BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT

POTENTIAL EFFECTS OF CHANGES TO HYDRO POWER GENERATION

APPENDIX 4:

GORDON RIVER FLUVIAL GEOMORPHOLOGY ASSESSMENT

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EXECUTIVE SUMMARY

This report summarises the fluvial geomorphic investigations conducted for the preparation of the Basslink Integrated Impact Assessment Statement. The aim of the investigation was to identify the main geomorphic processes operating under the present power station operating regime and predict what impacts the proposed Basslink operating regime would have on the geomorphology of the river. The study area encompasses the Middle Gordon River, from the confluence of the tailrace of the Gordon Power Station to the confluence of the Gordon and Franklin Rivers. The investigations were completed between September 1999 and April 2001.

Little previous geomorphic information is available for the study area. Regionally, it is believed that the establishment of dense riparian vegetation over the past 10,000 years has resulted in extreme stability of the river channels and floodplains of Southwest Tasmania with little change to river channels in the past 3,500 years.

In the study area, bank materials consist of bedrock, cobbles, sandy alluvium, or a combination of these. About 60% of the study area is bedrock controlled, and there are numerous gorges of up to several km in length. Sandy alluvial banks account for approximately 35% of the study area, with vertical cobble banks making up the remainder. The largest concentration of sandy alluvial banks is found in a 3 km reach of the river between the mouth of the Albert River and the Splits, designated as "Zone 2, where about 75% of the banks are of this type.

The development of the Gordon Power Scheme has increased median flows and water levels in the river. This has lead to the loss of riparian vegetation up to 4m above low water level through inundation and water logging, and exposed the underlying banks to river erosion through scour and seepage processes. The sandy alluvial banks in Zone 2 have been most affected by these processes. In the 7 km immediately downstream of the power station (Zones 1 & 2), power station flow dominates the hydrology, water level fluctuations are large (up to 4.5 m), and drawdown rates are high (up to 2.6 m/hr). In these zones alluvial bank slopes have been altered and channel widening of up to 10 m has occurred since the dam was built. Power station related impacts decrease with distance downstream, especially below the Denison River which contributes approximately 30% of the downstream flow on a yearly basis. Below this tributary, water level fluctuations are of the order of 2 m, and drawdown rates are about half of those upstream.

Measured scour rates are highest upstream of the Denison, and are believed to increase during periods of maximum discharge from the power station. Seepage erosion was observed during power station shutdowns following long-duration maximum power station discharge, which leads to the banks becoming saturated to high water level at least 18 m back from the river. The seepage erosion takes the form of flows of saturated sand and silt moving down the bank, leaving behind voids that can be metres deep. The overlying vegetation can then collapse into the void. The voids are concentrated on the upper bank between the water levels corresponding to 2-turbine and 3-turbine power station operation. Because the third turbine was only installed in the power station in 1989, and three-turbine usage has been limited to approximately 10% of the time over the past 10 years, it is believed that the observed seepage erosion is associated with river adjustment to the 'new' turbine. Inspection of nearby unregulated rivers (the Franklin and Denison) suggests that the seepage erosion processes taking place in the Gordon River also occur in natural streams. However, before regulation, such erosion was sporadic and discontinuous

Sandy alluvial banks are more stable where stands of tea-tree occupy the riparian zone, and where large woody debris derived from tree fall on the bank has accumulated. Below the Denison River, there is more vegetation between the power station controlled high and low water levels that also contributes to bank stability.

Impacts to bedrock banks are limited to the removal of vegetation below the power station controlled high water level, and to increased vegetation colonisation above the Plimsoll line due to the elimination of very high flows under the present operating regime.

Cobble banks were found to have retreated less than alluvial banks since flow regulation, and are generally stable. An exception occurred during the study year when it is theorised that unusually long duration maximum power station discharge (weeks) resulted in extensive bank saturation. This resulted in cobble bank failure following drawdown.

Aerial photo comparisons have found no change to the planform of the river since regulation. The placement and number of cobble bars have remained the same, except for the deposition of one new bar within 3 km of the power station, and minor narrowing and elongation of existing bars. Cobble bars tend to be armoured, and above the Splits, some are cemented. Channels have been incised in the cemented bars, but in general, the flanks of the bars are more active than the surfaces. It is also theorised that there has been little change to the armoured bed because the present flows are insufficient to transport the large cobbles, with bed load presently consisting of predominantly gravels and sands above the Denison River.

The Basslink flow regime is predicted to increase the proportion of time that flow exceeds 200 m^3/s from the power station and increase by 3 to 4 fold the number of times the power station shuts down as compared to present operations. Draw down rates and water maximum water level fluctuations will be unchanged compared to present operations.

The investigation concluded that these Basslink changes would increase the potential for scour throughout the study area, with the largest potential increase upstream of the Splits. This could increase the rate of scour in the extensive sandy alluvial reach upstream of the Splits. Below the Denison River, the greater presence of vegetation is likely to limit the acceleration of scour.

Seepage erosion under a Basslink operating regime will vary on a seasonal basis. In summer, when longer duration high flows from the power station are projected, the risk of seepage erosion will be high due to extensive bank saturation, similar to present operating conditions. In autumn, when the power station is off for more than 50% of the time, the risk of seepage erosion is lower due to the reduced extent of bank saturation. During the other seasons, bank saturation and seepage erosion will be dictated by the pattern of power station usage. Overall, the banks will have increased opportunities to drain under Basslink, but will also be subjected to an increase in maximum power station discharge.

Cobble banks are predicted to be least stable during the summer months, under both Basslink and the present operating regime, due to the possibility of extensive bank saturation.

The incision of cobble bars, re-working of bar flanks and elongation of mid-stream bars is anticipated to continue under either Basslink or the present operating regime. The increased proportion of maximum flow under Basslink may increase the rates of these processes. The bed of the river is not expected to change compared to present under a Basslink flow regime.

Overall, it is anticipated that under Basslink the present readjustment of sandy alluvial bank profiles will continue, especially in response to 3-turbine power station usage, and some additional channel widening is expected. Banks stability will increase as large woody debris accumulates on the bank toe and bank face, reducing scour and limiting seepage erosion. As with present power station effects, the planform of the river is unlikely to change.

Mitigation options for Basslink include reducing bank saturation and scour by limiting the duration of maximum power station discharge events; reducing groundwater slopes out of banks following drawdown by implementing a ramp-down or step-down rule for reducing flows following maximum power station discharge; and the establishment of a minimum flow in the river to decrease the range of water level fluctuations and decrease river surface slopes associated with the starting up of the power station. Additional monitoring is required to refine the understanding of threshold conditions leading to seepage erosion, and to determine the effectiveness of a step-down or ramp-down rule.

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1 INTRODUCTION

This report is a technical assessment of the potential geomorphological changes to the Gordon River arising from the implementation of Basslink using the present status of the river as a baseline. Hydro Tasmania (HT) identified the need for this investigation in Appendix 1 of this report series - Scoping Report: Basslink Aquatic Environmental Project (2000), which examined potential changes to the management of the Tasmanian hydro system related to Basslink. This report along with the findings of other environmental investigations identified by the Scoping Report will form the basis of the Integrated Impact Assessment Statement (IIAS) to be completed as part of the Basslink approvals process. A summary of this technical report is included in the Basslink Integrated Impact Assessment Statement – Potential Effects of Changes to Hydro Power Generation – Summary Report (Locher, 2001).

The Gordon River geomorphological investigations were initiated in September 1999 with the establishment of a study team led by Dr. Helen Locher (HT), and comprised of representatives from Universities, Hydro Tasmania and private contractors. A detailed list is contained in Attachment 1. *List of Contributors*. During some of the field investigations, a representative from Nature Conservation Branch, Department of Primary Industries, Water and Environment participated as an official observer.

This report focuses on the middle Gordon River, defined as the area between the tailrace of the power station and the Franklin River.

1.1 Research question & investigative approach

The research questions addressed by the study team include:

1. What are the potential fluvial geomorphological changes to the Gordon River arising from alterations to the flow operations downstream of the Gordon Dam as a result of Basslink, and

2. What management or mitigation options are available to minimise any potentially negative impacts to Gordon River geomorphology arising from Basslink?

Of most interest here are changes in the form of the bed, banks and planform of the river, and changes in the rates of processes presently operating in the stream and its floodplain.

These research questions recognise the current power station operation in the Gordon River catchment as the 'baseline' condition, and seek to address geomorphological changes associated with altering the present power station operation.

The approach adopted for the investigation was to first understand the present geomorphological processes operating in the river and how they relate to the present hydrology of the catchment, and then use this as a basis for predicting potential geomorphic changes due to predicted hydrologic changes under Basslink. It must be clearly stated that this investigation is not a 'pre-dam' - 'post-dam' study, nor an attempt to quantify natural rates of geomorphic change in the catchment. However, components of these topics are relevant to the present investigations, as it is necessary to understand the current impacts of flow regulation on the natural river system in order to define the 'baseline' condition. Therefore, aspects of these issues are included in discussions.

Translating this approach into practice has required three components:

- Identify changes to the hydrology and geomorphology of the Gordon River related to the present regulated flow regulation;

- Describe the present geomorphological processes operating in the river based on field observations and measurements, and relate these observations to the current flow regime; and
- Predict how the hydrological changes forecast under Basslink will translate into alterations to the current geomorphic processes, based on modelling, information available in the literature, and observations.

The results presented in this report are therefore the culmination of an iterative process of field observations, literature review, consultation and modelling work focussing on the dominant geomorphological processes presently operating in the Gordon River catchment.

1.2 Structure of this report

This report is structured as follows:

- Background information (Section 2);
- Literature review and theoretical framework (Section 3);
- Methods (Section 4);
- Current condition and processes (Sections 5 – 8);
- Comparison of predictions with observations (Section 9)
- Prediction of the geomorphic consequences of Basslink (Section 10)
- Mitigation Options (Section 11); and
- Monitoring Recommendations (Section 12).

2 BACKGROUND DESCRIPTION OF GEOLOGY, GEOMORPHOLOGY AND HYDROLOGY

This section contains a summary of previous geological and geomorphological descriptions of the study area, and the natural and present hydrology of the river. Information relating to karst features is presented in Appendix 5 of this report series – Gordon River Karst Assessment (Deakin *et al*, 2001).

Detailed geological and geomorphological investigations of the study area are lacking due to the inaccessibility of the region. Previously, only one large-scale investigation of the area was undertaken as part of the Lower Gordon River Scientific Survey (LGRSS). The LGRSS was initiated by the HEC (now Hydro Tasmania) in 1974 as a means of obtaining the scientific information required for preparation of the environmental impact statement associated with expansion of the Gordon River Power Scheme into the middle Gordon River. The goal of the LGRSS was to "describe the physical and biological characteristics of the region and their interrelationships, so far as was possible in the time and with the resources available" (Christian and Sharp-Paul, 1979). Roberts and Naqvi (1978), who completed the geological and geomorphological investigations for the LGRSS, note that due to the lack of existing information and complexity of the geomorphologic history of the region, the study should be considered as preliminary. A summary of geology of the World Heritage Area compiled in 1990 suggested that less than half of the WHA had been geologically surveyed at an adequate scale (Banks and Williams, 1990).

In the Lower Gordon River, downstream of Warners Landing, geomorphological investigations have been conducted related to bank erosion in the stretch of the river navigated by tourist boats. This work included an examination of bank morphology, landslips, and backwater areas (Soutberg, 1991; Bradbury *et al.* 1995; Nanson *et al.* 1994). The description of the present erosional features in the middle Gordon River draws on examples from this downstream stretch of the river where applicable.

