expected to increase the incidence of slumping slightly.

Of more concern than slumping in the Glenelg River is slumping in the incised tributaries. Recall that most of the major tributaries (eg. Pigeon Ponds Creek, Schofields Ck, Mathers Ck, Chetwynd River, Wando Vale Ponds, Wando River, Bryans Ck, Henty Ck) were in the process of being converted from chains-of-ponds to deep incised streams when the sand filled the channels. Sand fills a large proportion of these channels and one would predict that removing the sand will lead to bank slumping. In some cases this is true, but in many, migration of the outer bank has solved the problem.

As described in Section 6.3.3, many of the incised streams have responded to the influx of sand by widening. The widening occurs by migration of the outer (concave) bank, and the erosion tends to occur within 0.5m of the sand surface, which is the scouring depth. This means that the deep thalweg of the incised stream is now often abandoned. Although this has implications for sand storage (Section 9.3.3), it also has implications for bank stability. If sand is removed quickly the level of the bed will fall, exposing the banks. However, where the channel has widened the toe of the vertical outer bank, which is the bank most prone to slumping, the sand is now less than 0.5m deep. This compares with the two to four metres of sand that would have been present without the widening. A 0.5m increase in bank height is unlikely to measurably increase bank slumping.

There are also many channels, and individual bends, that have not widened in this manner, and a rapid fall in bed level with sand extraction could well lead to a rapid increase in bank height and possible bank failure. This has certainly occurred on some banks in Bryans Ck above and below Coleraine. For example, the bed of the creek below Coleraine deepened by up to 0.9m between 1989 and 1993, with most of the deepening occurring between 1989 and 1991 as a result of upstream sand extraction (Figure 11.1). The deepening from extraction extends from the Coleraine Bridge to about 6 km down the creek. Below this point the 30cm or so of degradation is probably due to local sand extraction operations at the Hilgay Lane Ford at about kilometre 9.5.

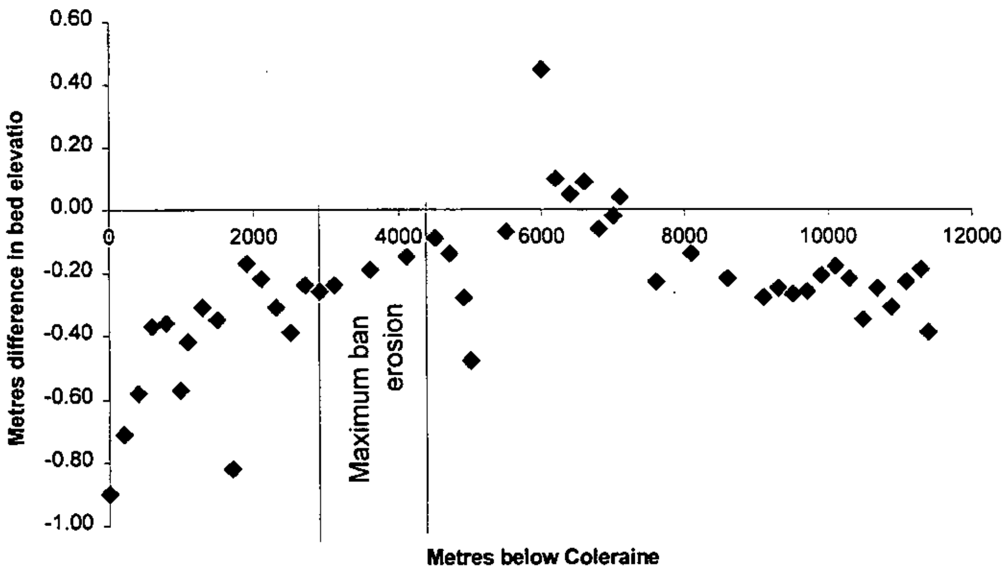


Figure 11.1: Changes in elevation of the bed of Bryan Creek between 1989 and 1993 between the Coleraine Bridge and the Wannon River junction.

The types of bank erosion below Coleraine were classified into three types in the Bryan Creek rehabilitation study [Rural Water Corporation of Victoria, 1993 #1157]. The most serious of these erosion types, category A, are vertical banks exhibiting slumping or scour. These occupy about 3 km of the 11.5 km reach (about 25%), most of which occur within the 1.6 km reach shown in figure 11.1 (18 of the category A bends occur in this reach, and nine occur through the rest of the creek). We can make two observations about erosion in lower Bryans Creek. First, the slumps that we have seen, and the photographs in Rural Water Commission (1993) suggest that the bank slumps all have their toes at the sand surface. This means that the critical height for failure is only exceeded if there is some channel deepening and removal of sand. The second observation is that most of the slumping occurs in a reach that deepened about 20cm or less between 1989 and 94 (Figure 11.1). This suggests either that some banks are very sensitive to small changes in height, or that bank failure is not controlled entirely by the removal of sand. Nearly one metre of degradation further upstream has not triggered any noticeable slumping.

Our conclusion is that rotational failures will not occur when the banks are less than say 1.5m high, and they will not fail where the toe is protected by sand. Some sections of Bryans Creek are already experiencing severe bank slumping, but these sites do not correspond to the section of channel that has experienced most degradation. There is no doubt that the future removal of the remaining 1 to 1.5 metres of sand in the bed of Bryans Creek is likely to encourage further slumping. This will not occur at those bends at which the channel has widened. The widening means that the sand against the cut-bank is shallow.

11.2 Bank scour that occurs when the raw banks of a channel are exposed by a fall in sand levels.

Colonisation of stream banks by vegetation is critical to their stability. As mentioned elsewhere, many of the tributary streams are now developing sandy benches within their channels. Eventually these benches will vegetate and form new floodplains. However, if the level of sand in the channel falls too fast, the faces of these sandy benches will not have time to vegetate, and they will be eroded. This process can be seen on Bryans Creek where sand extraction has dropped the bed level quickly. Grass has not been able to stabilise the exposed sand banks quickly enough, and the benches have eroded. In the absence of extraction, grass will progressively invade the benches as they are slowly exposed by bed degradation.

Again using the example of Bryans Creek, the degradation of the bed below the Coleraine bridge is said (by local landholders) to have triggered erosion of sandy point bars and benches because they were not protected by grass. If the sand bed fell at a slow rate, then the grass and vegetation would have an opportunity to colonise and stabilise the benches. Thus the key issue is the rate at which the sand is removed.

11.3 Up and downstream erosion triggered by extraction.

In most streams the major concern with sand and gravel extraction is up and downstream bed degradation. That is, the extraction hole will trigger erosion that progresses upstream as the sand transport rate is increased into the hole (a sediment transport discontinuity in the terms of Pickup (1977)) The loss of sand into the scour hole will trigger downstream erosion of the bed (Galay, 1983). Much sediment extraction from Australian streams is from 'natural' streams that have a low background bedload transport rate (Erskine, Geary et al., 1985; DWR, 1992; DPI, 1995; Erskine and Terrazzolo, 1996; Erskine, 1996). Thus, in these streams the concern is that extraction will trigger bed erosion up and downstream of the extraction hole. This scour will then erode bridges, trigger bank erosion, and generally destabilise the river. However, the Glenelg River and its tributaries do not fall into the same category of problem. The slugs of sand stored in these channels represent an excess of bedload over transport capacity. This means that extracting these slugs will produce erosion of the slug, but not of the underlying channel into which the slug has migrated.

This can be demonstrated by considering a simple slug of sand that moves into a reach (Figure 11.2). The slug migrates by transporting material over the slug and onto the front of the slug. Extraction from a migrating slug simply moves the 'avalanche face' of the slug further upstream. The extraction hole serves to increase the rate of sand transport from the slug upstream of the hole, and increases the rate of transport downstream of the hole. Since there is less material being contributed to the avalanche face of the slug, its rate of downstream migration will be slowed. It is important to note that the upstream degradation triggered by the extraction hole will not extend above the upstream end of the sand slug (ie. into the original, pre-slug channel floor) except in the special circumstances described in the next section. The slope upstream of the slug is greater than the slope on the upstream surface of the slug, so it will already be transporting material at a greater rate than the slug - that is why the slug is there! However, note that the extraction hole does drop the depth of sand in the slug, and this could lead to an increase in bank erosion as discussed above.

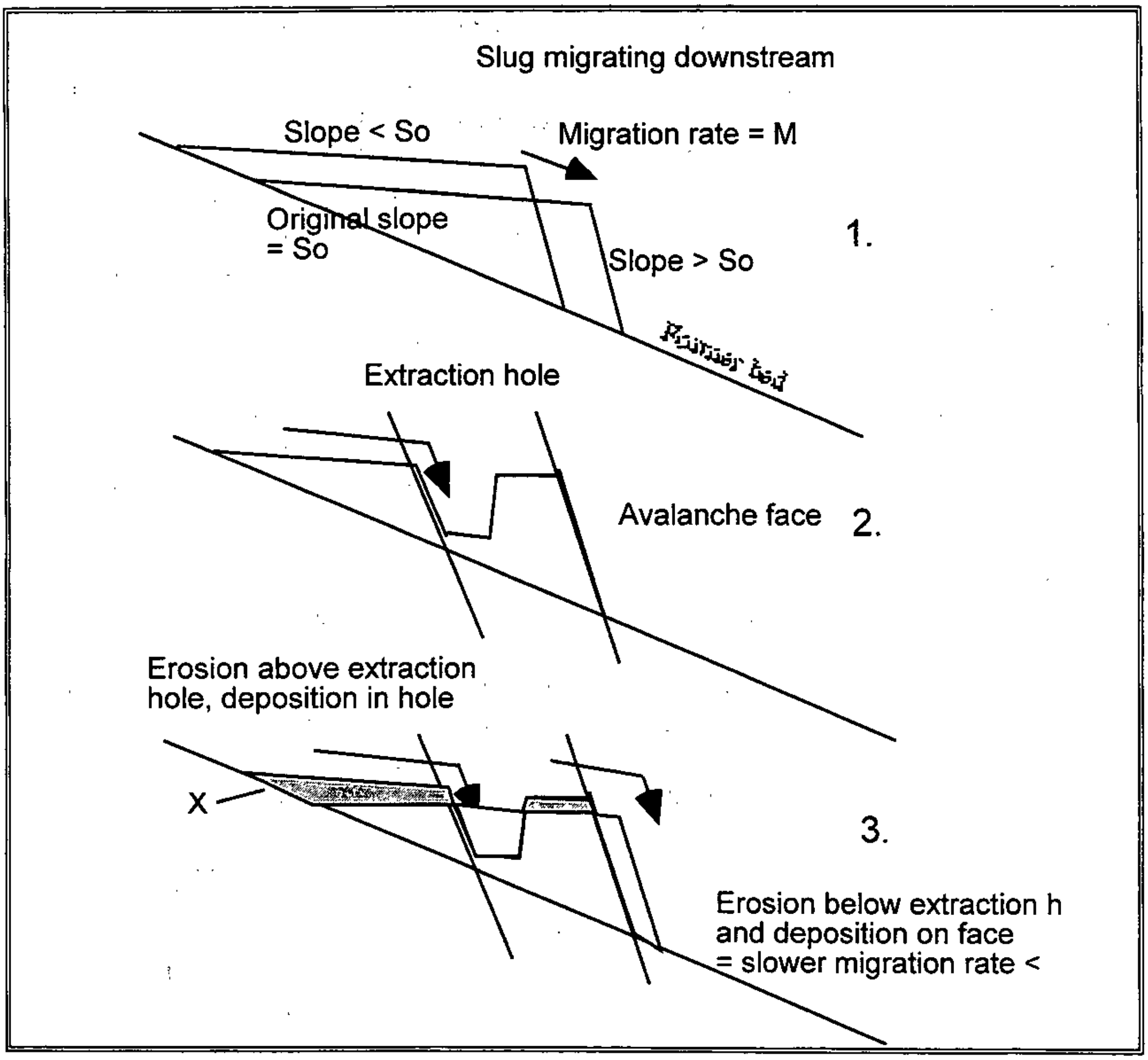


Figure 11.2: Sand extraction from a migrating slug simply serves to reduce the downstream migration rate.

Although extraction of a sand slug will not lead to erosion of the bed underlying the slug, the act of exposing the bed will lead to erosion. This can be shown by considering the example of Bryans Creek.

11.4 Recent erosion of the bed of Bryans Creek

Bryans Creek is often cited as a stream that has suffered severe bed erosion because of sand extraction. The GCWMS (1992) and Erskine (1994) describe up to two metres of degradation in Bryans Creek since 1940, exposing seven kilometres of clay bed. Above the junction of Robsons Ck the clay bed has incised up to three metres in recent decades. This erosion has been associated with the intense period of sand extraction on Bryans Creek in the 1970s and 80s (Figure 10.4). With the development of the Alcoa aluminium smelter and other large projects in Portland, the extraction rate in Bryans Creek reached 50,000 cubic metres per year in 1981 (Figure 10.2), which is approximately 9% of the remaining sediment store in one year. A total of over 400,000 m^3 has been removed. Surveys by the Shire of Casterton show that the upstream end of the sand slug in Bryans Creek migrated downstream.

It is important to note that there are two elements to the erosion in Bryans Ck. There is erosion of the sand slug, and there is erosion of the clay bed beneath the sand slug. The sand slug was eroded because of downstream extraction, possibly exacerbated by reduced sand supply from the catchment (Erskine, 1994). However, the erosion of the underlying clay bed (which is the major management problem) is caused by the removal of the sand exposing the channel to a new hydrological regime.

The influence of sand extraction on erosion is demonstrated by changes in the bed of Bryans creek between 1981 and 1991 (Figure 11.3). This was the period of the most intense sand extraction from the creek when over 250,000 cubic metres of sand was extracted from the creek (Figure 10.2). Immediately above and below the extraction hole the bed has deepened by about 0.5m. This deepening declines to about 0.1m within 2 km downstream, and 4 km upstream. It is particularly important to note that there has also been deepening in the clay bed above the limit of the sand. Unlike the deepening in the sand, the erosion in the clay has increased in depth in the three kilometres upstream of the sand (from 0.1m to 0.4m). Inspection of Bryans Creek for 3 km above Douglas Bridge confirmed that the deepening increases above the bridge. The stream has cut 0.5m into the channel bed at the bridge, but this increases to a 3m slot cut into the clay bed near the junction of Robsons Creek (this occurs well upstream of the portion shown in the Figure 10.2). Rock chutes have been constructed in this reach to control the erosion. Repeat cross-sections made in Bryan Creek in 1991 suggested that the scour of the bed had continued, with erosion of between 0.35 and 1.5m (Erskine, 1994).

The upstream decrease in deepening that has occurred in the sand reach of Bryans Creek represents 'knickpoint rotation' which is characteristic of knickpoint migration in non-cohesive materials (Gardner, 1983). The knickpoint generated by the extraction hole gradually decreases in height as it moves upstream. Models of knickpoint migration suggest that knickpoints in cohesive materials should either rotate, or remain parallel as they migrate upstream (Gardner, 1983; Pickup, 1977). This is not what happens to the clay bed in Bryans Creek. Instead the bed deepens more upstream, which suggests that erosion in the clay bed is not triggered from downstream (ie. from the extraction hole), but is caused by an upstream control. The most likely upstream control that would erode a lower stream slope is an increase in stream discharge. We conclude that, on Bryans Creek, knickpoint erosion associated with sand extraction produces channel deepening that extends about 4 km upstream, and 2 km downstream. This exposes the original clay bed that is then eroded by a changed hydrological regime from the catchment. This process is best illustrated by considering the evolution of Bryans Creek over the last century.