2.1 Regional Geology

Regionally, the geology of the middle Gordon River is dominated by north-south trending Proterozoic rocks more than 1000 million years old known as the Tyennan region (Turner, 1989). This resistant core is composed of quartzite and schist (Banks and Williams, 1990) and has been subjected to several periods of deformation, most notable during the Penguin Orogeny (Late Precambrian, Turner, 1989), and Taberabberan Orogeny (mid-Devonian, Solomon, 1962; in Roberts and Naqvi, 1978). Strata flanking this central core ranges in age discontinuously from the Palaeozoic (350 – 500 million years) to the present (Christian and Sharp-Paul, 1979). The Gordon limestone, which occurs extensively in the study area, was deposited during the Ordovician period (Banks and Williams, 1990). Between the mid-Devonian and late Tertiary periods, glaciation and volcanic activity occurred regionally (Banks and Williams, 1990). Glaciation during the Quaternary consisted of mountain glaciers, with fluvio-glacial beds of sand and gravel deposited in valleys (Roberts and Naqvi, 1978).

2.2 Geology of study area

Figure 1 shows north-south trending Precambrian rock present from the Gordon dam site to the Orange River fault, which marks the contact with the younger Gordon limestone and undifferentiated sediments. Physiographically, these units form broad north-south trending valleys separated by mountain ranges ranging from 220 to greater than 600 m high above sea level (Roberts and Naqvi, 1978). The more resistant quartzite beds form mountain chains, and the more erodable schists, phyllites and dolomites form valley floors (Roberts and Naqvi, 1978). The younger Gordon limestone sequence has formed a long-thin valley, stretching from the Hardwood River in the south, to the lower Franklin River in the north.

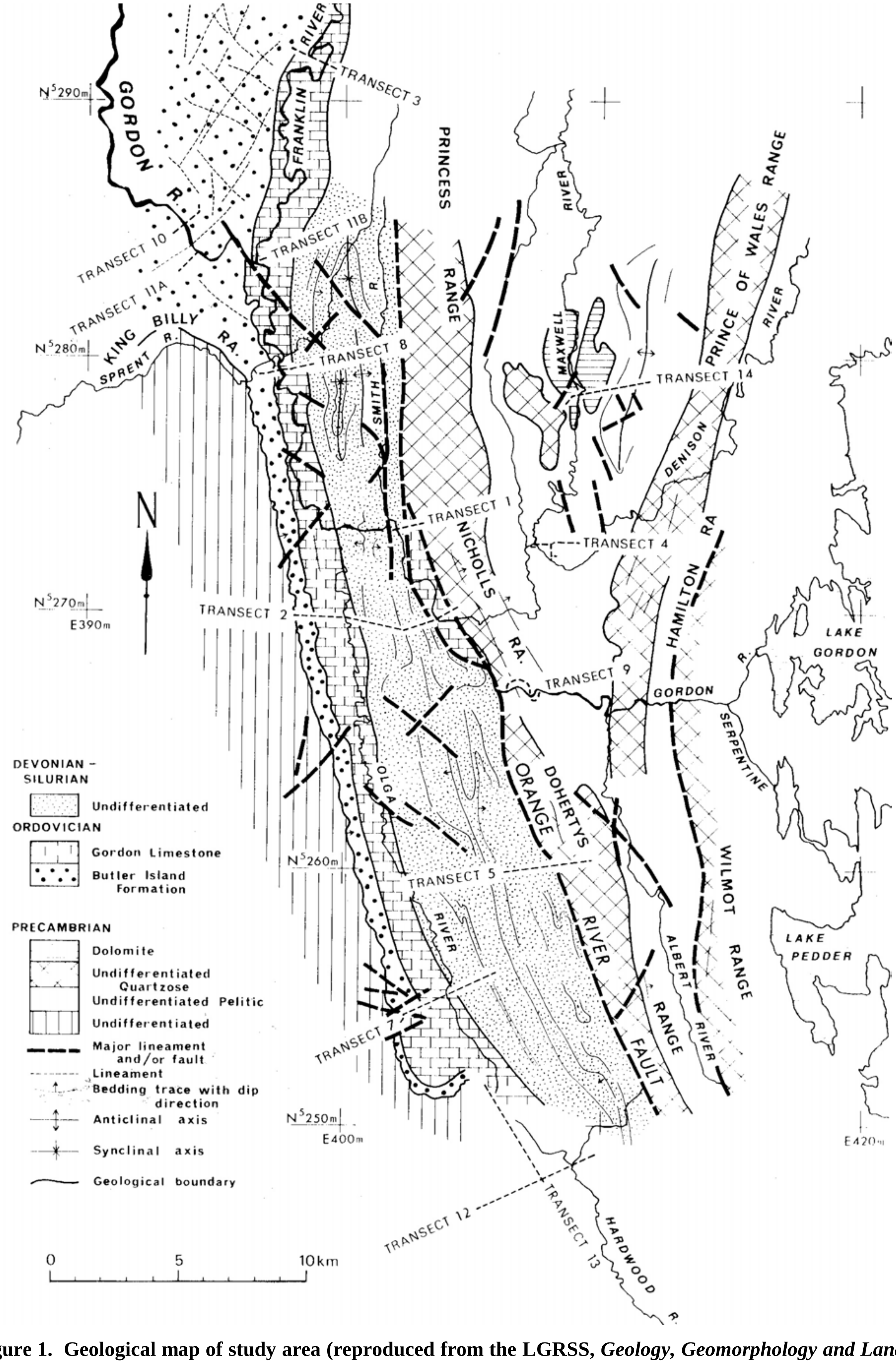


Figure 1. Geological map of study area (reproduced from the LGRSS, *Geology, Geomorphology and Land Systems* (1978)).

2.3 Geomorphology of the study area

The present course of the Gordon River is the result of a pre-existing drainage modified by the underlying geologic structure of the region. The east-west superimposed drainage pattern, postulated to be derived from an earlier higher land surface of approximately 350 m above present sea level (Roberts and Naqvi, 1978), has produced numerous narrow gorges through the Hamilton-Wilmot, Nicholls and Elliot Ranges. Drainage lines associated with tributaries in the east-west trending section of the Gordon have formed through the erosion of softer, more erosionally susceptible units to create broader valleys parallel to geologic controls (Roberts and Naqvi, 1978). In the Hardwood – Olga – Gordon – Franklin valley the carbonate substrate has been modified by solution processes, producing cave systems along the Gordon and Franklin Rivers (Roberts and Naqvi, 1978).

Based on the geological and geomorphological observations, Roberts and Naqvi (1978) delineated 16 geomorphic land systems for the middle Gordon River (Figure 2). Attachment 2. *Description of Geomorphological Units*, contains more complete descriptions of these geomorphic units.

The east-west trending section of the Middle Gordon River study area transects zones 'N', 'M' and 'K' in Figure 2, which consist of dissected mountain and valley underlain by competent Precambrian strata. Downstream, the river trends northwest and west through zones of younger limestone and sediment (G; H; in Figure 2), before entering the area designated in Figure 2 as a low lying alluvial plain associated with the Gordon Limestone and Hardwood – Olga – Gordon – Franklin River valley.

2.3.1 Regional Fluvial Geomorphology

Little work has focused on the fluvial geomorphology of the middle Gordon River. The lower Gordon River, which is tidally controlled, has been investigated due to bank erosion associated with boat wakes over the last few decades (Soutberg, 1991). A possible evolutionary scenario was presented by Soutberg (1991) with the caveat that further field investigations were warranted. The development of the landforms of the lower Gordon were attributed to the five chronologically ordered periods:

- The sculpturing by denudation processes, of the study area's bedrock valley form over tens of millions of years.
- The multiple phases of fluvio-glacial infilling and fluvial excavation within the valley during at least the last one million years.
- Sea level rises during the latter part of the Post Marine Transgression PMT (ie 10,000 years BP to 6,000 years BP.
- The stabilisation of sea level 6,000 years BP (ie Holocene Still Stand).
- Recent (<15 yrs BP) activities

During the Holocene Stand Still, Soutberg (1991) suggests that the development of levees along the river channel 'locked' the channel in a position similar to what is present today.

With respect to investigations conducted on the West Coast of Tasmania that are of relevance to the present investigations, Nanson *et al.,* 1995 examined the Stanley River in western Tasmania and documented strong river channel stability since the Pleistocene as a result of the re-establishment of dense riparian rainforest, and the longevity of fallen trees in the channel which reduce stream power and boundary shear stress. The authors suggest this trend is applicable to the river channels and floodplains of Western Tasmania, and would suggest that the middle Gordon River and its tributaries have very low natural erosion and channel migration rates.

2.4 Soils

Tarvydas (1978) completed a soil survey in the Middle Gordon River as part of the Lower Gordon River Scientific Investigations. The investigation involved the interpretation of aerial photographs and an examination of over 200 soil pits. The most common soil present in the Gordon and Franklin valleys was described in the following way:

- Along riverbanks, there is stratified alluvium with flat to gently sloping surfaces. The fine fraction of the alluvium ranges from medium to silty clay, with variable amounts of boulders, stones and gravel.
- Beyond the riverbanks, there is an almost universal occurrence of dark reddish-brown, acidic fibrous peat, 20 – 50 cm thick, grading into the shallow to deep siliceous sands.
- There is little pedogenic differentiation of the sandy material below the peat, with the exception of occasional diffuse iron-oxide staining.
- Iron-oxide hard pans are present within some of the sands.
- The soils are well drained externally and internally, with almost a complete absence of any evidence of surface soil erosion on the peat, indicating a very high hydraulic conductivity.
- The organic rich fibrous root mats are not related to the mineral substrates, although there is some admixture within the organic horizon or at the base of it.

Watson (1978), in an investigation of hydrology of the Olga River, estimated the field capacity of the fibrous peat to be 7.3 to 7.6 cm/10 cm soil thickness, and for the basal sand unit, approximately 1.0 cm/ 10 cm. High hydraulic conductivity of the soil was reported by Tarvydas (1978) based on the absence of surface soil erosion.