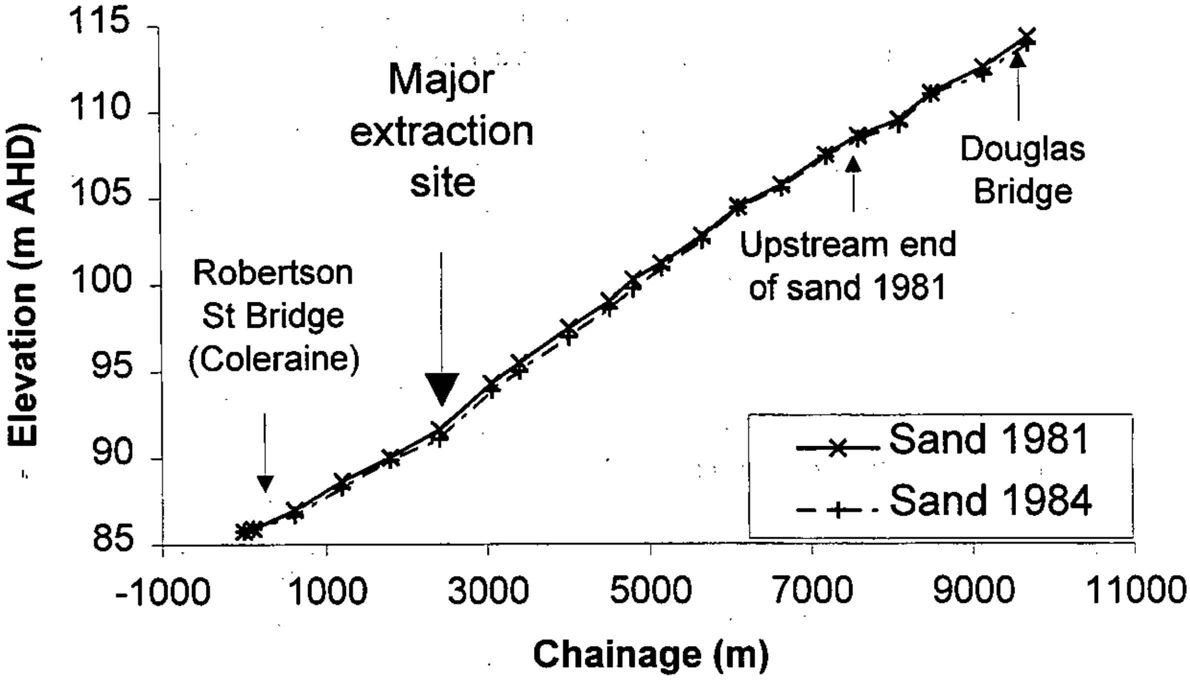


Figure 11.3: Survey of sand surface in the ten kilometres of Bryan Creek above Coleraine (1981-84)

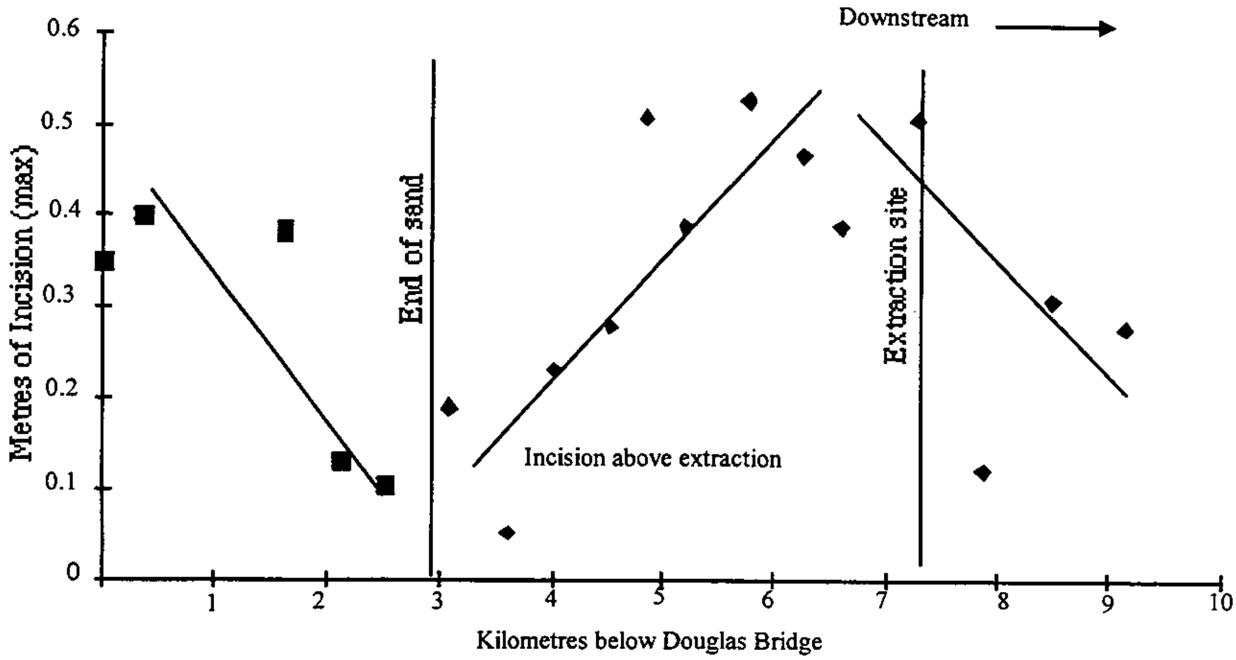


Figure 11.4: Incision in the bed of Bryans Creek, 1981 to 1984 between Douglas Bridge and Coleraine (Source: RWC bed surveys, file no. 85/1830, from survey data supplied by Shire of Wannon)

Blackburn and Leslie (1949) have related the development of erosion in the catchment to various periods of human activity, and these are summarised in GCWMS (1992).

1838 - 1862 Beginning of wool production

1862 - 1910 Wool industry consolidated, accelerated gullying, rabbits, channelisation.

1910 - 1925 Dairying

1940 - 1950s Drought

1960s - 1970s Catchment management and erosion control, improved pasture.

Figure 11.5 is a schematic representation of the changes in stream form, and changes in the hydrograph, associated with the different periods of land-use. At first settlement, Bryans Creek was a chain-of-ponds (GCWMS, 1992) and the hydrograph peak in the creek would have been attenuated by dense vegetation along the stream. Clearing, and possibly channelisation, between 1860 and 1910 led to the development of gullies in the headwaters, but also erosion of the chain-of-ponds into a 'valley-floor incised stream'. Such incised streams are very common throughout SE Australia (Eyles, 1977; Eyles, 1977; Bird, 1985). Sometime between 1910 and 1940 the lower reaches of Bryans Creek filled with sand. This sand came predominantly from gully erosion and from the enlargement of the creek itself. Anecdotal reports from local farmers suggest that the tributaries to the Glenelg filled with

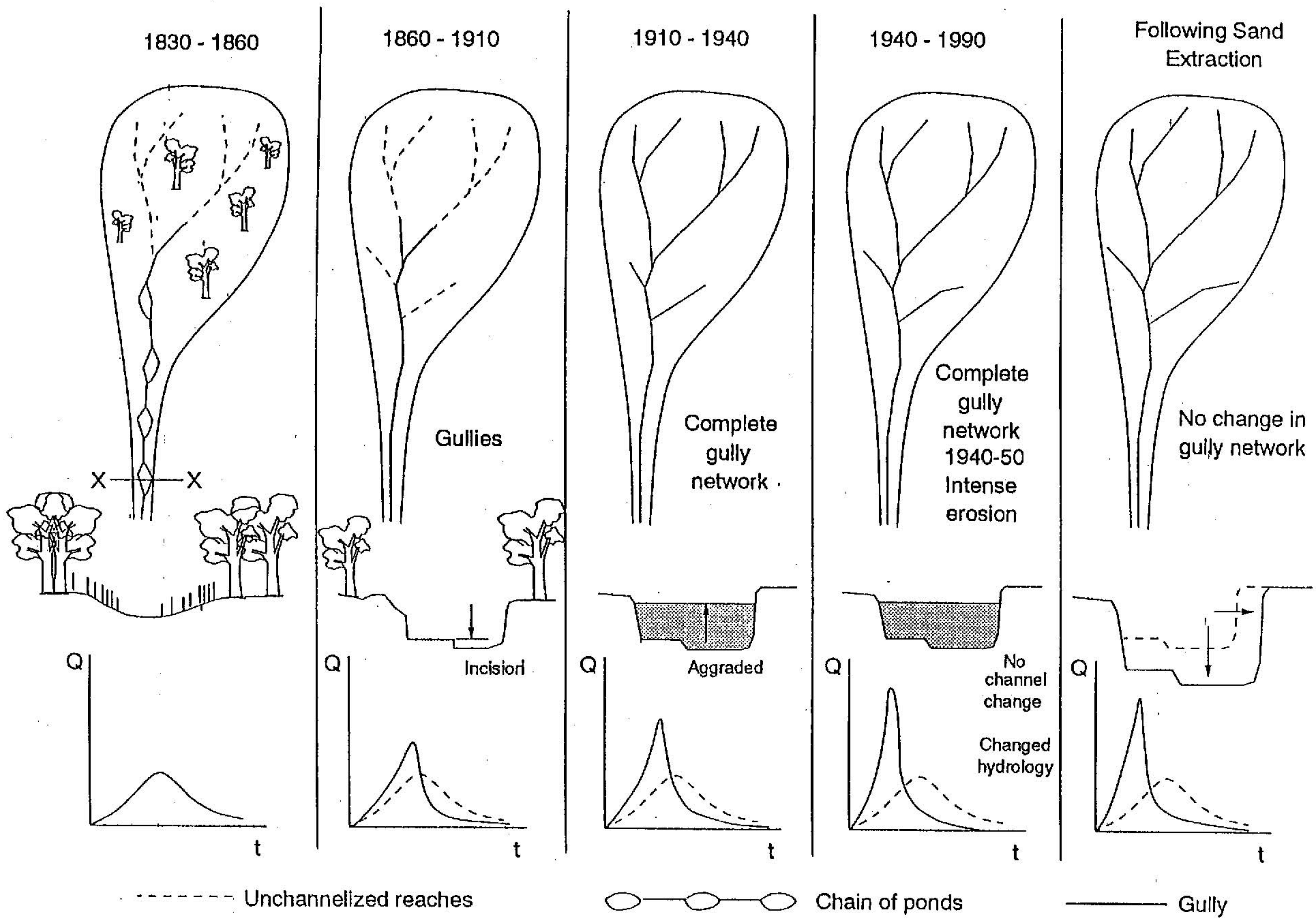


Figure 11.5: Schematic model of stream incision and sand movement in Bryans Creek since European settlement (note: Q = stream discharge, t = time)

sand very rapidly, probably during a few floods. The 1947 photographs of Bryans Creek show that the 1946 flood deposited large splays of sand across the floodplain.

By the 1940s the gully network had reached its full extent and this extended drainage network, in combination with a cleared granite catchment, would have produced a major change in catchment hydrology. It is almost certain that the flood peaks following clearing would be larger, and floods would be flashier .(Burch, Bath et al., 1987). The period of intensive catchment pasture improvement in the 1960s may have served to reduce total runoff , but flood peaks would still be much larger than pre-settlement. These changes in flow regime would have continued to erode the channel of Bryans Creek except the channel was now protected by sand. Specific gauge records suggest that the sand stored in these creeks and rivers is not periodically scoured, removed and replaced by new sand. Instead the same body of sand (1.5 to 3m deep in Bryans Creek) has been in storage for over 50 years with new sand moving over the top of the sand deposit. This means that the original clay bed of the channel was not periodically scoured, even during large flood events.

In essence the sand has served to protect the bed of the channel from a changed hydrological regime. Removal of the sand, whether by extraction or by natural attrition, would have led to erosion. Extraction has accelerated the removal of sand and so exposed the bed to erosion some decades earlier than would naturally have occurred. Bryans Creek is one example of this phenomena, but most of the tributaries of the catchment will also tend to erode after their buffer of sand is removed.

It is also important to note the effect of 'abandoned thalwegs' (see Section 6.2.3) upon bed scour. When the level of sand has fallen in these over-widened cross-sections, the exposed clay bed will be up to three metres *higher* than the original bed level (ie. the bed that was originally filled with sand that is preserved below the thalweg). This may mean that the bed will then erode to re-establish the original pre-sand slope. This suggestion has not yet been confirmed.

Summary of impacts of sand extraction

Artificial sand extraction will lead to a fall in the elevation of the sand bed. If this occurs quickly it can lead to bank instability, first because the banks will become over steep and they will slump, and second because vegetation does not have a chance to become established on the in-channel deposits and banks. Widening of many bends has protected them from deepening associated with sand removal because the sand is now shallow at the outside banks.

Extracting sand from the slugs of sand stored in the Glenelg River and its tributaries can trigger erosion of the pre-slug channel bed. This will occur where the sand has protected the former incised stream from changed catchment, hydrological conditions. In addition, widening of tributary streams that have been filled with sand could also lead to bed erosion because the new thalweg can have a steeper slope than the thalweg that it replaced.

11.5 Tributary rejuvenation

Apart from concerns about bed degradation, the other general concern about sand and gravel extraction is rejuvenation of tributaries as a result of the falling level of the trunk channel. There are many anecdotal records of tributary erosion following extraction, and the effect is analogous to tributary erosion following bed degradation below dams (Germanoski and Ritter, 1988).

Extraction of sand will lead to tributary erosion in the Glenelg catchment, but we must define two types of tributaries. These are tributaries that incised before and after the trunk streams filled with sand.

Tributaries that incised before the trunk streams filled with sand

The arguments about tributary rejuvenation in this type of tributary are an extension of the arguments that we made above concerning bed degradation following extraction. In short, sand extraction itself is unlikely to cause erosion of these tributaries, but once the sand is no longer protecting the beds of the trunk and tributary streams, both are likely to incise. The process can be described in three steps as in Figure 11.5.

i. Following settlement, gullies form and valley floor streams are incised.

ii. Part-way through their development both the incised streams and the tributary streams are filled with sand. The sand also protects the tributary mouths from incision.

iii. When the sand is removed (artificially or naturally) erosion of the trunk and the tributaries will continue.

Many of the larger tributaries will follow this sequence. These tributaries are now typically filled with sand at the lower ends, and this sand has been colonised with reeds. An example is Salt Creek at Harrow.

Tributaries that incised after the trunk streams filled with sand

Where the tributary stream has incised *after* the trunk channel filled with sand, the eroded tributaries will be graded to the higher sand-bed of the channel. These tributaries will definitely incise following extraction from the trunk stream. There are examples of such tributaries on Bryans Creek (Photo 11.4). As sand has been removed from Bryans Creek and the bed has degraded (as described in Section 7) there has been a renewed period of incision in several small tributaries, and the floor of the gullies is now graded to the clay floor of Bryans Creek. The gullies show two definite phases of incision. The second phase of incision has proceeded up the tributaries very rapidly, and where there is no grade control (such as a crossing) there is no longer any sign of active knickpoints in the gullies. Thus the tributaries in this case equilibrated to the removal of the sand within a decade.

Removal of sand in the trunk streams, whether by extraction or naturally, will lead to incision of tributaries. Where tributaries are graded to the channel floor below the sand the amount of incision will be less than in those smaller tributaries that incised after the trunk streams had already filled with sand. Examples from Bryans Ck suggest that the small tributaries will adjust within a few years.

11.6 Saline pools

In a survey by McGuckin and others (1991) saline pools, with conductivities at the bottom of the pools of up to 12,000 EC units, have been found in the Glenelg River between Rocklands Reservoir and Fulham Bridge (upstream of Harrow) Not surprisingly, no saline pools were found below Fulhams Bridge because the channel has been infilled with sand. Saline pools will only develop if there is some local source of saline seepage. Would saline pools form in a deep dredge hole at Harrow, for example? They probably would. Harrow has the same flow regime as the Glenelg above Fulham Bridge, and there are probably saline seeps in the vicinity. For example, the 1854 County of Dundas map describes Salt Creek (which is just upstream of Harrow) as consisting of saline pools. In June 1994 we measured the conductivity of Deep Creek (a left bank tributary downstream of Harrow) at 7,000 EC units. Therefore, it is very probable that deep extraction holes (ie. deeper than 4m) would form stratified salt pools. Similarly, the deep holes that will be reestablished by extraction may also become saline. This is true in the Harrow area, but probably less so further downstream, say around Casterton, where there is no evidence of saline seeps.

11.7 Limits to sand extraction as a management tool

Artificial sand extraction is the most useful management tool available for the Glenelg River, especially given the shortage of quartz sand in western Victoria. However, there are some limits to the effectiveness of sand extraction as a management tool.

i. The major market for sand from the Glenelg has been Portland, and Casterton is apparently about as far north as it is economic to haul sand to Portland (at present charge rates).

ii. If government decides to encourage commercial sand extraction from the Glenelg River, extraction could be encouraged by reducing royalty rates. However, this may not be a powerful incentive to extract. Royalties in 1990 were $1 per cubic metre, whilst the haulage cost from Morree to Portland was about $20 per metre (Gary Andrews, Boral, pers. comm.). With other costs included, the government royalty on sand represents less than 5% of the cost of extraction.. In addition, the real cost (in 1993 dollars) of the royalty on sand actually fell between 1981 and 1989 (Figure 11.6), whilst the other costs, such as haulage, will have increased dramatically. Hence, by far the most important variable in the cost of sand extraction is distance to the markets, and unfortunately the major stores of sand (ie. the Harrow to Chetwynd reaches) are as far away from Portland as possible. River regulation reduces the rate of sand transport during summer which limits the length of time that sand can be removed. This is because the drag-line extraction holes do not fill quickly enough to maintain a viable extraction rate. Note that this is one of the major reasons for later suggestions for extraction behind constructed weir.

iii. Only some points along the river provide good access to the sand, and these do not necessarily coincide with the areas that require the most extraction.

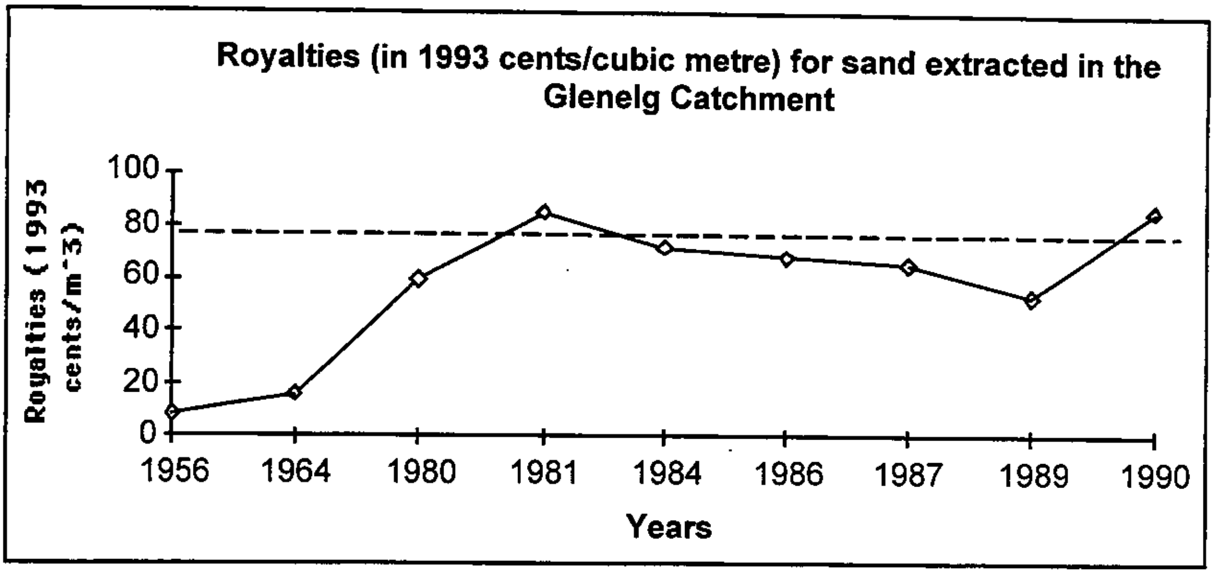


Figure 11.6: Royalty paid per cubic metre of sand from the Glenelg River (adjusted to 1993 cents) (Source: DCNR sand extractor licence files)

Sand extraction will not remove all sand from the Glenelg system because there are limits to the economics of extraction. The main sources of sand are far from the main demand centres, and royalty charges are only a small proportion of the cost of extraction.

12. SAND MANAGEMENT OPTIONS FOR THE GLENELG RIVER

12.1 Introduction

The Glenelg River can be managed to avoid certain damage, or to preserve **or improve** existing human and natural assets.

Following is a list of the damage done by sand slugs:

- Reduces channel capacity and increases nuisance flooding (in some cases only).
- Produces an almost sterile stream (reduced biological values) (reduced habitat, increased water temperatures, unstable substrate).
- Reduces aesthetic and recreational values of the stream (dramatically decreases fishing and swimming opportunities).
- Compromises stock (cattle) management by providing easy access across streams. The result is that the river no longer represents a well defined property boundary.

Table 15.1: 'Variables' that are relevant to sand management on the Glenelg River.

VARIABLE	PREMISE	DESIRED MANAGEMENT OUTCOME	MANAGEMENT OPTIONS
•Bank erosion	Bank erosion is undesirable, particularly around assets (bridges, roads). Slow rates of bank erosion are a realistic management goal because banks eroded before European settlement.	Reduce severity, avoid future erosion	• Limit rate at which sand levels fall by controlling extraction. Structural control measures (grade control and bank protection)
• Bed deepening	Deepening can improve habitat by developing pools. Bad when bed is clay. This can increase bank height and hence erosion, and undermine assets (esp. bridges).	Depends on position and risk. Must also differentiate between scour of sand slugs and scour of original clay-rich perimeter.	• In tributaries, extract the sand at the transport rate to limit bank erosion • In Glenelg encourage deepening to improve stream habitat (increase in height is insufficient in a big stream to trigger erosion)
•Riverine habitat* (in practice this is wetlands, backwaters, and particularly deep pools)	Sand slugs have destroyed habitat, but also created habitat behind TJPs. Filling pools with sand never improves environmental values.	• Empty pools that have filled with sand, and prevent any more from filling. • Replace flat sheets of sand in the channel with a deeper defined channel.	• Ensure summer flow by constricting channel (eg. limit grazing in the channel to encourage vegetation) • Produce or protect deep holes by extracting sand. • Preserve wetlands (pools) by protecting TJPs.

•Flooding	Aggradation of sand reduces channel capacity and increases the frequency of minor floods.	Increase channel depth and capacity to reduce the frequency and duration of nuisance flooding.	• Remove sand by extraction or by flow regulation
• Heritage River	Under the Victorian Heritage Rivers Act 1992 the tidal reach of the Glenelg cannot be damaged in any way. Large volumes of sand will damage the heritage reach.	• Prevent sand from reaching the Heritage Reach.	• Intercept sand above the heritage river and artificially extract • Tolerate slow rate of sand movement into Heritage Reach • Artificial weir to trap sand
Recreation	Fishing, boating and swimming have been curtailed as a result of sand accumulation in the river. A sand choked channel is not as aesthetically pleasing as the original river.	• As for riverine habitat above • Remove as much sand as possible from the river to provide deep reaches.	• As for riverine habitat above • Artificial weirs to trap sand
Commercial and Shire Sand Extraction	Sand deposited in stream channels has many commercial advantages over other sources of sand. The Glenelg River is one of the few sources of high quality quartz sand in Western Victoria.	Extract a specified volume of sand from locations that complement the broader management objectives	Commercial sand extraction should be encouraged wherever it does no harm because removing the sand slug is, in general desirable.

*Riverine habitat: In practice there is less point managing sand in isolation for habitat improvement. We may be able to remove enough sand so as to produce deep pools and varied substrate, but this will do little good if the flow regime does not allow biota to become established, or if there is some other limiting variable such as salinity. This is important in the upper Glenelg where saline pools are biologically limiting, and where the regulated flow regime out of Rocklands also compromises habitat. In addition, the desnagging of the river has reduced habitat and flow diversity in the channel.

12.2 Glenelg River Sand Management Strategy

Appendix 1 presents management options for various reaches of the Glenelg River. The emphasis of the plan is sand management, which has been identified as the major in-channel management issue in the catchment. The river is divided into reaches defined in Figure 12 (a large map that can be found in a pocket at the rear of the report). For each reach, beginning at Rocklands Reservoir and working downstream, we describe the physical character of the reach, channel change with no intervention, and management priorities. We also suggest management activities. The evidence and substantiation of the points in Appendix 1 are contained in the report, so no evidence for various assertions are presented here.

There are three general types of deposit from which sand can be extracted in the Glenelg catchment. Extraction from each of these locations has specific consequences.

i. Extraction from major slugs in the Glenelg and Wannon Rivers (eg. at Casterton). These sites have continuous sheets of sand in the bed so extraction will lead to deepening above and below the extraction site. There will be limited bed and bank erosion following extraction because of the size of the channel and the volume of sand available. The major management issue is the supply of sand to downstream reaches, particularly reaches in which there are still ponds, and upstream progressing erosion that would remove a TJP and drain a wetland.

ii. Extraction from the 'chains of slugs' reaches (eg. between Dergholm and the Wando Junction, or below the Wannon Junction). Extraction from these reaches will produce only local erosion of sand because the 'sluglettes' of sand are separated by deep pools. That is, there is not a continuous hydraulic connection between the extraction site and a large slug of sand.

iii. Extraction from the lower ends of tributaries (eg. Pigeon Ponds Ck.). There are three issues with extraction in these sites. (1) A rapid fall of sand levels can trigger bank erosion. This problem is reduced by the widening of the channels. (2) Removing the sand exposes the channel bed and banks to erosion. (3) Extraction will lead to erosion of the TJPs and eventual draining of the upstream wetlands.

Thus the major negative impacts of sand extraction could be (a) to bring forward bed erosion, (b) to increase bank erosion, and (c) to accelerate the removal of wetlands behind TJPs.

There are four sites in the Glenelg River system that should be priority areas for sand extraction. The priority attached to each extraction site depends upon the goals of the managers. Please note, first, that all of the priority sites are on the Glenelg River itself. Sand extraction on the tributaries is either discouraged, or limited to the transport rate (< about 2,000m^3 per year). Second, the extraction sites are not mutually exclusive. That is, extractors could take about the recommended quantity of sand from any of the four sites without any danger of interaction between the effects of the extraction.

Site 1: *Glenelg River at Harrow.*
Sand Volume in storage: Up to 1,000,000 m^3 (40,000 m^3/km)

Sand volume extracted: More than 20,000 m^3 per year
Benefits: The slug of sand at Harrow is trapped behind the backwater from the Deep Creek TJP. Artificially removing this sand would restore the deep pools below the town if the upstream supply could be controlled. An extraction site upstream of the Harrow Bridge would be best, and extraction should occur from deep holes that will stop sand from moving past the extraction site.

Site 2: ***Glenelg River at Burkes Bridge (below the Chetwynd River Junction).***
Sand Volume stored in reach: 200,000 m^3 (20,000 m^3/km)
Sand volume extracted: 20,000 m^3 per year
Benefits: Extraction at this site (at the slug of sand from the Chetwynd River) would stop the supply of sand to the sluglette reach between Burkes Bridge and the Wando River junction. This would preserve the deep pools.

Site 3: ***Glenelg River between Wando Junction and the Wannon River Junction***
Sand Volume stored in reach: 400,000 m^3 (20,000 m^3/km)
Sand volume extracted: 20,000 m^3 per year would begin to have a measurable impact on the sand level and would not threaten stream stability.
Benefits: Reduction in the bed-level past Casterton. Re-establishment of pools in the bed. Extraction could best be combined with a weir in the channel because the weir would ensure that a sufficient volume of sand was stored to guarantee extractors a reliable source of sand. Sand could be extracted from the weir, and the sand bed below the weir would gradually erode. Extraction from this reach would also reduce the sand load to the chains-of-sluglettes below the Wannon Junction, and preserve the remaining pools in this reach.

Site 4: ***Glenelg River in the vicinity of Myaring Bridge***
Sand Volume stored in reach: 300,000 m^3 discontinuous sluglettes below the Wannon (6,000 m^3/km)
Sand volume extracted: If a low-level weir was built about 10,000 m^3 per year could be extracted without producing erosion of the clay bed.
Benefits: Extraction would limit the movement of sand into the Heritage River, and preserve the remaining pools downstream. Would have no upstream impact because the sand bed is not continuous (it is punctuated by deep pools). Again, a weir would ensure a reliable sand source for extraction.

12.3 Regulation of extraction

This report concludes that there would be many benefit from an increase in the volume of sand extracted from certain defined reaches of the Glenelg River. It is very important to emphasise that this extraction should be closely managed and monitored in case there are any unforeseen impacts of the extraction. For example, the bed of the river should be surveyed (long-profile and cross-sections every 200m) each year for at least 5,000m above and below each extraction site. This will assess the impact of the extraction on bed levels and bank erosion.

12.4 Concluding points

Goals of increased sand extraction

A central aim of managing sand in the Glenelg River is to improve the biological and recreational condition of the stream. Removing sand will provide pools for fish habitat, and a more varied hydraulic environment for riverine species. The management plan described here should also preserve the lakes that have formed above the TJPs. The evidence presented in this report suggests that under natural conditions, and particularly with the regulated flow from Rocklands Reservoir, the sand will take perhaps 40 years to reach the Heritage River, and probably hundreds of years to evacuate the stream system entirely. Direct sand extraction provides the best hope for accelerating this slow process, and restoring some of the values of this river. Extraction is most appropriate on the Glenelg River itself rather than on its tributaries.

Extraction rates

Extraction from tributary streams should be limited to the **annual transport rate** so as to limit bank erosion problems. A safe extraction rate is probably less than 2,000 m^3 per year from the major tributaries (excluding the Wannon River).

The extraction rate from the main trunk of the Glenelg River is not limited by concerns about bed or bank erosion. The annual bedload transport rate of 10 to 30,000 m^3 indicates the minimum safe extraction rate. With adequate management controls it may be possible to exceed this rate.

Even at the maximum conceivable extraction rate, it will still take many decades for the sand to evacuate the stream network. This time will be reduced because a large proportion (say 0.3 to 0.5) of the sand will remain in some type of long term storage in floodplains, benches, or in abandoned holes in smaller streams. The storage of sand in in-channel benches and floodplains is desirable because it reduces the active sand in transit. Such deposition can be encouraged by limiting grazing in the channel floor. Keeping stock (predominantly cattle) out of the river will promote bank stability, but it will also contribute to the stability of the entire channel. Every season the unstable sandy point bars begin to grow vegetation (river red gum seedlings and grass) that is then eaten-out by stock over the summer. If this vegetation was able to develop it would stabilise large areas of the sand bed

Thus we are left with the 2-4 million cubic metres of sand that will not be stored in the channel, that could be affected by sand extraction. Targetted extraction could have a significant impact on this volume of sand. Therefore, sand extraction can be looked upon as an important tool to restore the health of the Glenelg system and, as such, could be encouraged.

Consequences of over-extraction

Over-extraction of sand from tributary streams will result in accelerated bed and bank erosion. A proportion of the bed erosion would have occurred in any case, but the extraction brings the erosion forward in time.

The lakes formed upstream of the TJPs from Deep Ck, Bryans Ck and Pigeon Ponds Ck, and the Chetwynd River, are probably valuable habitat. There biological significance should be assessed. Extracting sand from below these junctions will accelerate the fall in the level of the sand slug, and so the draining of the backwater lakes. For this reason, priority should be given to extraction at the downstream end of these TJPs where possible.

Limitations of extraction as a management tool

It should be emphasised that removing sand will not guarantee a return to the original condition of the stream. A major impediment to rehabilitating the Glenelg River remains the regulation of the river's flow by Rocklands Reservoir. In any case, there are numerous commercial constraints on the places in the catchment from which sand can be profitably extracted. These limitations will constrain the utility of this management strategy.