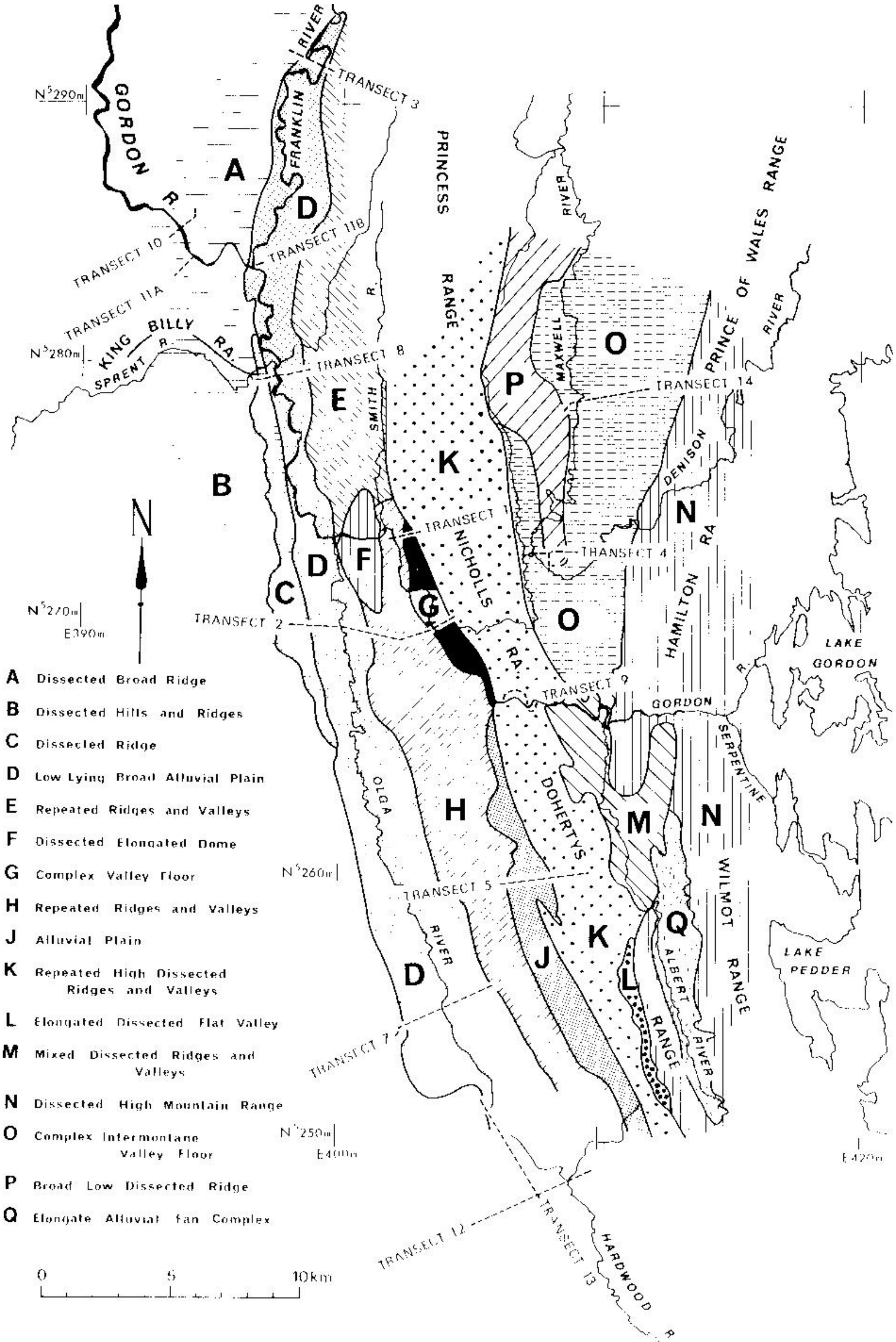


Figure 2. Geomorphic Map of Middle Gordon River

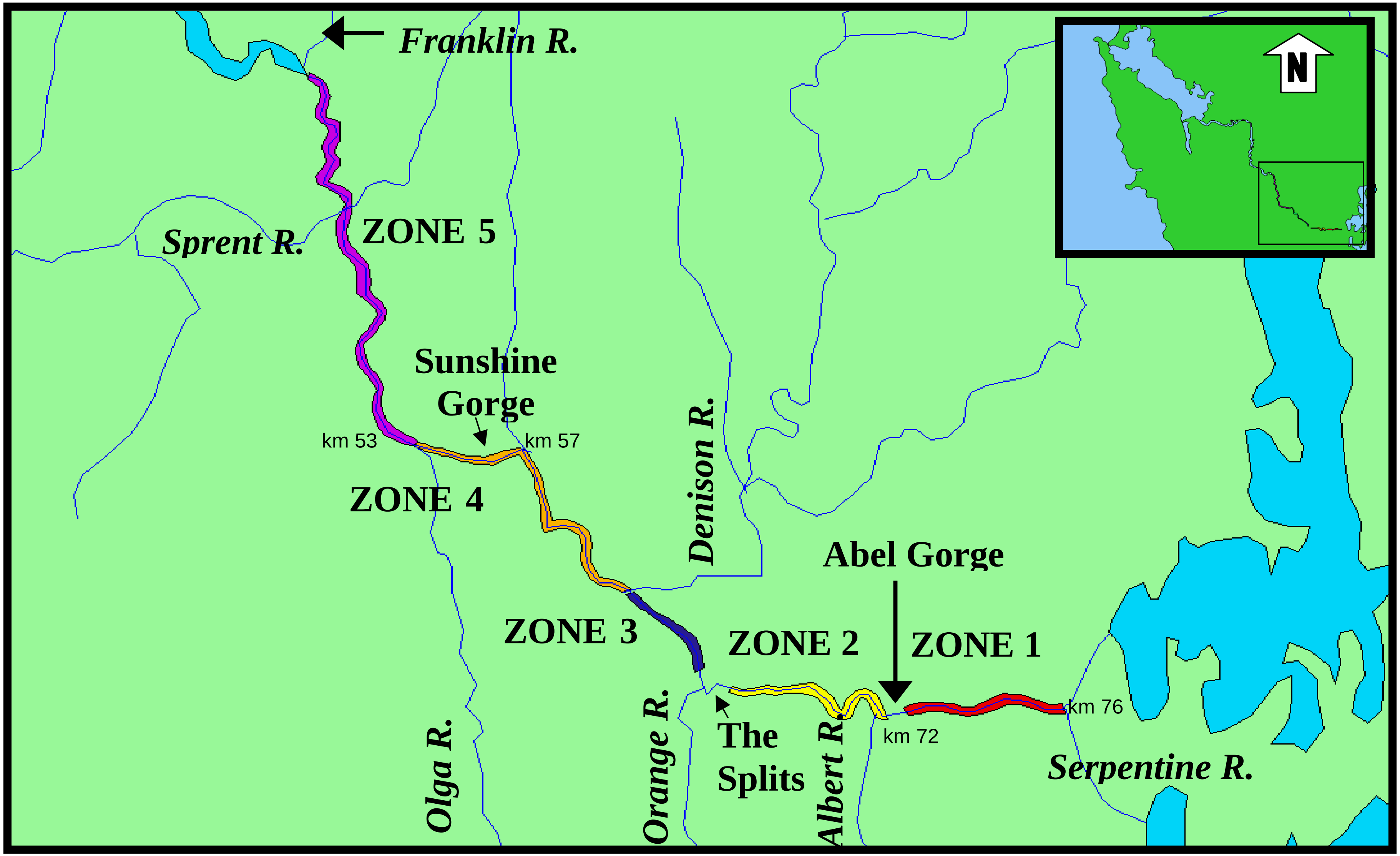
2.5 Hydrology

2.5.1 Introduction

The existing condition of the Middle Gordon River is the manifestation of the 'natural' Gordon River responding to an altered flow regime associated with impoundment in the 1970s. These hydrologic changes are important to understand, as they are a major control on the channel morphology of the system. Hydro-Tasmania's Resource Analysis group has completed an extensive comparative analysis of the natural hydrology of the Middle Gordon River compared to present flows in the Middle Gordon, with the information presented in Appendix 2 of this report series – Gordon River Hydrology Assessment (Palmer *et al*, 2001). Here a summary of that information is presented and discussed in a geomorphological context.

This section begins with a description of the development of the Gordon Power scheme and a discussion of how the present hydrology of the Gordon River differs from the pre-dam condition at the dam site. This is followed by a discussion of how these changes are propagated downstream through the study area, and a description of the hydrology during the study period. Throughout the section, river 'Zones' established for the geomorphic investigations are referred to. These Zones are shown in Figure 3 and discussed more fully in Section 4, Investigative Methods.

Figure 3. Map of Middle Gordon River indicating Geomorphic Zones established for investigation. Zones discussed more fully in Section 4.



2.5.2 Development of the Gordon Power Scheme

The Tasmanian State Parliament approved the development of the Gordon River for power generation in 1967, with dam construction taking place between 1971 and 1974. During this construction phase, a considerable but unquantified amount of sediment was deposited on the river banks between the dam site and the Albert River (Coleman, 1978; photos in Jarman and Crowden., 1978).

The filling of Lake Gordon occurred between 1974 and 1977, with no flow released from the lake during this time. The concurrent damming of the Serpentine River, as part of the development of Lake Pedder, reduced flow in the Gordon between the power station site and the Albert River to pickup derived from the catchment below the power station.

Power generation was initiated in November 1977, with the commissioning of one 144 MW turbine in the power station, with a maximum discharge capacity of approximately 70 m^3/s. Coleman (1978) observed the flushing of fine sediment from areas in Zone 1 of the present study in 1978 associated with the initiation of power station operation. The loss of moss and algal communities on the riverbed and in the riparian zone was also noted by Coleman (1978).

A second similar turbine was brought on line in 1979. The Gordon Power scheme operated with two turbines for a decade, during which time the maximum discharge from the power station ranged from about 150 to 180 m^3/s depending on Lake Gordon levels. The operating range of the power station resulted in fluctuations of river level of about 2.5 m to 3 m in the river upstream of the Splits (Zone 2), and approximately 1.5 m downstream of the Denison River where the Gordon is wider (Zone 4). In 1989 a third 144 MW turbine was installed, which increased the water level fluctuations associated with power station operation to about 4 or 4.5 m upstream of the Splits and 2 to 2.5 m below the Denison.

Based on the present configuration of the power scheme, the total storage capacity of Lake Gordon is approximately 4-times the mean annual discharge of the power station, with the combined storages of Lake Gordon and Lake Pedder providing a storage capacity of approximately 5-times the mean annual discharge.

2.5.3 Hydrologic Changes at the Power Station Site

The tailrace of the power station can effectively be considered to be the start of the middle Gordon River, as there is little catchment area between the Gordon Dam and this point. Figure 4 shows the natural flow in the Gordon River at the power station site prior to flow regulation. The hydrology was characterised by short duration high-flow events occurring year round but with a higher frequency during the winter months. The wet winter periods resulted in increased base flow. Figure 5 (note different scales) shows a comparison at the power station of the modelled natural flow for 1994 and the actual power station controlled flow. The most apparent differences are that the modified flow is now characterised by a change in seasonality, longer duration high flows, consistent high flows and a reduction in flows greater than 200 m^3/s. Less apparent from the plots, but very important, is that total flow in the Gordon as measured at the power station has increased by about 15-20% due to the diversion of water from other catchments into the power scheme. Pre-dam mean flows were 86 m^3/s compared to the present mean flow of 101 m^3/s.

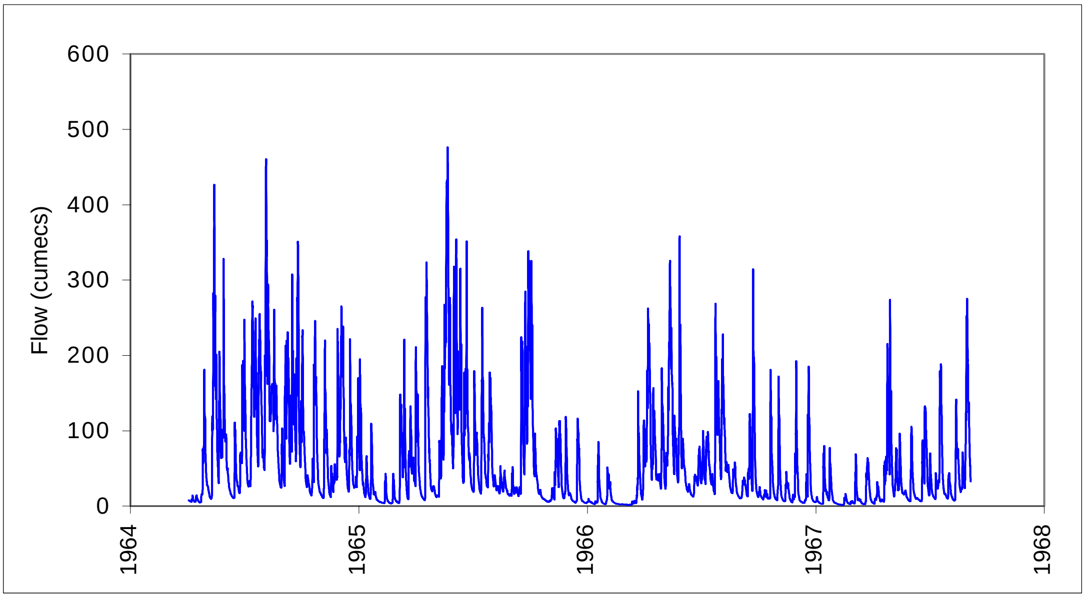


Figure 4. Hydrograph of the Gordon River at the dam site prior to regulation, year marks January 1