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Appendix 1: Sand management plan, by reach, for the Glenelg Catchment

(Note: This management plan is summarised on Figure 12. This is a map located in a pocket at the rear of the report. The Reach Numbers are also shown on this map).

Reach Name:	**Mathers Ck., Yarramyljup Ck., Glenelg between Rocklands and Mathers Ck.**
Reach Numbers:	**Y1, M1, G16 & G15**

Description of Reach: Anastomosing reach of the Glenelg River, characterised by deep pools separated by vegetated reaches with multiple channels. Mathers and Yarramyljup Creeks drain granite areas and their lower reaches are filled with sand. These are the only tributaries supplying sand to the Glenelg above Fulhams Bridge. Sand from both creeks has dammed flow in the Glenelg River (Tributary Junction Plugs TJPs). The backwater above the Yarramyljup TJP is called Fraser Swamp (about 120 ha) and represents a major restriction to flow below Rocklands Reservoir.
For about 2kms below the tributary junctions sand has choked the anastomosing channels of the Glenelg. However, the sand then enters large ponds. The sand from Mathers Ck has prograded about 30m into the top end of a large pond (2.8 km long, 4 - 6m deep).

Volume of sand in storage: Lower end of Mather Ck. = 140,000 - 200,000 m^3
Yarramyljup Ck = 50,000 - 80,000 m^3

Channel change with no intervention: Sand supply from the catchments of the creeks is declining. So sand levels in Mathers Creek should decline. The downstream ends of the sand slugs (at the Glenelg Jnc) have been invaded by reeds which is reducing sand movement to the Glenelg. Eventually the river will cut a narrow channel through the sand slug, so that most of the sand will remain in storage indefinitely. The small volume of sand entering the Glenelg River will progressively fill the upstream end of the large holes in this reach of the Glenelg, but very little sand is transported through the holes. If all of the sand from both creeks entered the Glenelg River, it would fill the large pool directly below Balmoral.

Management Issues: * Restricted flow from Rocklands Reservoir through Fraser Swamp (Yarramyljup TJP)
* Damage to the large pools by sand (The sand occupies a small proportion of the large pools, and other environmental problems, such as salinisation and deoxygenation related to flow regulation are more important issues).

Management Goals: The major justification for managing the sand in this reach is to improve flow below Rocklands. In particular, sand in Yarramyljup Ck and its TJP could be removed to assist in the clearing of Fraser Swamp.

Management Actions: Investigate the benefits of improving flow through Fraser Swamp. Sand from Yarramyljup Ck may continue to block the channel and extraction may be justified.
No other management actions are suggested for these creeks.

Investigate the biological value of Fraser Swamp.

Reach Name:	**Mathers Creek to Fulhams Bridge**
Reach Numbers:	**G14**

Description of Reach: This is the anastomosing reach of the Glenelg River, made-up of pools (4 to 9m deep) separated by shallow multiple channels. Little sand has moved through this reach, apart from some fine sand deposited on the floodplain. The large body of sand from Mathers and Yarramiljup Creeks is stored in pools above the reach.

Volume of sand in storage: None

Channel change with no intervention: The gross morphology of this reach has remained stable since the 1850s and there is little prospect of its changing.

Management Issues: No sediment related issues. Major issues are flow regulation from Rocklands Reservoir and saline pools.

Management Goals: Maintain unique morphology and flow characteristics. Increase flow allocation to the stream.

Management Actions: Monitor condition.

Reach Name: **7 km below Fulhams Bridge to Harrow (25 km in length)**	
Reach Numbers: **G12**	

Description of Reach: Glenelg leaves the stable Devonian Rhyolites and older Schists and gneisses, and passes onto the unstable Ordovician granodiorite portion of the catchment. Sand aggradation in the channel begins at this point, with the source of sand being local tributaries. This 25 km reach had the earliest record of sand aggradation in a tributary (in 1872 in Schofields Ck). Sand from tributary and sheet erosion has filled the deep pools in the reach (up to 10m deep) and extends downstream to the township of Harrow. Harrow is the upstream extent of the backwater formed by a tributary junction plug from Deep Creek. Scour chains at Harrow indicate that there is very little sand transport at the downstream end of this reach.

Volume of sand in storage: 800,000 - 1,200,000 m^3 (max 50,000 m^3/km)

Channel change with no intervention: Change in this reach is not likely to be rapid. There are still some stores of sand in tributaries to be flushed into the Glenelg River, and downstream sand movement is restricted by the Deep Ck backwater. It will be several decades before the Deep Ck TJP is removed, and several more before the slug of sand stored above Harrow has migrated downstream to Deep Creek.

Management Issues: The Harrow reach is the largest volume of sand stored in the Glenelg River. Being choked with sand, the river is no longer a major asset to the township of Harrow. It will be many decades before the slug of sand stored above Harrow will move downstream. In any case, the backwater-lake formed above the Deep Ck TJP may have ecological value and may be worthy of preservation. If it is worthy of preservation, then the sand at Harrow will choke the channel permanently unless it is artificially removed.

Management Goals: Returning the river at Harrow to its original morphology of deep pools separated by shallow riffles.

Management Options: **1.** Extract sand from Deep Ck and below Deep Ck to remove the Deep Ck TJP, drain the backwater, and allow the sand at Harrow to move downstream at a faster rate. Removing the backwater would see an initial rapid movement of sand from the sand slug at Harrow because deposition in the upstream end of the backwater has produced a steeper section of the slug. The initial flush of sand would decline, returning the sand sheet to a stable slope. Sand would then move past Harrow at a slow rate of 10 - 20,000 m^3 per year. With 50% of the sand stored in benches etc. it would still take a minimum of 20 years for the sand slug to pass Harrow. Downstream reaches of the river would not be improved with the introduction of this new wave of sand to the channel. **This option is not advised.**

2. Recurrent sand extraction at Harrow. At least 30,000 m^3 would need to be removed to see any immediate improvement in the reach. However, this extraction would immediately trigger erosion of more sand from upstream so that no improvement would be seen. Extraction of over 30,000 m3 of sand from deep extraction holes above the Harrow Bridge would see a rapid deepening of the channel at Harrow Township. Unfortunately, the deep pools that may develop would probably become salt stratified.

Reach Name: **Deep Creek, and the Glenelg River between Deep Ck and Pigeon Ponds Ck.**	
Reach Numbers: **D1, G11**	

Description of Reach: Deep Creek is a left-bank tributary joining the Glenelg River about 5 km below Harrow. The lower kilometre of Deep Ck is filled with sand, and a 4.5m deep fan of sand from the creek (a TJP) has dammed the Glenelg River, producing a 4 km long swamp that extends nearly to Harrow. Sand from Deep Ck has moved down the Glenelg in a slug that extends about 3 km below the TJP. This slug gradually peters out into a series of discontinuous sluglettes filling deeper pools. In the lowermost of these pools, two pools above the Harrow-Casterton Rd Bridge, the landholder has seen the slug migrate 100 to 200 m into the 3 - 4 m deep pool over the last 25 years. Schofields Ck (the next Glenelg tributary upstream) was filled with sand by the 1870s, and it is probable that Deep Creek was similarly affected. Certainly the Deep Ck TJP had already dammed the Glenelg by 1946. However, comparing the 1946 and 1991 aerial photographs shows that the sand slug in Deep Ck is about 1000m shorter, suggesting that the sand slug has begun to migrate downstream as sediment supply to its upstream-end is exhausted. Scour chain measurements indicate that there was little movement of sand in the creek, or on the TJP, in 1995 despite high flows in August.

Volume of sand in storage: 50 - 70,000 m^3 in Deep Creek (18,000 m3/km), 200 -300,000 m^3 in reach G10 (40,000 m^3/km).

Channel change with no intervention: Deep Ck will continue to supply sand to the TJP for many decades, although the rate could decline. It is probable that the TJP will be maintained for many decades.

Management Issues: Preservation of the backwater swamp above the Deep Ck TJP. The movement of sand from Deep Ck into the Glenelg River has removed many pools, and the backwater lake behind the TJP, even though they are not 'natural,' may represent valuable natural habitat in the river. Dr Brad Mitchell (Deakin University) has suggested that these may be important habitats in the river.

Management Goals: * Preserve the Deep Ck TJP backwater lake
* Investigate the biological significance of the backwater wetland.

Management Actions: Limit sand extraction from Deep Ck and from the reach of the Glenelg between Deep Ck and Pigeon Ponds Ck.

Reach Name: **Pigeon Ponds Creek, and down the Glenelg River to Chetwynd River**	
Reach Numbers: **PP1, G10**	

Description of Reach: Pigeon Ponds Creek was originally a narrow, deep, chain-of-ponds. The channel has widened and the lower reaches are now choked with sand. A TJP from Pigeon Ponds Creek has dammed the Glenelg River. About 30,000 m^3 of sand have been extracted from the lower section of Pigeon Ponds Creek (below the Chetwynd Moree Bridge), and an unknown (but small) volume of sand from the Glenelg just below the junction. As a result of this extraction, the level of sand has fallen by nearly a metre below the Chetwynd-Moree Bridge in the last 20 years. In addition, the TJP was largely removed in 1995, probably as a result of sand extraction. This demonstrates that TJPs are sustained from tributary sand, and when this sand supply is removed or exhausted, the plugs will be removed by flow in the Glenelg. Although sand supply from the catchment of Pigeon Ponds Creek has declined, there are still large volumes of sand in storage in the lower 5km of creek bed. The lower two kilometres of Pigeon Ponds Creek is experiencing bank slumping and general widening.

Volume of sand in storage: 250 - 350,000 m^3 in Pigeon Ponds Creek. 200 - 300,000 m^3 in the Glenelg River between Pigeon Ponds Creek and Chetwynd River.

Channel change with no intervention: Sand supply to Pigeon Ponds Creek from its catchment is small, and most of the sand in the catchment is stored in the lower four kilometres of the creek (see section 6.2.2). Sand stored in the channel of Pigeon Ponds Creek will continue to supply the Glenelg with sand, maintaining the TJP. A large proportion of the sand will remain stored in the abandoned thalweg and point-bar benches because of channel widening and migration.

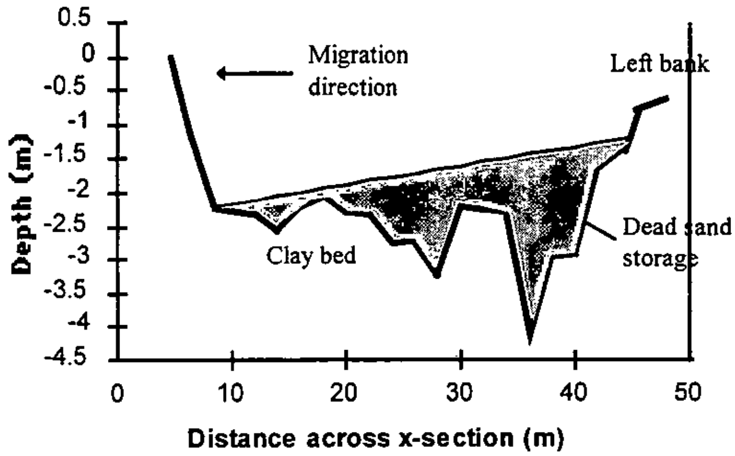


Figure A1: Dead sand storage in the abandoned thalweg, surveyed in Pigeon Ponds Creek.

That is, less than half of the sand in storage in the creek bed will be available for transport and supply to the TJP (known as dead-sand storage). Eventually the TJP will disappear and sand will move down the Glenelg River from the Deep Ck slug that is trapped above the Pigeon Ponds Creek TJP. When sand has left the Pigeon Ponds Creek (either naturally or artificially) there will be an increase in erosion of the unprotected bed and banks. The amount of erosion will be limited if the sand level falls gradually.

Management Issues: * Impact of sand extraction on the maintenance of a backwater in the Glenelg River.
* Movement of sand down the Glenelg River that is trapped above the Pigeon Ponds Creek TJP (the Pigeon Ponds Creek TJP is not as important as the Deep Ck TJP, because Pigeon Ponds Creek TJP does not produce such a major backwater).
* Impact of sand extraction on bank stability in Pigeon Ponds Creek because of the rate of fall of the sand level.
* New phase of erosion following the removal of sand.

Management Goals: Limit bed and bank erosion. Limit the movement of sand in the Glenelg River. The importance of this goal depends upon the biological value of the backwater above the Pigeon Ponds Creek TJP. Erosion in the creek will be worse if the sand is removed rapidly. Extraction should avoid taking the deep sand deposits stored below the point bars. Taking these deposits would re-route the channel through the low points of the channel.

Management Actions: Limit sand extraction to 'active' sand deposits - those deposits that would be likely to erode under natural conditions (so avoid abandoned thalweg sand and benches). This is best done by only extracting at the annual sand transport rate. This could be done by building a weir across the lower end of the creek and only removing what was stored each year. This would protect against rapid falls in sand levels so that the banks are protected, and it would avoid removing the deep stores of sand in the abandoned thalweg. Extracting at the transport rate would starve the slug of sand below the creek junction which would begin to erode and move downstream at a slow rate.

Reach Name: **Chetwynd River and Glenelg River reach from Chetwynd Jnc. to Burkes Bridge.**

Reach Numbers: **C1, C2, G9**

Description of Reach: As with the other tributaries of the Glenelg River, the Chetwynd River has been transformed from a narrow, deep, chain of ponds (described by Major Mitchell) to a broad channel filled by a uniform sheet of sand. There are the usual stories of 'standing on a horses back 50 years ago collecting eggs from under the Chetwynd-Junction Road bridge'. The lower 20 km of the Chetwynd River have aggraded up to three metres with sand in the last 40 years . There is evidence that the lower Chetwynd River is still aggrading with sand. Certainly scour chains show that the sand is being actively transported. Sand from the Chetwynd River is the main source of sand to the 65km of the Glenelg River between the Chetwynd and the Wando Junction. A TJP dams the Glenelg River above the Chetwynd, producing a backwater swamp. The slug of sand extends about 15km downstream of the junction (falling from 3 to 1m depth), before becoming a chain of sluglettes. Several reaches of the channel are now narrowing as reeds stabilise the channel bed.

Volume of sand in storage: Maximum of 700,000 m^3 in lower 17.4 km of Chetwynd
200,000 m^3 in the 4.5 kilometres of the Glenelg to Burkes Bridge.

Channel change with no intervention: The Chetwynd River is still aggrading at the township of Chetwynd, and the next bridge upstream (1.5m in 20 years). Erskine (1992) suggests that this is occurring because the catchment has not been stabilised by soil conservation works. Further downstream there is some evidence of bed degradation. The slug of sand below the Chetwynd-Glenelg junction will continue to provide sand to the chain-of-sluglette reach down to the Wando Junction at the same rate as in the past.

Management Issues: * Flooding at Chetwynd
* Continued aggradation of the bed of Chetwynd River
* Supply of sand to the sluglette reach

Management Goals: * Reduce the level of sand in the stream (especially for flood conveyance and bridge clearance)
* Avoid bank erosion from excessive extraction.
* Reduce supply of sand to the sluglette reach below Burkes Bridge to preserve the remaining pools in this reach.

Management Actions: Encourage sand extraction from the Chetwynd River. This is appropriate because the channel is still aggrading. Extraction rates should reflect the rate of aggradation so that bed levels do not fall too fast. This is important because removing sand from much of the lower five kilometres of the Chetwynd's channel would more than double bank height, with vertical banks. If sand is to be taken from any tributaries to the Glenelg River, the Chetwynd River would be the best. Extraction volumes should not exceed 2,000 m^3 per year. Extraction from the Glenelg River below the Chetwynd River junction should also be encouraged. This would reduce the sand supply to the sluglette reach, preserving the remaining pools. Extraction rates could be over 20,000 m^3 per year.

Reach Name: **Glenelg River from Burkes Bridge to Wando River Junction**

Reach Numbers: **G6 - G8**

Description of Reach: The original form of the river in this reach was a series of deep pools in a sinuous, clay banked channel. Sand from the Chetwynd River has filled between 40 and 60% of the cross-sectional area of the Glenelg River between the junction and about Kadnook Ck (5km downstream). Below this point the volume of sand declines to less than 20% of the channel area. Downstream of Powers Ck the sand in the Glenelg is no longer continuous but occurs as small slugs of sand that occupy the inflection point of bends and terminate in the pools of each bend . These small slugs become both smaller and less continuous further downstream. Downstream of Dergholm the Glenelg River again develops into a series of long pools that have not been filled by sand slugs as yet. The five kilometres or so of river above the Wando junction is reasonably free of sand, although landholders in the Glenelg River below Dergholm report that the channel has shallowed since the 1950s.

Volume of sand in storage: max 750,000 m^3

Channel change with no intervention: Small slugs will continue to move into the lower end of the reach, eventually joining with the large slug of sand above Casterton. The slug of sand that occupies the full channel below the Chetwynd River will progressively move downstream, filling the pools between sluglettes, and supplying the sand for downstream migration of the sluglettes.

Management Issues: Progressive destruction of pools by encroaching sand (sluglettes)

Management Goals: Preserve existing pools	
Management Actions: Sand extraction should be encouraged **above** this reach of river so as to starve the sluglettes of sand. This will lead to progressive downstream erosion of the sluglettes. Upstream extraction, will not, however, alter the downstream migration rate of the sluglettes.	

Reach Name: **Glenelg River Wando River Junction to Wannon River Junction**

Reach Numbers: **G5**

Description of Reach: The deep pools of this reach of the Glenelg River have been replaced in the last 50 years by a continuous sheet of sand that occupies 20% of the channel cross-sectional area (about 1.5m deep on average). There is also up to 1m of sand deposition on the floodplain adjacent to the stream. This is the longest continuous slug of sand in the Glenelg catchment. The source of sand for this slug has been the Wando River (including Wando Vale Ponds). The slug ends in a steep avalanche-face of sand at the Wannon Junction.
The main front of sand probably entered this reach in the 1946 flood. Specific gauge records suggest that the depth of sand in the reach peaked in 1970 and is now declining slowly (about 10cm per decade). The upstream end of the slug has also moved nearly two km downstream following the reduction in sand supply from the Wando River. The major sand extraction from the Glenelg River occurs in this reach, with an official total volume of less than 1500m^3 being extracted per year (ie. a total of less than 20,000 m^3 which is less than 5% of the total volume in storage).

Volume of sand in storage: 400,000 m^3 (30,000 m^3/km)

Channel change with no intervention: Sand transport through this reach is between 10,000 and 30,000 m^3 per year, and the bed elevation changes little through the year. Sand transport capacity certainly increases below the Wannon Junction. The large volumes of sand moving down the river from higher reaches (above Burkes Bridge) will eventually reach this section of channel - but not for several decades, and even then at a low rate.

Management Issues: * Possible increased nuisance flooding in Casterton because of decreased channel capacity
* The sand slug has damaged the aesthetic and recreational values of the river, as well as any biological values of the stream.
* Sand from this reach supplies sand to the chain-of-sluglette reach below the Wannon Junction.

Management Goals: * Return the channel to a series of deep and shallow sections (to at least provide recreation and some biological habitat). Of course, full rehabilitation of the biological values of this reach are compromised by desnagging and, to a lesser extent, by flow regulation.
* Reduce sand load to the chain-of-sluglette reach to preserve the remaining pools.

Management Actions: * Encourage sand extraction from this reach. This is one of the highest priority reaches for extraction in the river system for the following reasons:

- There will be limited tributary or upstream erosion triggered by extraction in this reach.
- Removing sand in this reach would produce only a small relative increase in depth and hence little bank erosion. This is in contrast to removing sand from small tributaries that would produce a large relative increase in depth, and bank erosion.
- The larger the stream the less the effect of hydrological changes, so the Glenelg at Casterton is unlikely to erode when sand is removed from the bed - unlike the small tributaries that would erode.
- Extraction would probably not produce saline pools.
- Extraction would lower the bed and provide some flood benefits.
- Casterton is closer to Portland and the southern markets which is good for extractors.
- Removing the sand would improve the environmental and public value of the river, and this would be a boost to Casterton.

*The extraction rate would have to exceed 10,000 m^3 per year to have a measurable effect on bed levels, and a rate of 20,000 m^3 would be preferable.
* Extraction could be combined with a weir built at Casterton. The weir would trap some thousands of cubic metres of sand each year (depending upon trap efficiency), which could then be harvested.

Reach Name: **Glenelg River from Wannon River Junction to the End Slug (28 km above Dartmoor)**
Reach Numbers: **G3, G4**

Description of Reach: Like the reach of the Glenelg between Burkes Bridge and the Wando Junction, this reach of the Glenelg River is characterised by discontinuous slugs of sand. The flood of 1946 spread sand below Casterton. Discrete sand slugs formed at the riffles/inflections of bends, with the snout of the slugs ending in the upstream end of the next pool. At low flows the slugs prograde into the pools, but the sand is cleaned-out of pools at high flows. The sand filling the channel does not appear to have increased the rate of bank erosion.
The desnagging of this reach of river in the 1960s and 70s may have contributed to the downstream migration of sand, although there is little change in the position of sand slugs shown in the 1946 and 1991 aerial photographs. Some large pools in the reach remain, and these remnants are possibly important habitat. The most-downstream slug occurs about 28 km above Dartmoor.

Volume of sand in storage: maximum of 340,000 m^3

Channel change with no intervention: There is no reason why the rate of sand movement in this reach should change. The supply of sand from the Wannon and Glenelg will remain the same as it has been for the last 30 years. The slug of sand moving down the Wannon River from Bryans Creek will not reach the Glenelg Junction for many decades.

Management Issues: * Preserving the remaining pools
* Flood capacity of the channel (an issue for riparian land-holders)
* Stock access across the river/ the river as a property boundary
* Local bank erosion problems
* Sand transport through to the Heritage River reach.

Management Goals: Preserve and improve the remaining pools.

- *Management Actions:* To protect the Heritage River reach from sand, extraction would have to occur at the downstream end of the reach, say at Killara Bridge. A weir could be built to ensure a commercially viable sand supply.
- To preserve the remaining pools in the reach, sand would have to be extracted from the Casterton reach above the Wannon Junction. This should be a management priority.
- Sand extraction rate could be higher than 10,000 m^3 per year.

Reach Name: 28 river kilometres of **Glenelg River above Dartmoor**
Reach Numbers: **G2**

Description of Reach: The river in this reach has a narrow and deep cross-section. There is certainly sand in this reach, but it would most likely have been there naturally. Even at Dartmoor about 10% of the channel cross-section is sand. Small slugs of sand are depositing downstream of the End Slug (see above), and we observed deposition on these slugs after the minor 1995 flood.

Volume of sand in storage: 120,000 m^3

Channel change with no intervention: Slugs of sand will gradually migrate downstream, at about one km per year. This occurs by the gradual aggradation of 'sluglettes'.

Management Issues: * Movement of sand into the Heritage River
* Loss of remaining pools and habitat in this relatively undamaged reach of river.

Management Goals: Stop movement of sand into the Heritage River and preserve this remaining reach of river from sand.

Management Actions: Encourage extraction of sand from the upstream reaches (eg. from near Killara Bridge) to limit sand migration into this reach.

Reach Name: **Glenelg River - Heritage River reach below Dartmoor**
Reach Numbers: **G1**

Description of Reach: This 65km of river is estuarine, and it is declared a National Park and a Heritage River. The reach is known as a gorge where it cuts through limestone cliffs. Tidal effects extend as far as Dartmoor.

Volume of sand in storage: Unknown

Channel change with no intervention: The weak tidal influence at the upstream end of the Heritage River reach means that sand transport would still be dominantly downstream. Within about 30 to 40 years 'sluglettes' that are migrating down the Glenelg River will reach Dartmoor. Within 6km of Dartmoor the Glenelg River deepens from 2m deep to over 6m, and the gorge reach has many holes that are over 20m deep. At an estimated maximum bedload transport rate of 25,000 m^3 of sand per year, and assuming all sand is stored in the upstream end of the reach, the sand will prograde into the upstream end of the Heritage river at a maximum rate of 300m per year. This rate will decline rapidly because the channel deepens rapidly downstream.
Management Issues: Damage to the Heritage River by sand aggradation
Management Goals: Protect the heritage river from sand aggradation
Management Actions: * Intercept the sand before it reaches the Heritage River, particularly upstream at the present End Slug. * Extract sand from the Heritage River as it arrives (this is a less attractive option because it could cause local damage to the river).

Reach Name: **Bryans Creek (tributary to the Wannon River)**
Reach Numbers: **B1, B2, B3**
Description of Reach: Bryans Creek was a chain-of-ponds that began to incise last century. The incising channel was then filled with sand from gully and catchment erosion. A TJP from Bryans Creek has dammed the Wannon River, producing a backwater lake 2km long. Nearly 90% of the sand extraction in the Glenelg Catchment since the 1960s has taken place in Bryans Ck (about 415,000 m^3 officially), with a maximum annual rate being 50,000 m^3 in 1986. Following the sand extraction, the bed of the creek eroded up to 2m as the protection afforded by the sand was lost. In addition, the rapid fall in the bed level associated with sand extraction has led to accelerated bank erosion, first, because the rapid fall in sand levels left the banks steep and unprotected by sand, and second, because the increased bank height led to instability. This latter point is not as important where widening of the channel has led to a decrease in the height of the clay bank.
Volume of sand in storage: Robsons Ck to Coleraine = 370,000 m^3 Coleraine to Wannon Junction = 160,000 m^3
Channel change with no intervention: Sand supply to Bryans Creek has fallen dramatically in the last 30 years as gullies have stabilised and as soil conservation programs have done their work. Without any extraction the level of sand in Bryans Creek would have gradually fallen, with large volumes of sand being 'locked-up' in channel stores, such as benches and 'abandoned thalwegs' (see text). Because of these stores the volume of 'active' storage is probably smaller than the volume of sand artificially removed. As sand supply from Bryans Ck declines, the slug of sand in the Wannon River will gradually move downstream. This will, over several decades, drain the backwater swamp above the TJP.
Management Issues: * Sand extraction * Renewed erosion of the channel: bed and bank erosion * Supply of sand to the TJP on the Wannon * Flooding in Coleraine * Biological and aesthetic values of the creek
Management Goals: * Limit bank erosion * Limit bed erosion * Maintain the backwater on the Wannon? * Improve biological and aesthetic stream values * Reduce flood frequency in Coleraine.
Management Actions: * Restrict the rate of extraction to the rate of transport (say 3,000 m^3 per year). This will stop the rapid falls in bedlevel that promote bank erosion. * Gradual removal of the sand slug will allow the stream to re-establish a pool riffle sequence and some channel complexity that is good for habitat. * Constricting the channel by vegetating the point-bars will also stabilise the channel and accelerate the development of a stable channel profile. The bends will scour. * Investigate the biological value of the Wannon backwater. If it is biologically valuable then it will influence the management approach.

Reach Name: **Wannon River from Bryans Creek to the Glenelg River Junction, including Dwyers and Henty Creeks**	
Reach Numbers: **W1 & W2, H1, DW1**	
Description of Reach: The Wannon River has been filled by sand from Bryans, Henty and Dwyers Creeks. Of these, Bryans Ck is by far the largest contributor of sand. A TJP from Bryans Ck dams the Wannon, producing a 2 kilometre backwater. The depth of sand in the Wannon decreases downstream of Bryans Ck, from over 3m to less than 1m at the Henty confluence. There is one sand extraction site on the Wannon, just upstream of the Winnicott Ck junction, from which a total of 7,000 m^3 has been removed (about 2000 m^3/yr). Nine km of the lower Wannon at the Murndall Estate were desnagged in 1978.	
Volume of sand in storage: Bryans Ck to junction with Henty ck = 160,000 m^3 Henty Ck junction to Glenelg Junction = 70,000 m^3 This is a small volume of sand in comparison to the volumes stored in the channel of the Glenelg and its upper tributaries.	
Channel change with no intervention: The deeper sand below Bryans Ck is likely to migrate downstream as a slug, eventually increasing the delivery of sand to the Glenelg River. Repeat cross-sections on the lower Wannon suggest that the river bed has been stable for at least 20 years, so this will not be a major source of sand to the Glenelg. Desnagging of the river does not appear to have measurably increased the sand transport rate.	
Management Issues: The usual suite of sand issues, with the major issue being the fate of the backwater above the Bryans Ck TJP. Is this backwater of any biological significance?	
Management Goals: * Possibly preserve the Bryans Ck TJP backwater.	
Management Actions: Investigate the biological importance of the backwater.	

Appendix 2: Samples of surveyed cross-sections and grain-size analyses for the glenelg river and selected tributaries

Cross-section surveys were made of reaches of the Glenelg River and its tributaries. At each cross-section, bedload samples were taken (these were sieved for grain-size analysis), and the bed was probed to determine the sand depth. The following pages show a representative sample of this survey information.

Cross-sections were surveyed over the following reaches:

i. The Upper Glenelg River, with cross-sections every 1000m, between Deep Creek and Powers Creek (a distance of 22 river km) (Cross-sections are labelled by kilometres above Powers Creek)

ii. Pigeon Ponds Creek (four cross-sections at 1000m intervals above the mouth). Chainage in all tributary surveys is measured as distance from the junction with the Glenelg River.

iii. Chetwynd River (four cross-sections at 1000m intervals from the Glenelg River junction)

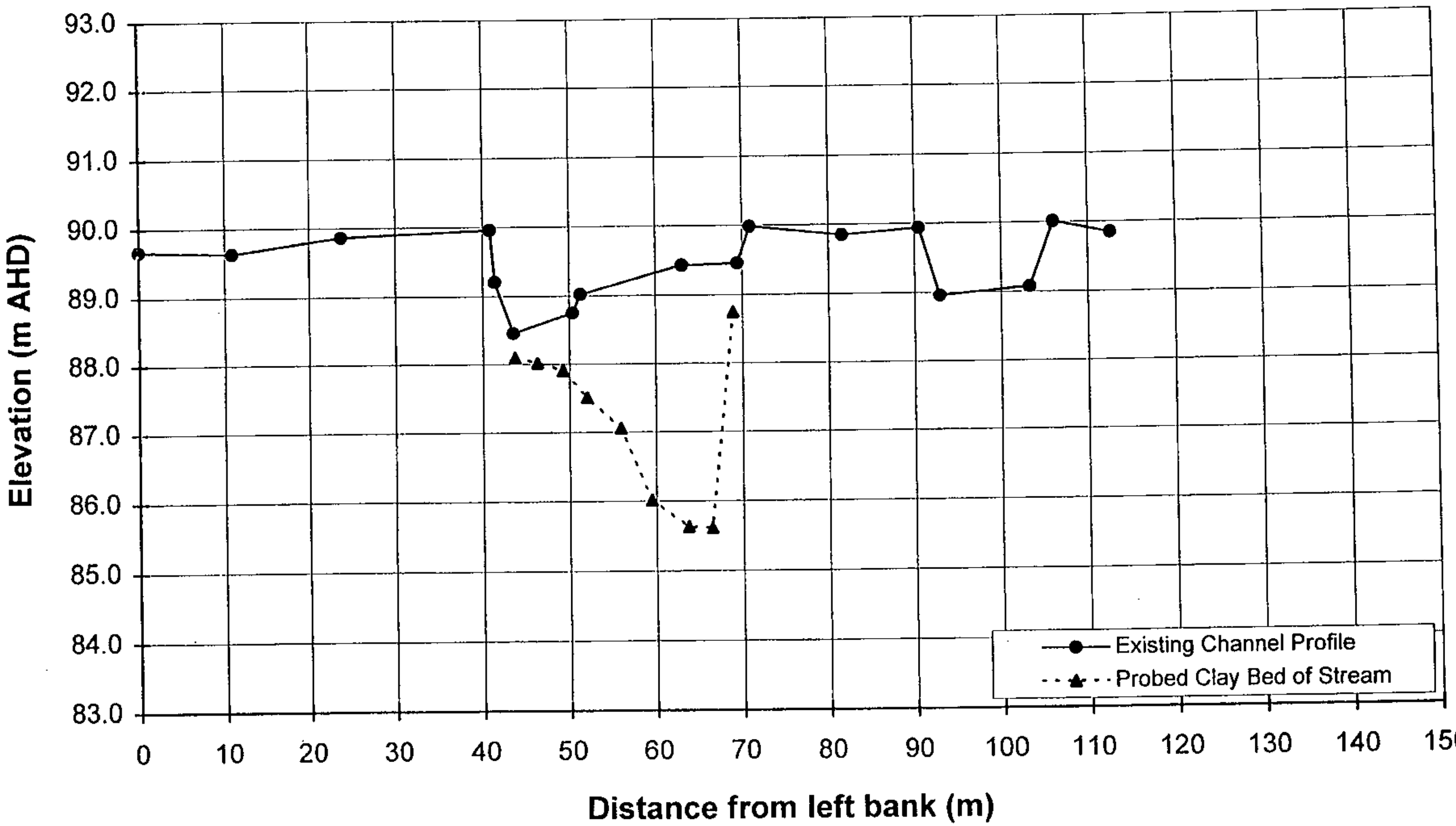
iv. The Lower Glenelg River (ten cross-sections at 1000m intervals above Dartmoor railway bridge). Numbered 1 to 10 from the bridge upstream.