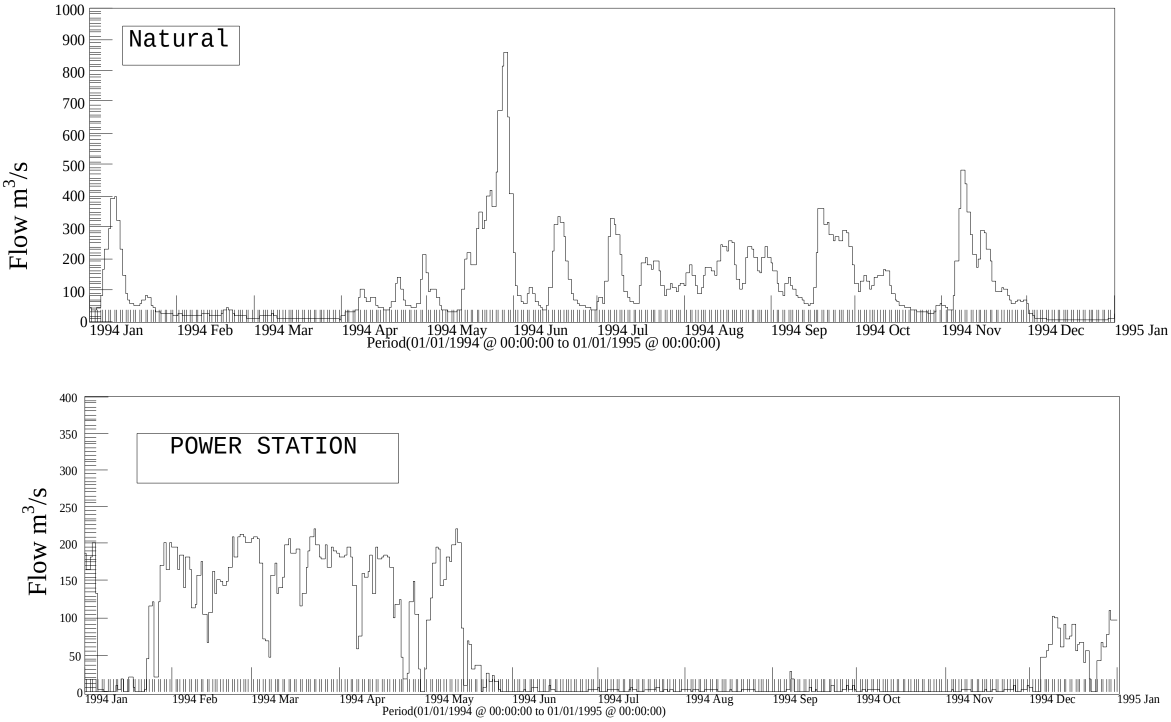


Figure 5. Comparison of modelled natural flows at the Gordon Power Station with present regulated flow (note difference in 'Flow' scale)

A flow duration plot for the pre- and post-dam scenarios at the power station site is shown in Figure 6. The plot illustrates the greater occurrence of flows between 20 and 200 m^3/s as compared to natural flow, with less frequent flow outside of this range. The median (50% duration) flow at this site has more than doubled due to power station operation, from 50 m^3/s to 120 m^3/s.

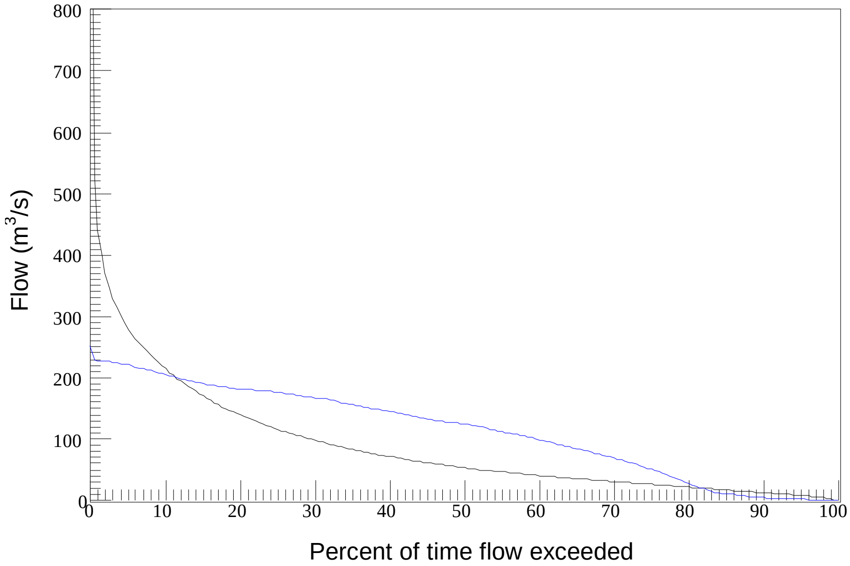


Figure 6. Flow duration in Zone 1 based on hourly flow data at River km 75 (Geo 1). Black line indicates natural (pre-dam) conditions, blue line shows present (regulated flow) conditions

The seasonal shift in flow at the power station, with reduced winter flows and increased summer flows, is shown in Figure 7 (and Figure 5). Summertime (October to March) flow under pre-dam conditions contributed approximately 36% of the total flow, with the majority (64%) occurring during the winter months (April - September). The regulation of the river has reversed these proportions, with 58% of the total flow occurring during the summer months, and the remainder (42%) being winter flow. Mean monthly flows for April through June are similar for the two scenarios.

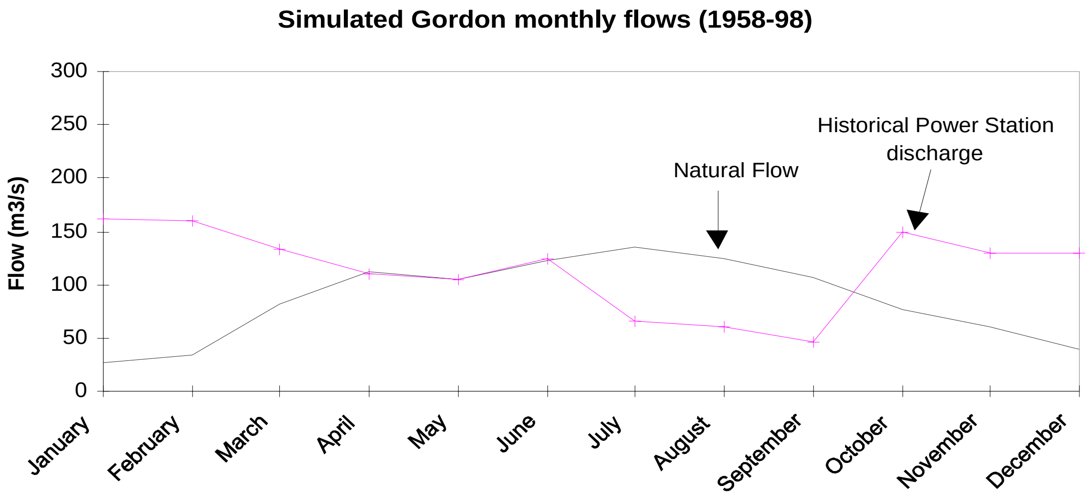


Figure 7. Monthly flows in Gordon River at power station for simulated natural flows and present power station operation

River regulation has also altered the rate of water level change within the Gordon River, with rates increasing by an order of magnitude or more as shown in Table 1.

Table 1. Maximum rates of river level rise and fall (m/hr) in the Middle Gordon River compared with maximum rates for natural floods at the Gordon above Olga in 1968 – 1971 (Palmer *et al.*, 2001)

		Maximum Rate (m/hr)				
		Zone 1	**Zone 2**	**Zone 3**	**Zone 4**	**Zone 5**
Drawdown (from efficient load)	Current	2.64	1.44	0.80	0.80	0.40
	Natural				0.013	
Flow rise to efficient load	Current	4.56	5.48	5.48	3.12	2.88
	Natural				0.150	

Table 2 shows the proportion of time that flow rates change less than 5 m^3/s per hour, and greater than 20 m^3/s per hour under Natural and Present conditions. This table indicates that under natural conditions, flow changed less than 5 m^3 /s per hour 94% of the time, with changes of greater than 20 m^3/s per hour limited to less than 0.5% of the time. Changes of greater than 20 m^3/s per hour now occur almost 15% of the time. These rapid changes in water level and flow rates are discussed more fully in Section 2.5.4.3, *Rates of flow change and river level fluctuations.*

Table 2. Proportion of time flow rate changes less than 5 m^3/s per hour, and greater than 20 m^3/s per hour at the power station under Natural and Present conditions. Present values derived from actual flow data; Natural values derived from flow data (pre-dam) and a flow routing model (post-dam).

	Flow change <5m^3/s per hour	**Flow change >20 m^3/s per hour**
Natural	93.8%	0.2%
Present (97 -98)	58.4 %	14.3%

2.5.4 Propagation of Flows Downstream

2.5.4.1 Natural Flows

The flow regime of the middle Gordon River is controlled by the amount of flow derived from the power station combined with the natural inflows in the catchment and the influence of hydrologic constrictions in the river. Figure 8 shows the modelled average natural daily flow at three points in the study area, the power station (top of Zone 1), above the Olga (bottom of Zone 4), and above the Franklin (bottom of Zone 5), for 1994. The hydrographs are characterised by large fluctuations in discharge, and an increase in the winter base flow. There is a large increase in flow between the power station and above Olga site, with typical high flows increasing from 400 to 600 m^3/s and peak flows increasing from about 800 m^3/s to over 1000 m^3/s. The inflow from the Denison Rivers in this stretch of the study area is largely responsible for these increases. Between the above Olga site and the above Franklin site, natural peak flows increase by about another 100 m^3/s.

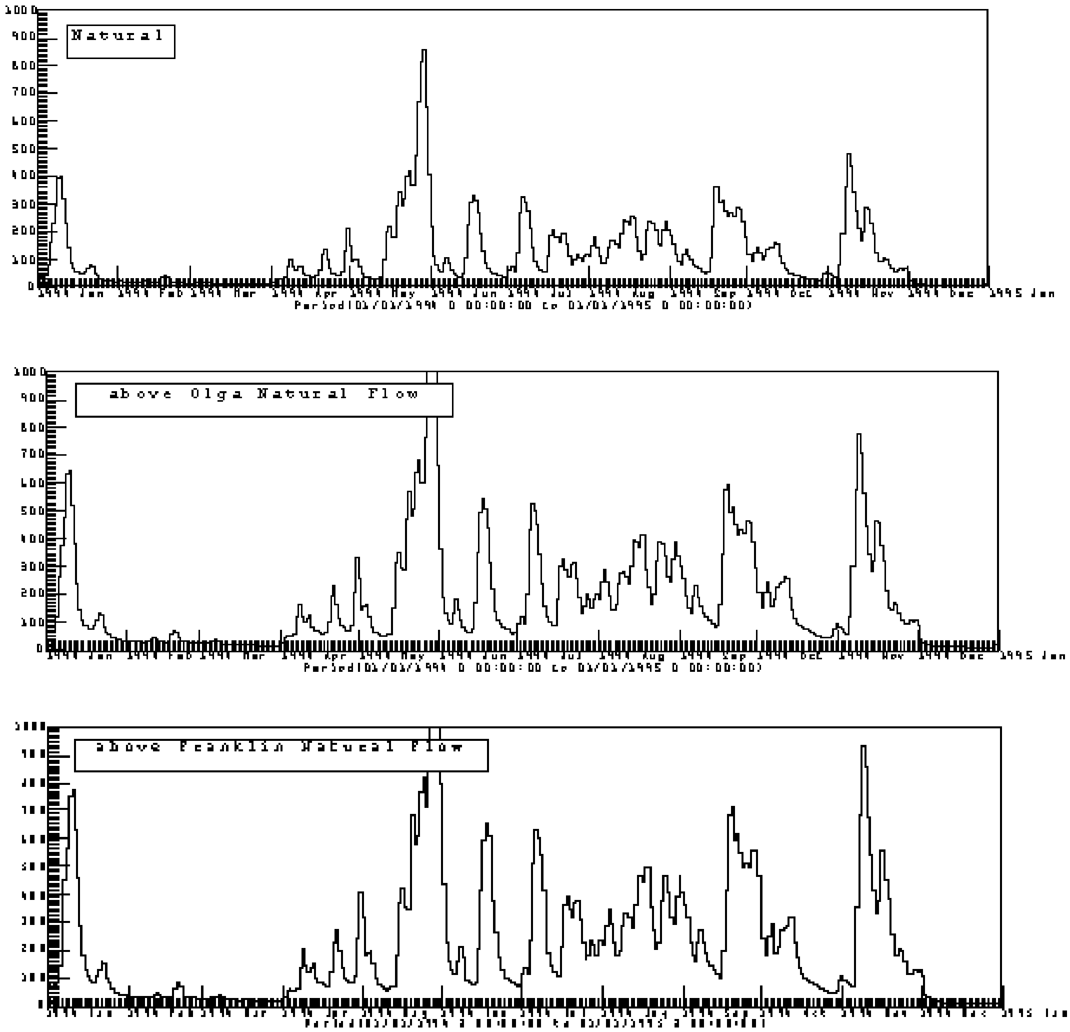


Figure 8. Modelled average natural daily flow at 3 points in the study area: at the Power Station (top); above the Olga River (middle), and above the Franklin River (bottom)

Figure 9 shows the percentage of total flow derived from below the dam site under pre-dam conditions for each of the geomorphic zones. The figure demonstrates that prior to regulation, Zones 1 – 3 derived a very uniform percentage of flow year round from the catchment below the dam. Zones 4 and 5, below the confluence of the Denison and other major tributaries, also received uniform inputs (as a percentage of total flow) from the catchment for most of the year. The lower summer percentages indicate that tributary inputs are proportionately and (in general) absolutely reduced during the summer months, increasing the percentage of flow derived from above the present dam site in these downstream zones. For the majority of the year, the flow input is roughly proportional with catchment areas, with the Denison accounting for about 35% of the total catchment at its confluence with the Gordon.