We also present some typical grain size distributions for the bed material at some sites.

Please note that we can only present some samples of the available data here. A full set of the data is available from Ian Rutherfurd, or from the archives of the Cooperative Research Centre for Catchment Hydrology.

Glenelg River

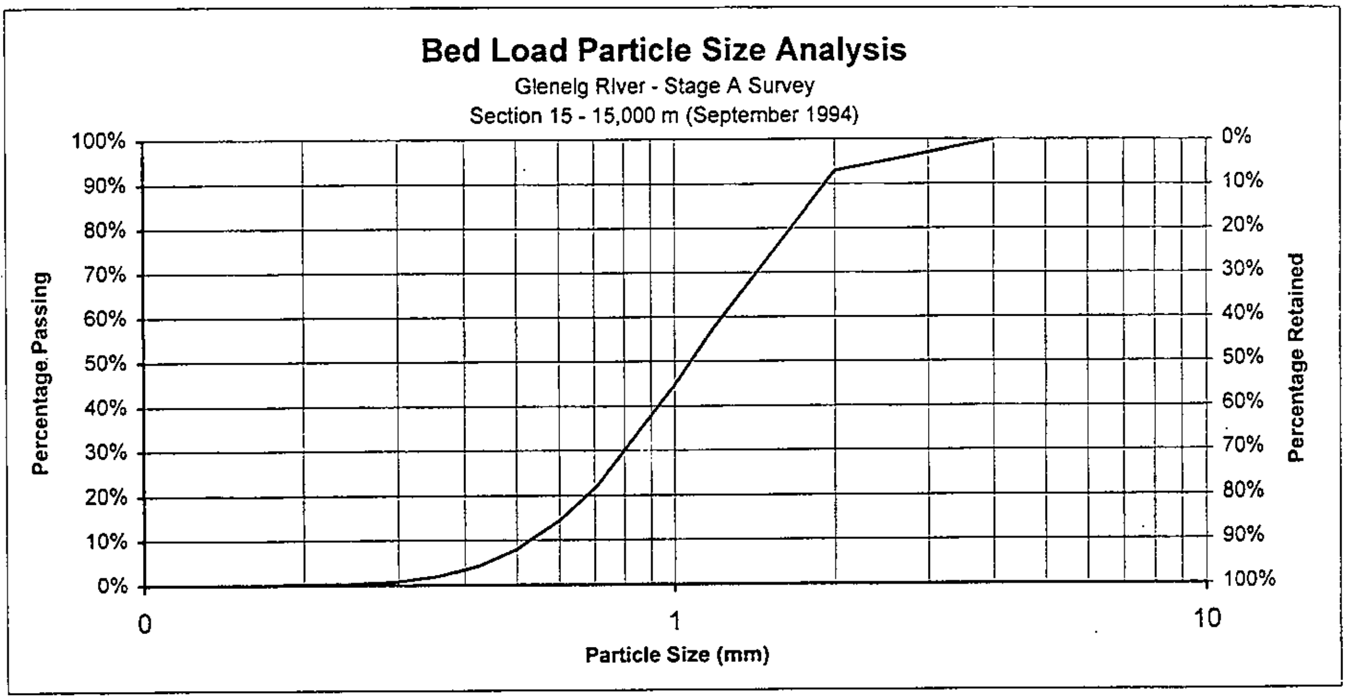
Cross-section 15 - Ch. 15,000 m (September 1994)

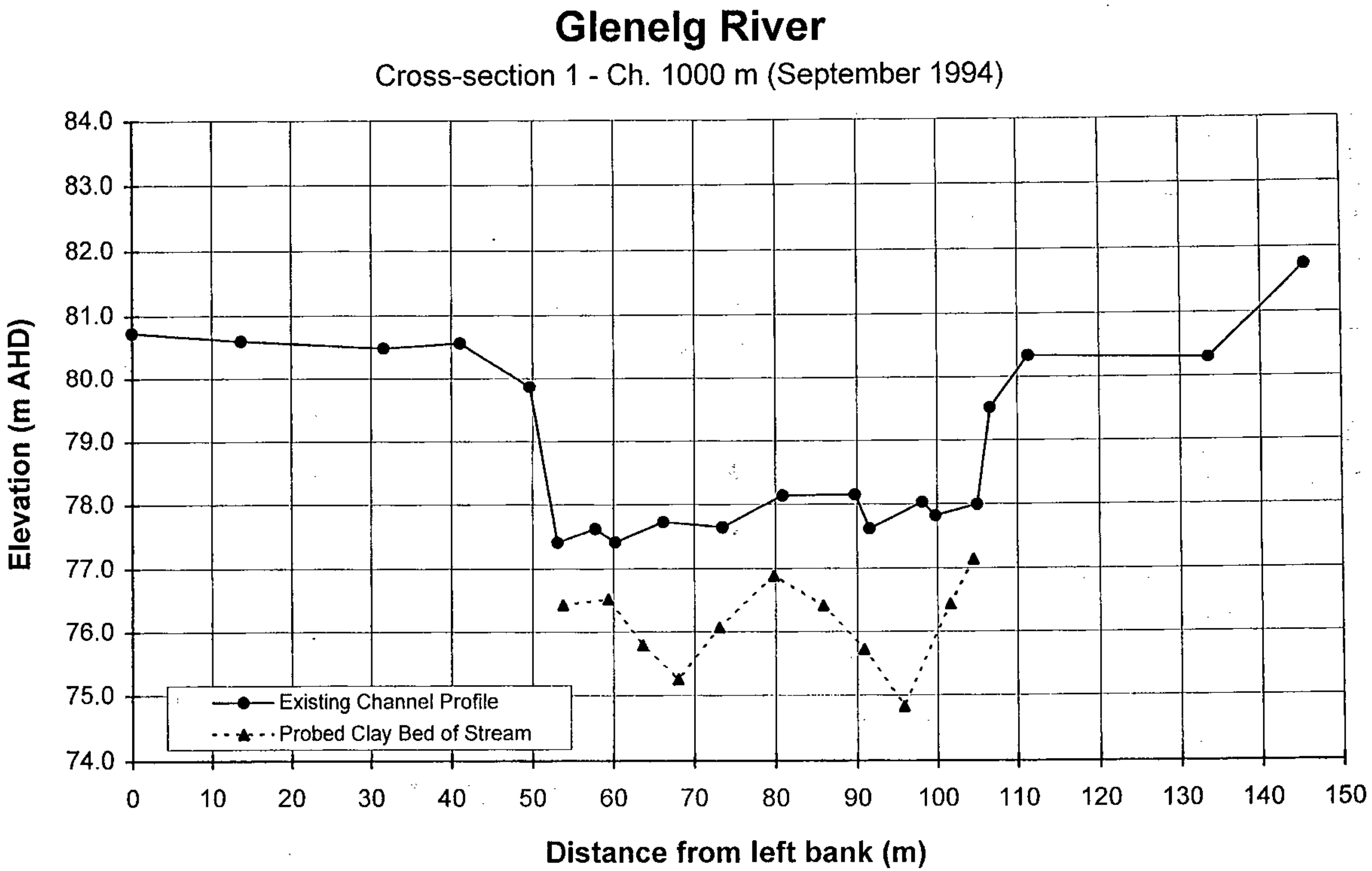


Upper Glenelg River Survey - Stage A
Particle Size Analysis

Sample: G15 **Stream Name:** Glenelg River

Sieve Size	Weight Retained on Sieve Class (grams)	Cumulative Weight Retained on Sieve Class (grams)	Cumulative Percentage Retained on Sieve Class	Cumulative Percentage Passing Sieve Class
4.00	0.13	0.13	0.0%	100.0%
2.00	19.36	19.49	7.0%	93.0%
1.18	98.82	118.31	42.7%	57.3%
1.00	34.92	153.22	55.3%	44.7%
0.71	62.08	215.30	77.7%	22.3%
0.60	21.40	236.71	85.5%	14.5%
0.50	18.09	254.80	92.0%	8.0%
0.43	10.40	265.20	95.8%	4.2%
0.36	6.36	271.57	98.1%	1.9%
0.30	3.15	274.71	99.2%	0.8%
0.25	1.35	276.06	99.7%	0.3%
0.21	0.35	276.41	99.8%	0.2%
0.18	0.14	276.55	99.9%	0.1%
<.180	0.40	276.95	100.0%	0.0%
TOTAL	276.95			

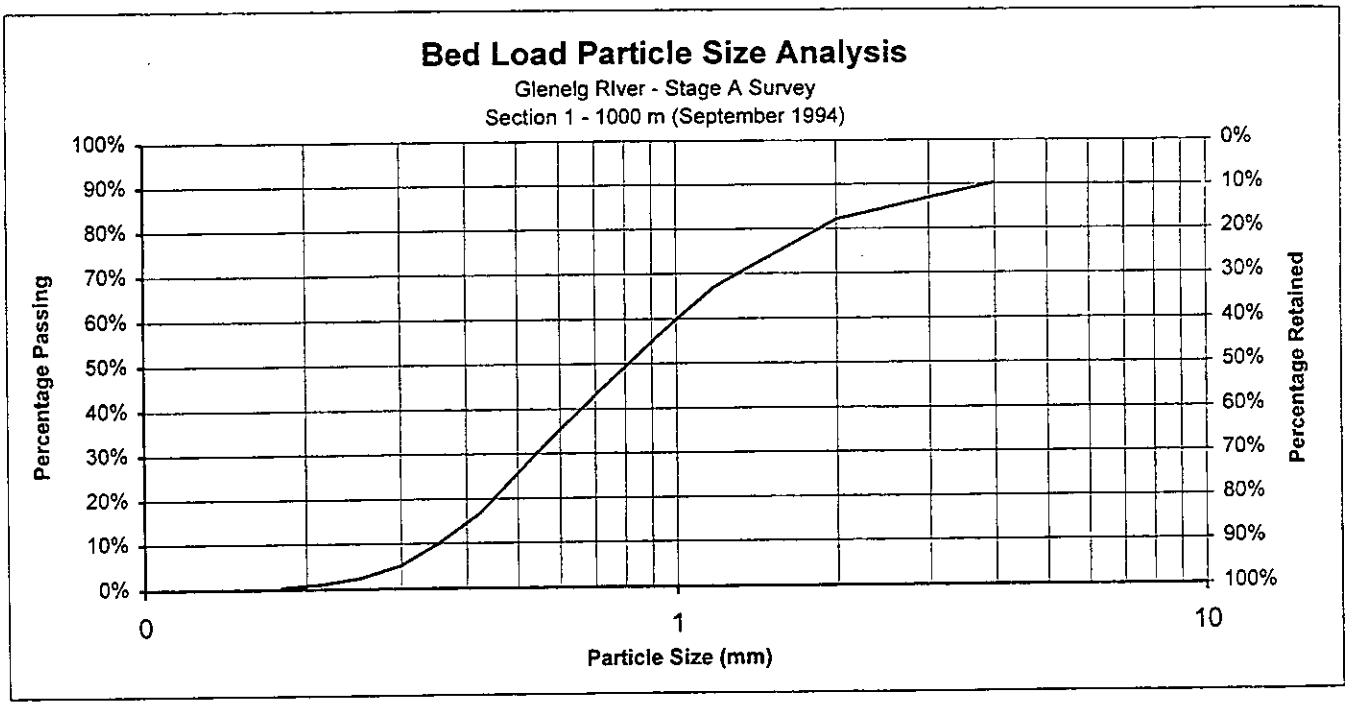


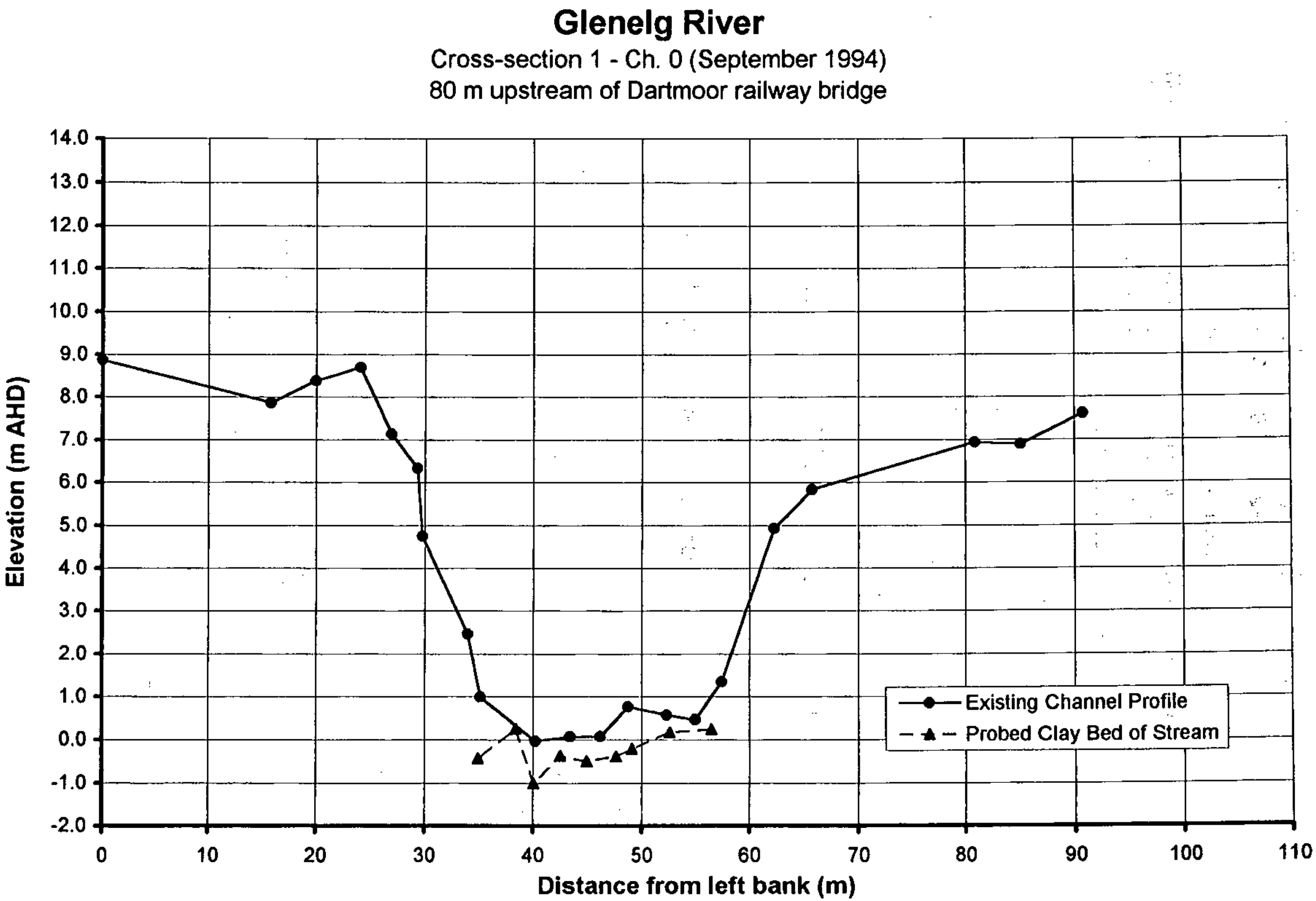

Glenelg River
Cross-section 1 - Ch. 1000 m (September 1994)
Elevation (m AHD)
84.0
83.0
82.0
81.0
80.0
79.0
78.0
77.0
76.0
75.0
74.0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Distance from left bank (m)
Existing Channel Profile
Probed Clay Bed of Stream