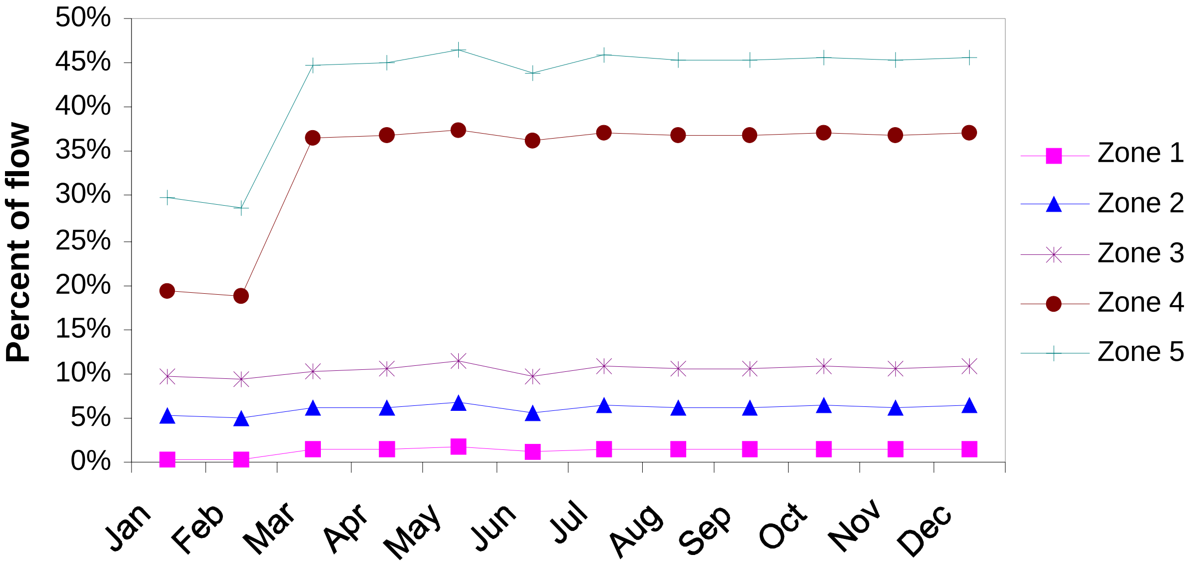
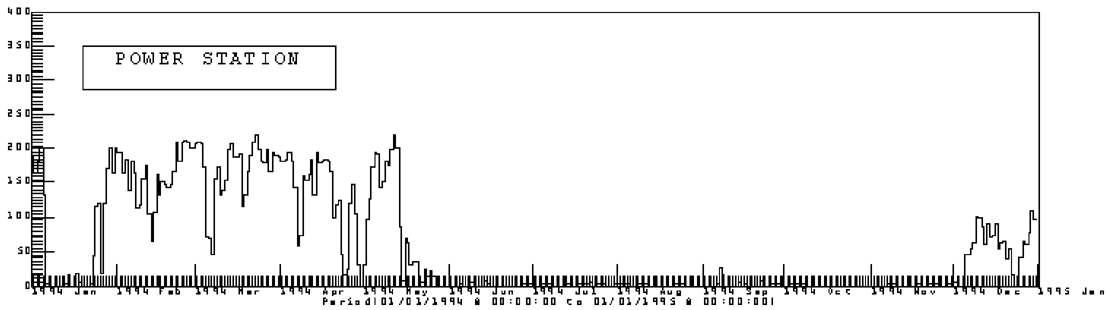


Figure 9. Percentage of natural flow pickup from the station to the Zones to total natural flow at the site for 1981 (an average flow year). Natural flows based on model results

2.5.4.2 Present Flows

Figure 10 contains hydrographs for two of the same sites (at the Power Station and above the Franklin R.) as shown in Figure 8 for present power station operation. The hydrographs show a reduction in annual peak discharge, an increase in the duration of moderate high flow events, a constant discharge during power station operation, more rapid fluctuations in river flow associated with turning the power station on or off and a change in seasonality of discharge. The uniformity of discharge decreases with increasing distance from the power station due to the influx of other water sources.



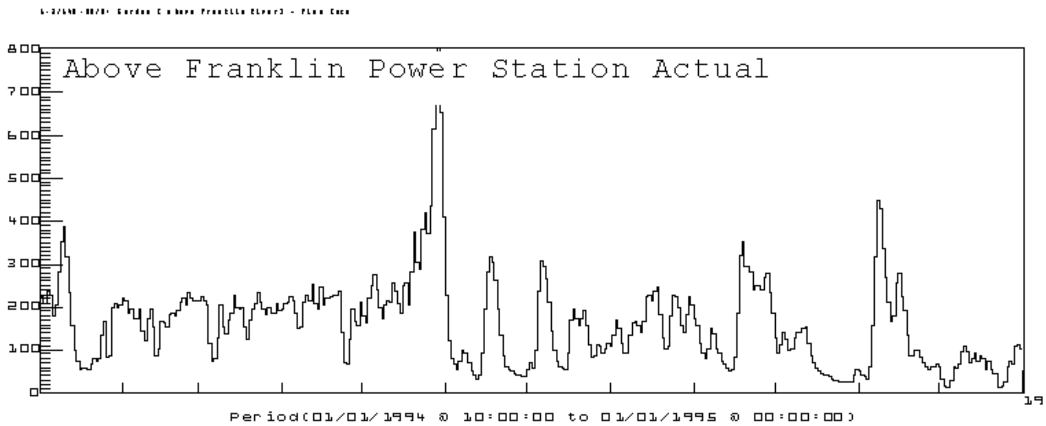


Figure 10. Hydrographs for present flow regime at the Power Station (top) and above the Franklin River (bottom)

Figure 11 shows the percentage of natural flow pickup from below the power station compared to total flow under the present flow regime of the power station for 1981. The graph shows that the relative flow input of the catchment varies greatly through the year, with a relative decrease in contribution during the summer months and associated increase in proportion during the winter months. This is the result of consistent discharge from the power station year round and seasonally fluctuating natural inputs. The large jump in catchment contribution below the confluence of the Denison River (Zones 4 and 5) is still apparent. Contrary to pre-dam conditions, the catchment contribution from Zones 4 and 5 exceed the flow derived from the upper catchment (power station) for several months of the year.

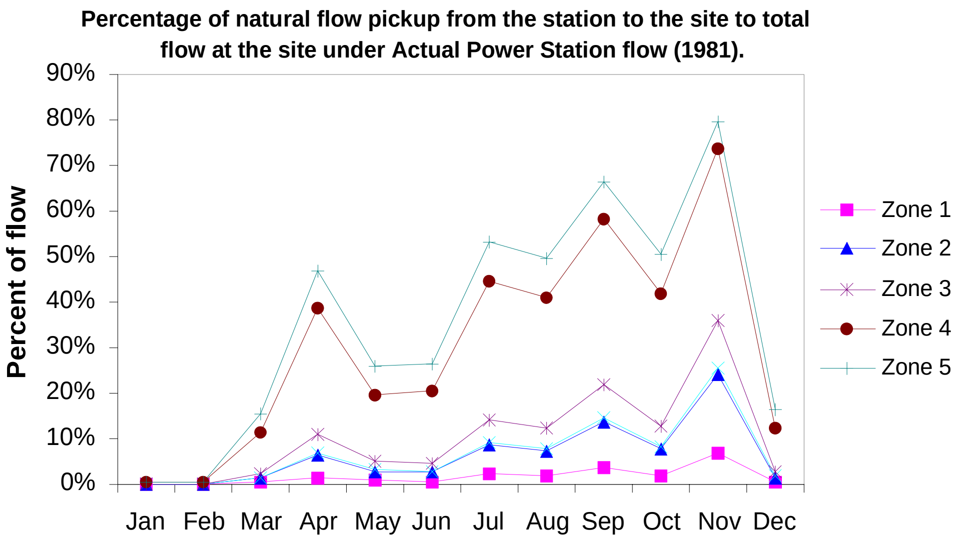


Figure 11 Percentage of natural flow pickup below the power station to each Zone under present power station flow, for 1981, an average flow year.

This greater influence of catchment-derived flows is reflected in flow duration curves for the downstream sites (Figure 12), as compared to immediately below the Power Station (Figure 6) although the reduction in very high flow, and increase in medium and low flows is consistent throughout the catchment.

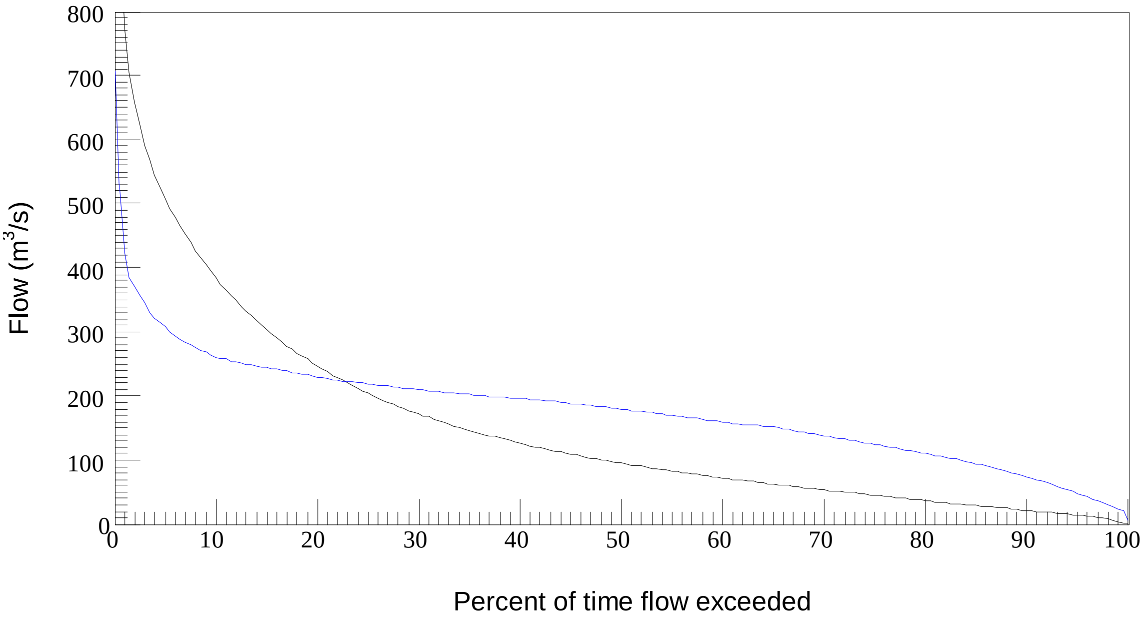


Figure 12. Flow duration curves for the Gordon River above the Franklin River (Zone 5) based on hourly flow data. Black = Natural; Blue = Present

2.5.4.3 Rates of Flow Change and River Level Fluctuations

Table 3 shows the rate of flow change per hour at the Power Station and above the Franklin River pre and post damming. Flow changes <5 m^3/s per hour naturally occurred less frequently above the Franklin as compared to the Power Station site, however, the implementation of the power scheme has reduced the frequency of change to approximately the same percentage. Flow changes in excess of 20 m^3/s per hour have increased from 2% to 5% in the Gordon River above the Franklin, which is comparatively less than the increase at the Power Station site. These changes are associated with turning on and off the power station as demonstrated in Figure 13, which shows power station discharge and the river level response in Zones 2, 4 and 5 during 3 weeks in March 2000.

Table 3. Percent of time flow change conditions are exceeded under natural and present conditions. Values derived from flow data for the 'Present at Gordon Power Station', a combination of flow data and flow-routing model results for 'Natural at Gordon Power station' case and from a flow-routing model for all other scenarios

	Flow change< 5m³/s per hour		Flow change >20 m³/s per hour	
	Gordon at Power Station	Gordon above Franklin	Gordon at Power Station	Gordon above Franklin
Natural	93.8%	85%	0.2%	2.0%
Present (97–98)	58.4*%	57%	14.3%	4.8%

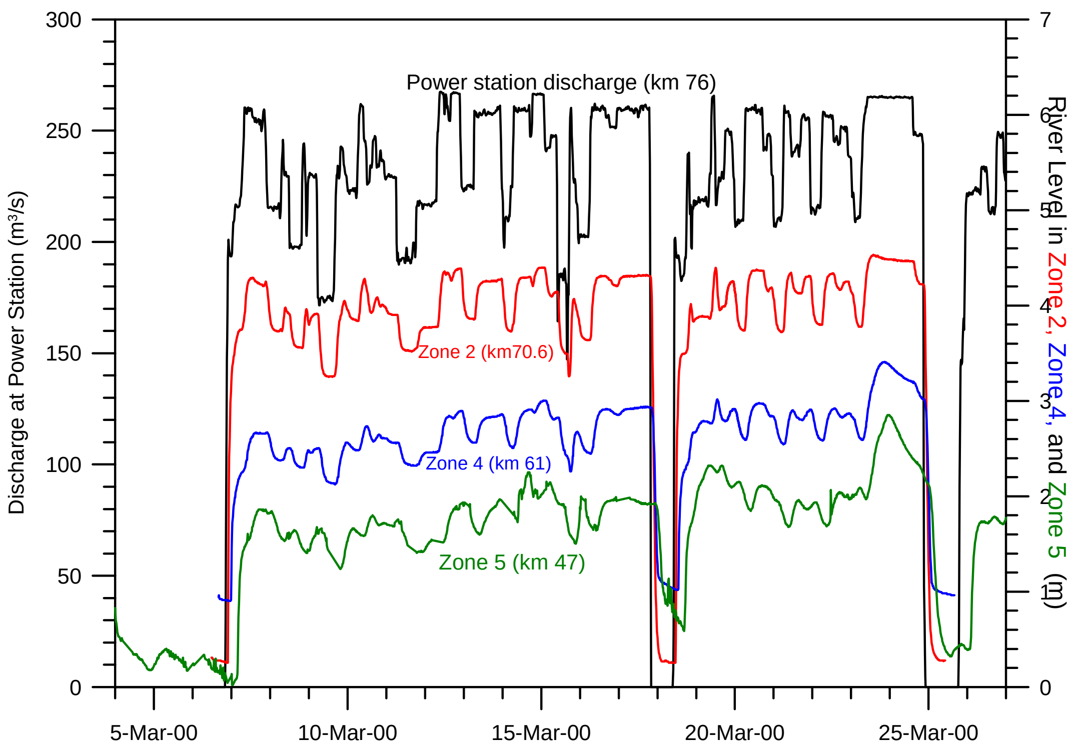


Figure 13. River level change compared to power station operation. Power station discharge is on the left axis, with level shown on the right. Note: river level scales are not relative to uniform datum.

Figure 13 demonstrates that the river level responds rapidly to changes in power station discharge, but generally reduces in magnitude and is smoothed with distance from the power station. In response to maximum discharge from the power station operation, river level in Zone 2 fluctuates by 4 m, whereas in Zones 4 and 5, level changes by about 2 to 2.5 m. The 'lag' time between power station operation and the water level response in each zone also increases downstream (see Palmer *et al*, (2001) for discussion). Increased flow due to rainfall is evident on March 24 and 25, especially in the downstream Zones 4 and 5.

The rate of change of river level also decreases downstream. During the power station 'off' event beginning on March 17th, a 4 m decrease in river level in Zone 2 occurred over 12 hrs (0.56 cm/min; calculated from initiation of water level response, not power station shut-down), whereas a 2 m decrease in Zone 4 and a 2.5 m decrease in Zone 5 required 16.25 hrs (0.19 cm/min) and 14.5 hrs (0.29 cm/hr) respectively. Some of the variation between the levels and rates is attributable to the placement of the river level recorders within the river channel. The data for Zones 2 and 4 were obtained from river level recorders situated in locally broad alluvial sections of the river. The recorder in Zone 5 is situated within a relatively narrow bedrock section of the river. These variations aside, there is a downriver trend of lower and slower river response to power station operation.

2.5.5 Power Station Variability

The operation of the Gordon Power station is highly variable, and controlled largely by rainfall trends in Tasmania. During wet periods, when there is abundant water available in the smaller 'run of river' Hydro-Tasmania schemes, the Gordon is typically used for short durations, at less than maximum capacity. Conversely, because the Gordon is one of the two large water storages in the State, when 'run of river' water storages are low the Gordon is run for long periods.

These variable power station operations result in variable flows in the Middle Gordon River, with flows and river levels controlled by the number of turbines (0 to 3) operating at any one time. Examples of power station discharge during 'wet', 'dry' and 'average' years are contained in Appendix 2 of this report series (Palmer *et al*, 2001).

2.5.6 Summary of Hydrologic Changes Relating to Present Power Station Operation

The following dot points summarise the important aspects of the present flow-regime for this geomorphological assessment:

- An increase in average flow at the Power Station of approximately 17% due to the diversion of the upper Huon River and Lake Pedder catchments (86 m^3/s pre-dam; 101 m^3/s post-dam).
- A reduction in annual peak discharge. Previously annual peak discharge ranged from approximately 280 m^3/s to 1500 m^3/s in the Gordon at the power station, whereas at present, power station operation limits peak flows to 260 m^3/s.
- An increase in the duration of flows greater than 170 m^3/s from about 15% of the time pre-dam, to now almost 30% of the time, resulting in higher river levels.
- Constant discharge during power station operation leads to constant river levels downstream. The difference in stage height between power station off and power station on is about 4 m in the middle of Zone 2 (km 72); 4.5 - 5 m above the Splits, and approximately 2.5 m below the Denison River.
- More rapid fluctuations in river level height associated with turning the power station on or off than under pre-dam conditions. Under pre-dam conditions, flow changes of greater than 20 m^3/s per hour occurred <0.5 % of the time at the dam site. Under present conditions, this rate of change is exceeded 14% of the time immediately below the power station. The fluctuations decrease downstream with the same flow rate exceeded almost 5% of the time at the Gordon above the Franklin as compared to 2% of the time under natural conditions.
- A change in seasonality of discharge. Under natural conditions, on average 65% of the flow occurred during the winter months (April – Sept) with the summer flows contributing 35%.

Present operation of the power station results in a reduction of winter flows to 44% of total flow, with the majority of the discharge (56%) occurring during the summer period.

From this summary, it is evident that the damming of the Gordon River has altered all critical components of the flow regime (magnitude, duration, frequency, timing and rate of change) in the river which would be expected to significantly alter fluvial geomorphic processes operating in the river.

2.5.7 Comparison of regulation by the Gordon Dam with other Australian dam

It is useful to have some comparison of the relative magnitude of the hydrological impact of the Gordon Dam, as compared with other dams in Australia. This is not to suggest that the geomorphic response of the Gordon River will be the same as the other rivers listed, but it merely puts the damming of the Gordon in context of other regulated systems. The Gordon Reservoir is the largest in Australia (Table 4), being nearly three times the size of the largest dam in Victoria (Dartmouth). It also has a relatively high mean annual runoff, and a low coefficient of annual flow variation (Cv). In short, it is a much more reliable source of water than the other dams described in Table 4.

Table 4. Selected characteristics of hydrological regimes and dam capacity for a sample of SE Australian rivers (source: from Table 7.1 in Gippel *et al.*, 1992).

RIVER	Gauge	Basin Area (km^2)	MEAN ANNUAL RUNOFF (MM)	COEFF. OF VARIATION CV	DAM	STORAGE CAPACITY (ML)
Gordon	Knob damsite	1,280	1,409	0.24	Gordon	11,316,000
Mitta Mitta	Hinnomunjie	1,460	330	0.37	Dartmouth	4,000,000
Tanjil	Blue Rock	363	348	0.42	Blue Rock	200,000
Yarra	Doctors Ck	334	537	0.4	Upper Yarra	206,000
Snowy	Jarrahmond	13,400	154	0.39	Jindabyne	690,000
Shoalhaven	Welcome Reef	2,770	149	0.88	Tallowa	110,000
La Trobe	Willowgrove	580	436	0.32	Narracan	8,400
Thomson	Narrows	518	523	0.45	Thomson	1,130,000

The relative hydrological impact of dams can be compared using several indices. An index that is now widely used is the amended Annual proportional flow deviation (amAPFD) which has been modified by Gehrke from an earlier index (Gehrke, 1995).

$$R_a = \sum_{j=1}^{p} \frac{\left(\sum_{i=1}^{12} \left(\frac{(c_i - n_i)}{\bar{n}} \right)^2 \right)^{\frac{1}{2}}}{p} \qquad \text{(Eq. 1)}$$

Where:
R = Amended annual proportional flow deviation (APFD) for p years of record
c_i = the actual flow for month i, in year j
n_i = the natural flow for the month i in year j
$\bar{n}$ =mean of all the monthly flows on record.

Table 5. Amended annual proportional flow deviation (amAPFD) for the Gordon River compared with 11 Victorian streams, based on monthly data (Source: Dr Tony Ladson, University of Melbourne, *pers. comm*.).

River	(downstream of) Dam	Post regulation period	AmAPFD
GORDON	**GORDON**	**20 years**	**2.67**
Buffalo	Lake Buffalo	1968 to 1993	0.30
Loddon	Laanecoorie	1943 to 1993	1.33
Loddon	Cairn Curran	1965 to 1993	3.18
Macalister	Lake Glenmaggie	1975 to 1993	1.40
Moorabool	Bungal	1973 to 1993	1.57
Jackson	Rosslynne	1975 to 1993	2.10
Tarago	Tarago Res	1970 to 1993	2.30
Mitta Mitta	Dartmouth	1980 to 1986	3.44
Goulburn	Eildon	1970 to 1990	4.04
Campaspe	Lake Eppalock	1981 to 1993	5.01

The Gordon is a heavily regulated stream. The effects of regulation can affect flows at an annual, monthly, daily or instantaneous time step. The amAPFD provides a measure of the effect of the dam on the monthly average flows. When compared with other Australian large dams it is clear the Gordon Dam has a major impact on monthly average flows - shifting them from the winter to the summer. The river is not quite as highly impacted as the big irrigation dams in the Murray Darling system (eg. Eildon). These dams have a similar reversed seasonality storing in winter and releasing in summer. The lower value amAPFD for the Gordon is probably because its annual variability is lower. Also, the hydrological impact of the Gordon probably extends a relatively shorter distance downstream than in the other streams shown in Table 5. This is because relatively large tributaries enter the river downstream of the dam.

2.5.8 Hydrology of the Study Period

Rainfall during the study year (October 1999 to October 2000) was characterised by a dry summer followed by a wet autumn (Figure 14), with rainfall for the study period totalling 2,106 mm at Strathgordon, compared to a long-term average of 1,835 mm.. The statewide summer drought resulted in the Gordon Power Station being operated at maximum discharge (3-turbines) for several months. Figure 15 contains the hydrograph of the Gordon River below the Power Station for the study period, and also indicates when fieldwork was under taken. During the 5 month period between mid-December 1999 and mid-May 2000, the Gordon Power station was only shut down to allow riverine access for the Basslink Environmental Investigations. These shut downs were 1 to 3 days long and corresponded to weekend periods.