Upper Glenelg River Survey - Stage A
Particle Size Analysis

Sample: G01 **Stream Name:** Glenelg River

Sieve Size	Weight Retained on Sieve Class (grams)	Cumulative Weight Retained on Sieve Class (grams)	Cumulative Percentage Retained on Sieve Class	Cumulative Percentage Passing Sieve Class
4.00	20.16	20.16	9.8%	90.2%
2.00	16.76	36.92	17.9%	82.1%
1.18	30.93	67.85	32.9%	67.1%
1.00	14.91	82.76	40.1%	59.9%
0.71	33.39	116.15	56.3%	43.7%
0.60	17.17	133.32	64.6%	35.4%
0.50	20.12	153.44	74.3%	25.7%
0.43	18.47	171.90	83.3%	16.7%
0.36	13.67	185.57	89.9%	10.1%
0.30	10.30	195.87	94.9%	5.1%
0.25	5.80	201.67	97.7%	2.3%
0.21	2.66	204.33	99.0%	1.0%
0.18	1.41	205.74	99.7%	0.3%
<.180	0.70	206.44	100.0%	0.0%
TOTAL	206.44			



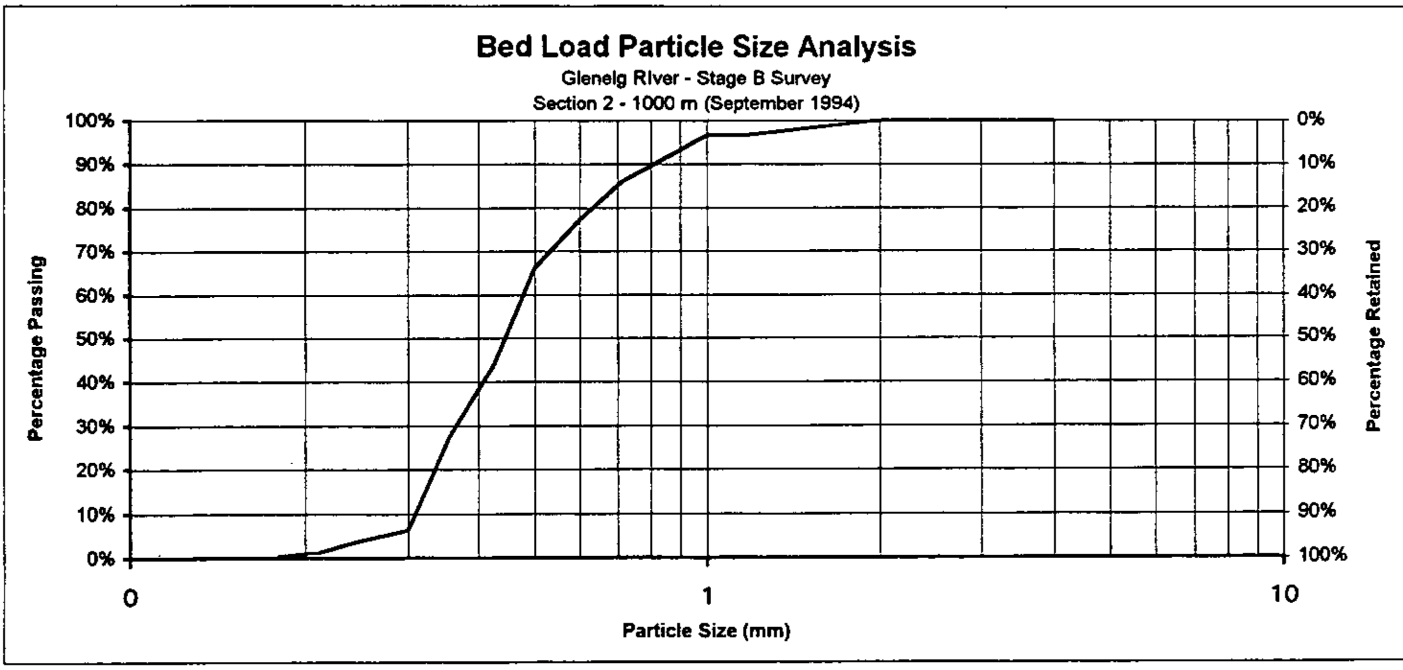


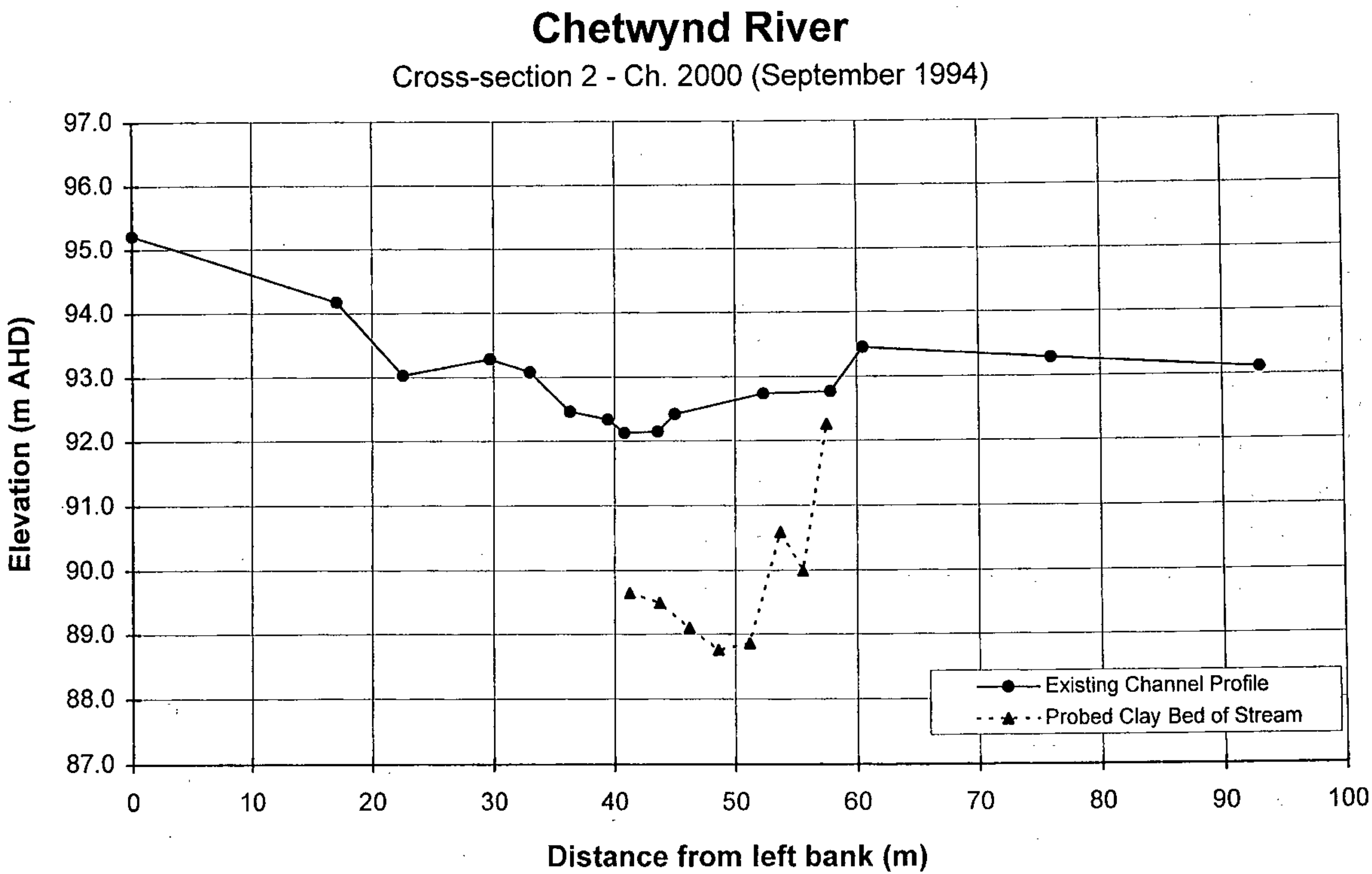
Glenelg River
Cross-section 1 - Ch. 0 (September 1994)
80 m upstream of Dartmoor railway bridge
Elevation (m AHD)
Distance from left bank (m)
Existing Channel Profile
Probed Clay Bed of Stream

Lower Glenelg River Survey
Particle Size Analysis

Sample: 101G **Stream Name:** Glenelg River

Sieve Size	Weight Retained on Sieve Class (grams)	Cumulative Weight Retained on Sieve Class (grams)	Cumulative Percentage Retained on Sieve Class	Cumulative Percentage Passing Sieve Class
4.00	0.00	0.00	0.0%	100.0%
2.00	0.00	0.00	0.0%	100.0%
1.18	8.70	8.70	3.4%	96.6%
1.00	0.00	8.70	3.4%	96.6%
0.71	27.61	36.31	14.1%	85.9%
0.60	22.58	58.89	22.8%	77.2%
0.50	28.09	86.98	33.7%	66.3%
0.43	57.94	144.92	56.2%	43.8%
0.36	42.64	187.56	72.7%	27.3%
0.30	54.08	241.64	93.7%	6.3%
0.25	6.17	247.81	96.1%	3.9%
0.21	6.56	254.37	98.6%	1.4%
0.18	2.44	256.81	99.6%	0.4%
<.180	1.08	257.89	100.0%	0.0%
TOTAL	257.89			





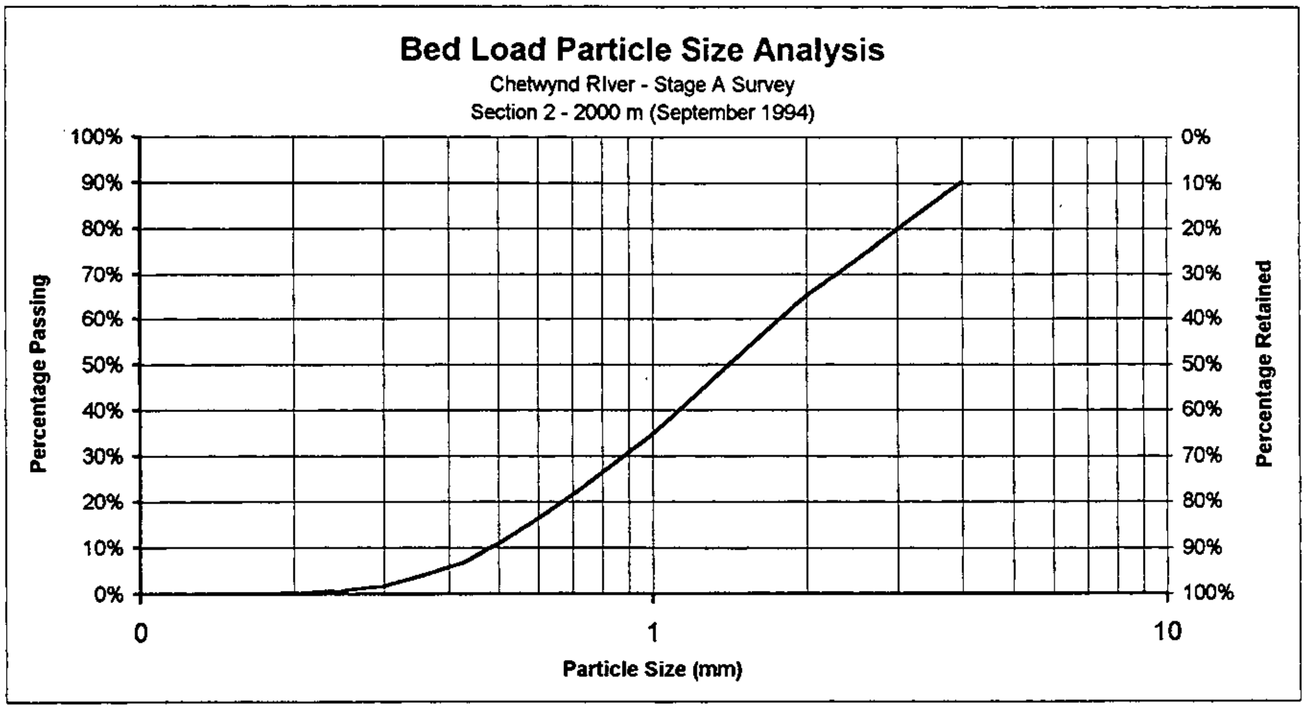
Chetwynd River
Cross-section 2 - Ch. 2000 (September 1994)
97.0
96.0
95.0
94.0
93.0
92.0
91.0
90.0
89.0
88.0
87.0
Elevation (m AHD)
0
10
20
30
40
50
60
70
80
90
100
Distance from left bank (m)
Existing Channel Profile
Probed Clay Bed of Stream