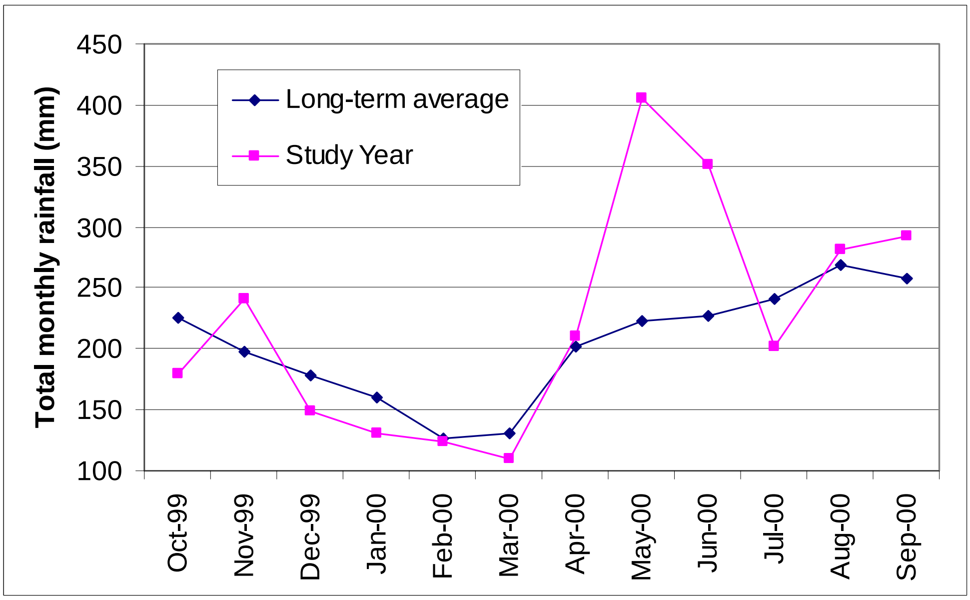


Figure 14. Monthly rainfall during study period and long-term average monthly rainfall, both at Strathgordon

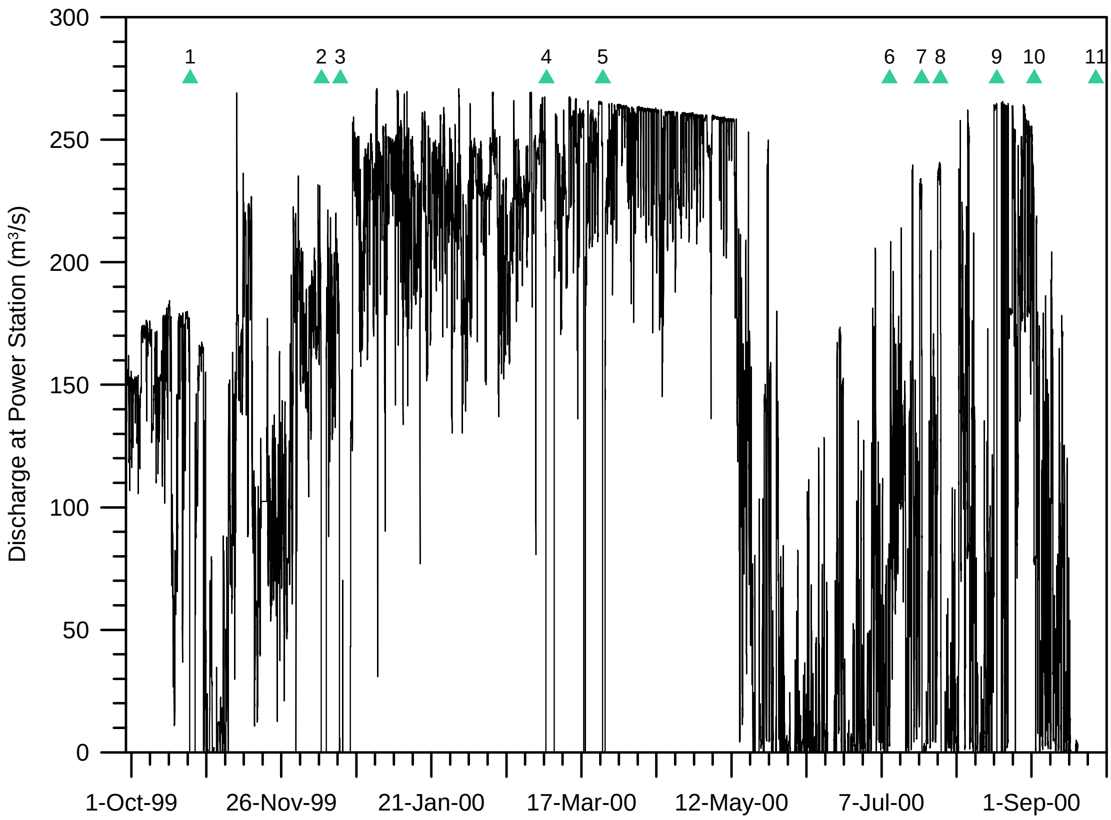


Figure 15. Discharge from the Gordon Power station between 1 Oct 99, and 1 Oct 00. The numbered arrows indicate geomorphic field visits by the authors.

The pattern of power station operation in the summer of 2000 was unique in the history of the Gordon Power scheme, as demonstrated by Figure 16, which shows the average monthly discharge at the station since 3-turbines have been operating (1989 – 2000) compared to the study year. Flow exceedence percentages are also shown, and indicate that the January, February and April discharges from the station were the highest on record. The March 2000 discharge is also very close to an historic maximum. This operation created a unique long-duration, 3-turbine flow event in the river. The flow duration curve in Figure 6 shows that on average, using daily data (1958-1999), a flow of 200 m^3/s is only exceeded in Zone 1 about 10% of the time. The average monthly flows for the study year (Figure 16) show that this flow value was exceeded for at least 4 months of the year, or 30% of the time.

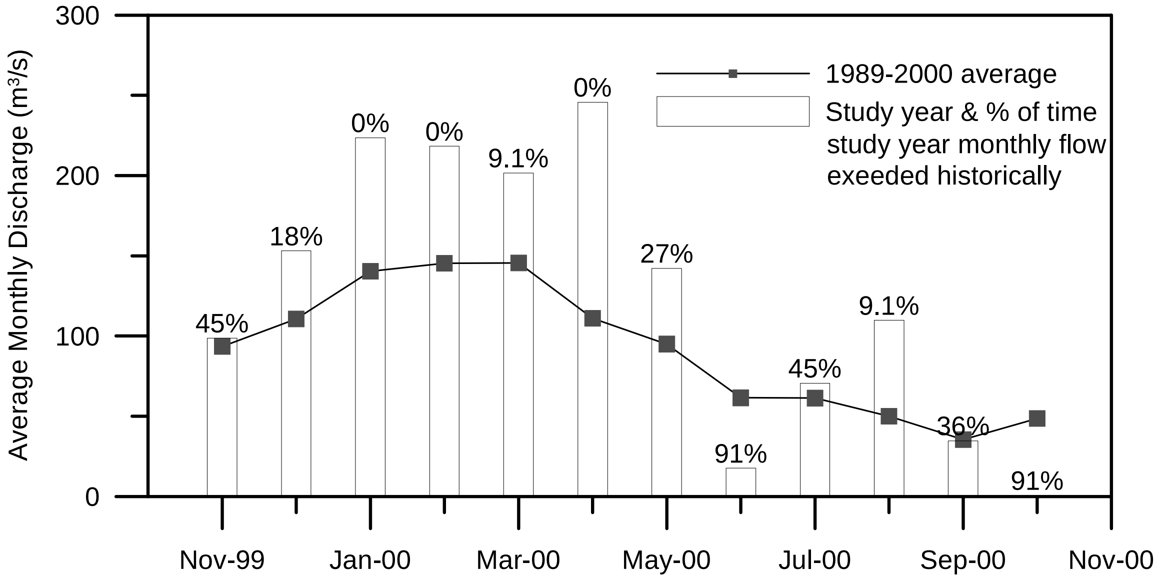


Figure 16. Long-term average monthly discharge from Gordon Power Station (line) compared to average monthly discharge during study year (bars). The percentage on each bar shows the percentage of time that the monthly average has exceeded the study-year average since the power station initiated operations.

The summer drought was followed by high autumn rainfall (Figure 14), which translated into reduced usage of the Gordon Power Station, due to the availability of the 'run of river' schemes. The close to zero power station discharge in October 2000 was caused by a power station shutdown for maintenance purposes.

The effect of the unusual hydrologic study year on the investigations is discussed in Section 4.7 *Limitations of Study.*

3 LITERATURE REVIEW AND THEORETICAL FRAMEWORK

3.1 Introduction

The purpose of this section is to review the geomorphic literature on river adjustments to help provide a theoretical framework for this research. This is an important component of geomorphic investigations as the time spans for geomorphic change, and the occurrence of threshold changes, means that short-term research studies alone cannot provide all the information required to make predictions. The research data provide a basis for comparison between the river under investigation and other rivers which have had the benefit of longer-term studies as summarised in the literature.

Sections 3.2 – 3.4 focus on the broad areas of predicting river response, timescales of river response and channel changes below dams. A more detailed discussion of bank stability and issues affecting bank stability under regulated flow regimes is contained in Sections 3.5 and 3.6. The discussion is concluded by making broad theoretical predictions of the response of the Gordon River to flow regulation (Section 3.7), and by identifying the aspects of the middle Gordon River that are necessary to investigate in order to describe the present response of the river to regulated flow and make predictions about the future response under Basslink.

3.2 Prediction of River Response

The overall geometry and morphological configuration of a river is determined most directly from the independent variables of discharge and sediment load (Leopold & Maddock 1953). The morphology within a reach is a result of the complex interaction of many variables including hydraulics of the flow, load entering the reach from upstream, and bed and bank materials (Morisawa 1985). Langbein (1964) defined five degrees of freedom with which rivers are able to adjust, being slope, roughness, width, depth and planform. The challenge is to predict the degrees of freedom that will adjust, and the direction and magnitude of the changes.

Large dams represent a major change in both the flow and sediment regime of streams and often produce changes in channel form and process (Petts 1979). The guiding questions for this study are how has the Gordon River responded to damming and flow regulation, and how will it further respond with the variation in the historical regulated flow regime caused by Basslink operation of the power station.

Many approaches have been taken to prediction of river behaviour and response. The earliest approaches utilised regime methods (e.g. Leopold & Maddock 1953, Smith 1974, Lane 1955 and Schumm 1969), based around development of empirical relationships between channel characteristics, water discharge and sediment load. For example, Schumm (1969) found that the width-depth ratio and sinuosity of a river are significantly related to the type of sediment load, and a functional relationship could be developed to express this relationship.

Alternative approaches have involved analytical methods, involving solving of equations describing the dominant fluvial processes. These analytical methods have been supplemented by ‘extremal hypotheses’ which argue that a channel develops towards some state which maximises or minimises an aspect of river behaviour (Phillips, 1991), e.g. minimum stream power (Chang 1988) or maximum sediment transport rate (White *et al.* 1982). Both regime and analytical methods have numerous critics.

3.3 Timescales for River Response

The timescales over which river channel changes occur have also received considerable attention in the literature. The theory of dominant discharge in shaping a river channel is a long-standing theory which fits in with (also long-standing) models of geomorphic systems slowly and incrementally changing towards some balanced equilibrium condition. This theory states that, for alluvial rivers in humid regions, the channel forming discharge is generally at or near bankfull stage, created by a flood of moderate magnitude with a recurrence interval of between one and two years on the annual series (Wolman & Miller 1960). Low flows are not considered to have the competence to alter the channel boundary, and high flows do not occur often enough to influence channel parameters.