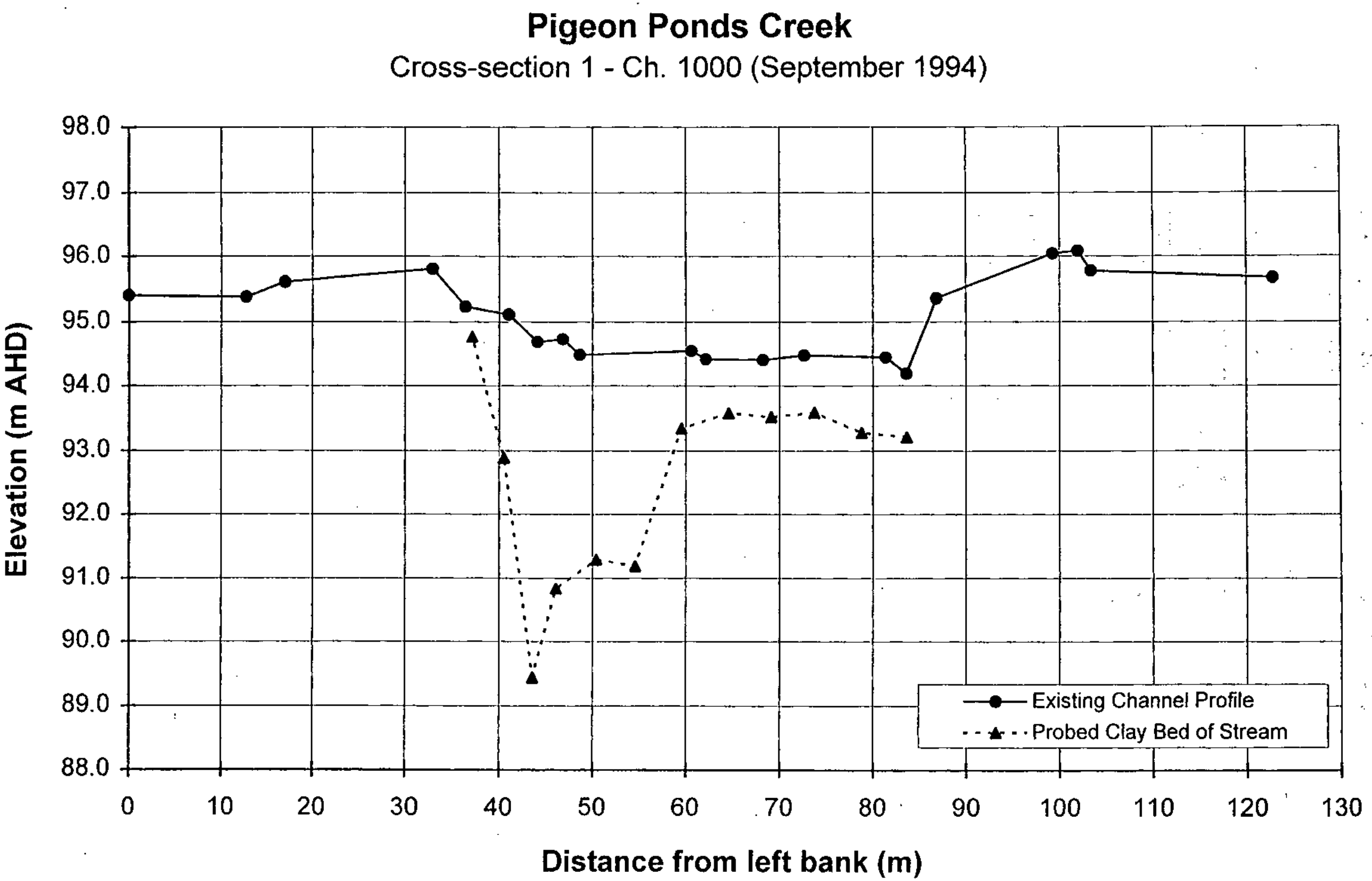
Upper Glenelg River Survey - Stage A

Particle Size Analysis

Sample: CH02 **Stream Name:** Chetwynd River

Sieve Size	Weight Retained on Sieve Class (grams)	Cumulative Weight Retained on Sieve Class (grams)	Cumulative Percentage Retained on Sieve Class	Cumulative Percentage Passing Sieve Class
4.00	35.61	35.61	9.6%	90.4%
2.00	93.96	129.57	34.9%	65.1%
1.18	85.31	214.87	57.9%	42.1%
1.00	27.29	242.16	65.3%	34.7%
0.71	47.15	289.31	78.0%	22.0%
0.60	20.95	310.26	83.7%	16.3%
0.50	20.47	330.72	89.2%	10.8%
0.43	14.67	345.39	93.1%	6.9%
0.36	10.96	356.35	96.1%	3.9%
0.30	7.91	364.26	98.2%	1.8%
0.25	4.16	368.42	99.4%	0.6%
0.21	1.56	369.97	99.8%	0.2%
0.18	0.60	370.57	99.9%	0.1%
<.180	0.26	370.83	100.0%	0.0%
TOTAL	370.83			



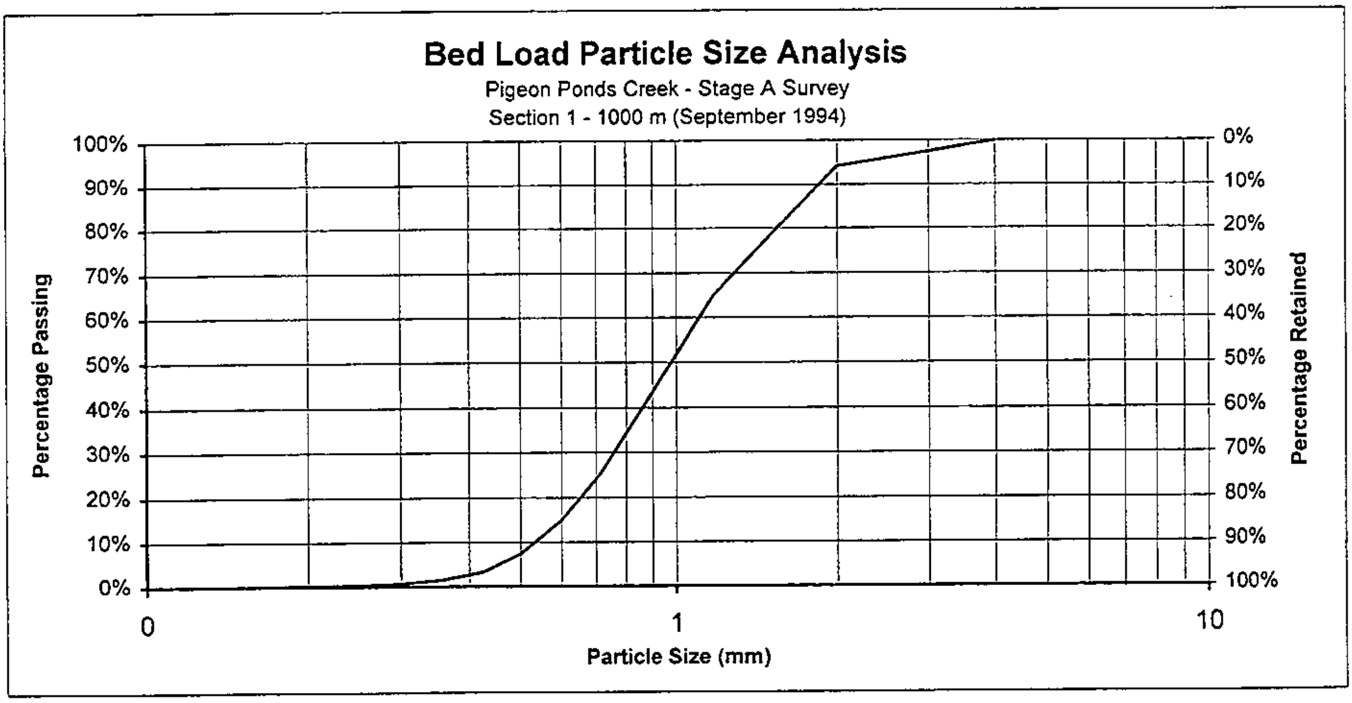


Pigeon Ponds Creek
Cross-section 1 - Ch. 1000 (September 1994)
98.0
97.0
96.0
95.0
94.0
93.0
92.0
91.0
90.0
89.0
88.0
Elevation (m AHD)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Distance from left bank (m)
Existing Channel Profile
Probed Clay Bed of Stream

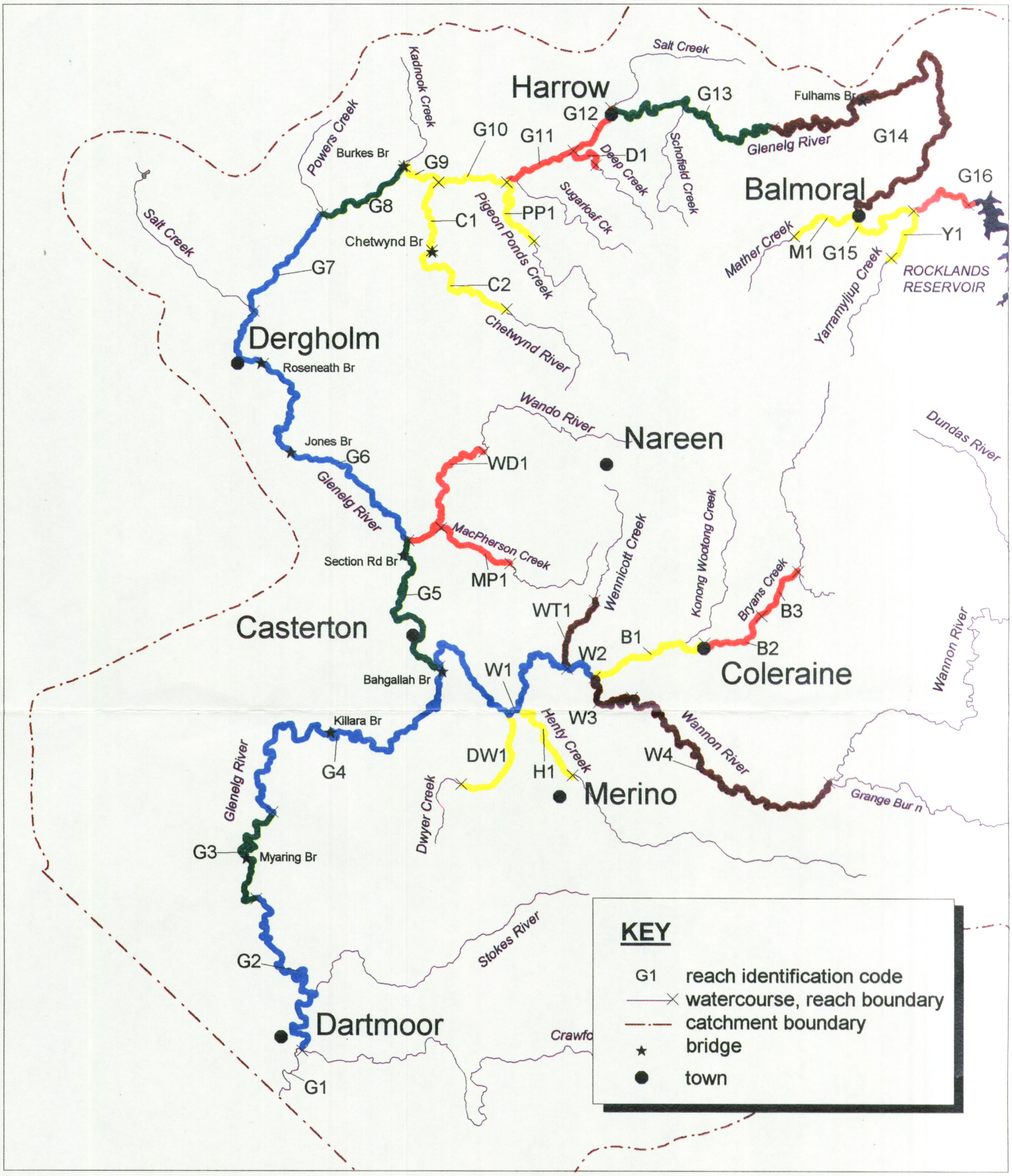
Upper Glenelg River Survey - Stage A
Particle Size Analysis

Sample: P01 **Stream Name:** Pigeon Ponds Creek

Sieve Size	Weight Retained on Sieve Class (grams)	Cumulative Weight Retained on Sieve Class (grams)	Cumulative Percentage Retained on Sieve Class	Cumulative Percentage Passing Sieve Class
4.00	0.20	0.20	0.1%	99.9%
2.00	13.54	13.74	5.8%	94.2%
1.18	68.73	82.46	34.8%	65.2%
1.00	31.65	114.11	48.2%	51.8%
0.71	63.67	177.78	75.1%	24.9%
0.60	23.75	201.52	85.1%	14.9%
0.50	17.91	219.43	92.6%	7.4%
0.43	9.64	229.06	96.7%	3.3%
0.36	4.56	233.62	98.6%	1.4%
0.30	1.68	235.30	99.4%	0.6%
0.25	0.75	236.04	99.7%	0.3%
0.21	0.32	236.36	99.8%	0.2%
0.18	0.17	236.53	99.9%	0.1%
<.180	0.31	236.83	100.0%	0.0%
TOTAL	236.83			



Sand Extraction Management Plan for Streams of the Glenelg River Catchment



Extraction Zone Code

Note: All extraction must be restricted to active sand bed

- Zone 1. No significant sand in storage. No extraction.
- Zone 2. No extraction.
- Zone 3. Extraction at transport rate only.
- Zone 4. Unlimited managed extraction, lower priority.
- Zone 5. Unlimited managed extraction, higher priority.

Figure 12 Sand extraction management plan for the Glenelg River catchment

This map forms part of the report 'Sand Management Strategy for the Glenelg River' by I Rutherfurd and M Budahazy (1996). Prepared for the Victorian Department of Natural Resources and Environment, and Southern Rural Water.

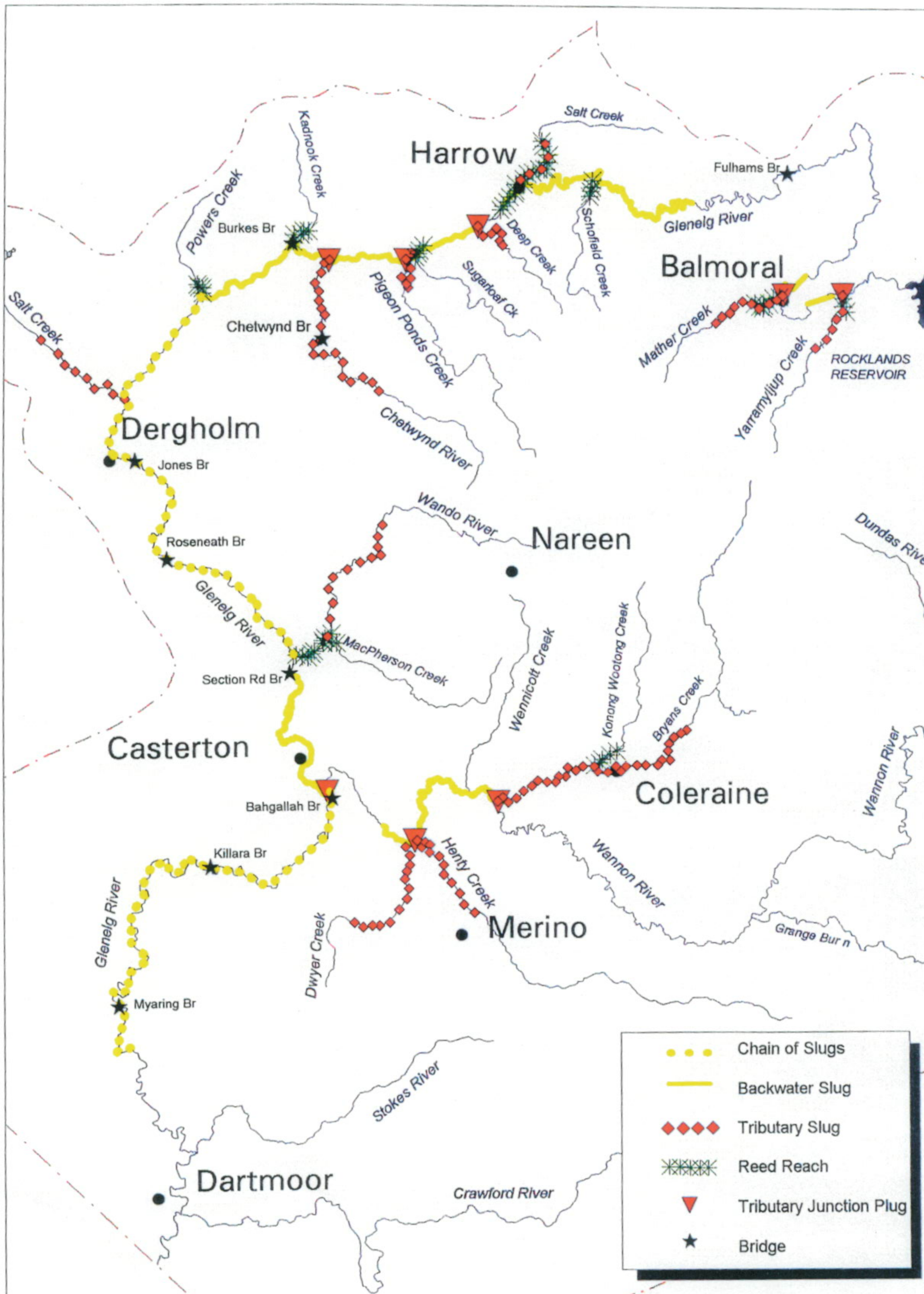


Figure 3.3. Controls on the distribution of sand in streams of the Glenelg catchment.

The Cooperative Research Centre for Catchment Hydrology is a cooperative venture formed under the Commonwealth CRC Program between:

Bureau of Meteorology

CSIRO Division of Water Resources

Department of Natural Resources and Environment

Goulburn-Murray Water

Melbourne Water

Monash University

Murray-Darling Basin Commission

Southern Rural Water

The University of Melbourne

Wimmera-Mallee Water

Associates

CSIRO Division of Soils

State Forests of NSW

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