Schumm (1973) introduced the concept of geomorphic thresholds (Coates & Vitek 1980). In terms of hydrologic systems, large floods can be important in triggering major geomorphic changes such as erosion of a resistant bed layer or destabilisation of a sediment bank, which subsequently allow smaller flows to continue their work in channel shaping. Infrequent events act as catalysts setting up whole series of complex feedback reactions within river systems (Petts 1979). Lag times between external changes and river response may occur until a threshold value is reached (Allen, 1974). Not only increased applied stresses, but decreasing resistance to stress, may influence a seemingly stable system over time until a limiting condition is reached, after which sudden dramatic changes occur (Schumm 1973, 1977). Geomorphic thresholds may be exceeded at different times in different reaches of a river system creating great complexities in river response (Petts 1979).

Adjustment may be episodic and rapid, and then followed by long periods of gradual change. Graf (1979) explored catastrophe theory as a model for adjustments of the fluvial system, a theory which is at odds with the theory of dominant discharge. Graf's (1977) rate law proposes a model of disturbed systems returning to new equilibrium states at a negative exponential rate, ever-decreasing over time.

3.4 Channel Changes Below Dams

The main changes to a river caused by impoundment are changes to the downstream flow regime, and sediment load. These in turn produce changes in channel morphology. Reviews of river response to impoundments are provided by Petts (1979, 1984), and the range of responses are summarised in Table 6.

Petts (1980) describes three orders of downstream impacts following dam closure. First order impacts are the magnitude and frequency of water and sediment flows down the river. The first-order impacts then control the second order changes which are changes in river channel geometry. Hey (1978) identified degrees of freedom by which channels can change their form. Third order effects are then the response of ecology to the change in the flow and stream channel. This report concentrates upon the second-order impacts of the Gordon Dam.

Table 6. Summary of River Response to Impoundment (from Petts, 1979, 1984)

CATEGORY	RESPONSE
FLOW	Reduction in magnitude of mean annual flood Altered flow frequency distribution Flows less variable on longer time-scales Flows potentially more variable on very short time-scales Less frequent bankfull and overbank discharges
SEDIMENT LOAD	Bed load sediments trapped in reservoir Suspended sediments settle out in reservoir Tributary rejuvenation can increase tributary sediment contribution to stream
CHANNEL MORPHOLOGY	Degradation and/or aggradation Channel width may increase or decrease Armouring of channel bed Lateral migration of bends

There are numerous case studies of the geomorphological impacts of large dams, but these are not necessarily useful analogues for the Gordon River. The channel response to regulation depends critically upon the character of the channel, and the form of the regulation. Of most relevance to this investigation are large dams that have not diverted large amounts of water out of the catchment, but that have altered the distribution of the flow in time.

Sediment loads are usually dramatically reduced downstream of a dam, because the impoundment effectively traps any bed load sediment delivered from upstream, and suspended sediments tend to settle out in the reservoir. Based on the findings of Brune (1953) it is suggested that the Gordon Dam will have reduced sediment load (both bedload and suspended load) immediately below the dam to almost zero (Brune, 1953). Leopold *et al.*, (1964) found that up to 95% of the sediment load may be effectively trapped in this manner. Sediment load may still be supplied downstream of the impoundment from tributaries, and this contribution can increase due to impoundment. The increase in bed load from tributaries occurs because the water surface elevation in the river is reduced, causing an increase in the gradient from the adjoining tributaries, thus increasing their bed load transport. This phenomenon, known as "tributary rejuvenation", has been well documented by Germanoski and Ritter (1988) on the Osage River below the Bagnell Dam, Missouri, USA.

Morphological changes below dams are highly variable, and can include degradation, aggradation, complete metamorphosis, width changes, armouring and migration of bends (Sherrard and Erskine, 1991).

Degradation is the most immediate response and has been well documented in the literature (Petts 1977). Erosion immediately below a dam and subsequent to dam closure has been commonly reported where the reservoir outflow has sufficient tractive force to initiate sediment motion in the channel (Gottschalk 1964, Williams & Wolman 1984). Wolman (1967, *in* Petts 1984) observed that maximum erosion occurs between the dam tail-water and a distance of 69-channel widths below the dam. The erosional front migrates downstream until either the slope has adjusted or roughness has increased to the stage at which critical shear stresses are below the threshold for sediment transport. Rates of migration vary between less than one kilometre per year in lowland streams to tens of kilometres per year in mountain streams (Petts 1984). Bed degradation and migration rates are greatest the first few years after dam closure, and less important in later years (Williams & Wolman 1984).

Degradation may be inhibited by the formation of an armour layer (Petts 1977, Erskine 1985). Armouring is the phenomenon in which the median grain size of the bed coarsens with time, as the reduced flows winnow out the finer material they are competent to carry (Harrison 1950, *in* Petts

1984). As little as a single grain thickness of sufficiently coarse material is sufficient to form an armour layer which limits degradation under normal flow conditions. Degradation may, however, develop downstream of the armour layer, as far as 150 km below Parker Dam was reported on the Colorado River (Stanley 1951 *in* Petts 1984).

The processes of both degradation and aggradation can occur simultaneously in a river below an impoundment. Aggradation occurs below dams at rates much slower than degradation. Aggradation is a result of either the introduction or redistribution of sediments in the channel below the dam. Redistribution occurs from the erosion processes just described, and the tendency for a narrower channel to form because of the reduction in competence (Richards & Wood 1977). A more common source of sediment aggradation in channels is from tributary rejuvenation as has been discussed.

Studies of channel changes below dams have shown both channel widening (e.g. Tilleard *et al.* 1994) and channel narrowing (e.g. Erskine 1985). Williams and Wolman (1984) found that channel width narrowed, widened or remained constant after dam closure, depending on the site. Studies from the semi-arid southwest USA, where impounded rivers experience prolonged periods of low flow, have shown reductions in channel width tending towards a well-defined channel. Width can also be reduced by redistribution of channel perimeter and floodplain sediments. On the other hand, rivers have experienced channel widening due to bank failure, which can occur after the bed has stabilised due to armouring or exposure of bedrock (Petts 1977). Wave action can erode banks, because relatively high in-channel water levels can be maintained for long time periods in regulated rivers. The sudden reduction in water level when turning off a power station can be particularly destructive, as reported on the Connecticut River where water fluctuations of 1.5m are common (Simons & Li 1982).

Dams that replace peak flood flows with long duration moderate flows appear to reduce meander migration rates. Studies of two dams in the USA indicated migration rates reduced by 75% (Bradley and Smith, 1984; Johnson, 1992). The mean rate of migration of the Missouri River below Fort Peck Dam fell from 6.6 m/yr before regulation to 1.8 m/yr after regulation (Shields and Simon, 1999). As discussed below regulation of this dam was similar to the Gordon. Overall, the absence of large floods (even bankfull floods) in the regulated river means that the bends do not develop the strong secondary circulation that is required to produce bank migration.

There are opposing tendencies at work in impounded rivers; the reduction in sediment load promotes net scour, but the reduction in transport capacity promotes sediment deposition. Whether a channel aggrades or degrades, widens or narrows, is related to the ratio of mean annual discharge pre- and post-dam (Wolman 1967), to the amount of sediment discharged from tributaries (Petts 1977), and to the resistance of the channel boundary sediments (Petts 1984).

Large dams can alter bank erosion processes in streams, leading to altered cross-sectional form and planform.

- Bed degradation following impoundment can lead to bank instability and overall widening. This is because the banks become less stable as they become higher.
- Longer durations of regulated flows can increase bank erosion rates. In effect, the flow energy that was dissipated on the floodplain during floods is concentrated in the stream channel. Interbasin transfers exacerbate this by increasing the size of the average channel discharge, leading to dramatic channel enlargement (Bucinskas, 1996).
- Meander migration rates could decrease as a result of decreased high flows.

A further complication in response to impoundment can be labelled *complex response* (Petts, 1979; Sherrard and Erskine, 1991). In many cases the direction of change of the stream varies with time. An example of this would be where the stream bed initially degrades, but later aggrades as sediment from tributaries reaches the trunk stream.

Thus in conclusion, regulated rivers have unique characteristics, and it is very difficult to draw any broadly applicable conclusions from a particular regulated river with its individual release policy and catchment characteristics (Knighton, 1988). Investigations into the downstream effects of reservoirs have rarely considered channel adjustments that might occur downstream from the confluence of the first major tributary, although there is evidence that the changes are quite significant (Andrews, 1986). In general terms, the greatest changes are often found in the first 5 km below a dam (Williams and Wolman, 1984) with changes complete within a timeframe that may range from 10 to more than 500 years (Petts, 1984).

One generalisation that is possible is that channel changes are much less profound in gravel-bed rivers than in suspended sediment load, predominantly sand bed rivers. Gravel bed rivers require rare high magnitude events to cause channel changes, whereas changes can be immediate in sand-bed rivers. In rivers with naturally low sediment loads, channel changes will be very slow. The final morphological consequences may not be realised for very long time periods, anywhere from ten to one thousand years (Petts 1984; Knighton, 1988).

3.5 Processes of Riverbank Instability Related to Flow Regulation

There are many factors that contribute to the stability (or instability) of riverbanks, and this overview is not intended to summarise all bank failure mechanisms nor all factors contributing to bank stability. In the case of the alluvial banks on the Gordon River, three broad areas have been identified as being important to bank stability, namely, the nature of the materials, the pore water pressure in the banks, and flow regime of the river.

3.5.1 Bank Materials

The predominant method of bank failure depends upon whether the bank contains cohesive or non-cohesive materials, or a combination of both (Thorne 1982, Simons & Li 1982). The classification of materials as either cohesive or non-cohesive is not always straightforward, as it depends on the relative influence of particle weight and surface attraction which can be very complex. Forces of attraction can be between particles themselves, or via water films between particles. These can react to changes in the physical and chemical environment, so the degree of cohesion of the sediments is not always stable (Grissinger 1982).

Detachment of non-cohesive particles, those with high sand or gravel contents, depends on particle and hydraulic characteristics (Simons & Li 1982). The stability of non-cohesive banks depends primarily on the angles of slope and internal friction, and on pore water pressure. Stability of non-cohesive sediment banks is independent of bank height. The mechanism of bank failure is by dislodgement of individual grains, or by shallow slips. Deep-seated slips do not occur in non-cohesive banks because shear stress does not increase with depth as quickly as shear strength. Partially saturated non-cohesive banks can behave like weakly cohesive banks due to capillary effects in the partially filled pore spaces, but this effect is absent when the bank materials are completely dried or completely saturated (Thorne 1982).

Detachment of cohesive particles, those with high clay contents, depends on a wider array of factors, including primary soil properties such as particle size, clay and organic content, and type of clay; composite soil properties such as electrical conductivity, permeability and dispersion; test conditions such as temperature, water content and pore water pressure; and hydraulic properties such as fluid shear force, Reynold's number, lift forces and turbulence, just to list a few (Grissinger 1982). The stability of cohesive bank materials depends upon both the bank height and the bank angle. Cohesive banks tend to erode by mass failure, often a deep-seated rotational slip but also by shallow slips and plane slips. Tension cracks play a major role in weakening of the bank (Thorne 1982).

A combination of cohesive and non-cohesive materials in a bank is common, and such banks are termed composite banks (Simons & Li 1982). In gravel bed rivers, the characteristic bank form is sandy gravel deposits formed from relict channel bars, overlain by sandy silt/clay laid down by overbank flow, with a well-defined interface between the two; the occurrence of several alternating layers is also possible (Thorne 1982). Layers differ in particle size, permeability and cohesion. Non-cohesive layers can be partly protected by the adjacent cohesive layers.

Hagerty and Spoor (1989) called the removal of coarse-grained layers in an alluvial bank by water flowing out of the bank face "piping", and found this was a dominant factor in erosion of composite banks on the Ohio River. Simons and Li (1982) confirmed in a laboratory study that erosion in composite banks is generally by subsurface flow and piping. A non-cohesive layer erodes due to fluvial entrainment of the particles; tension cracks, forward tilt and eventual failure occurs in the overlying cohesive layer; and wave wash causes formation of a berm.

Hooke (1979) examined composite banks on a river in Devon, England. The banks were composed of silty alluvial material overlying coarse gravel deposits. At high flows, the main bank erosion process was direct shearing of bank material by corrasion (vertical erosion by a river leading to downcutting); this was evidenced by smoothed banks remaining after flood passage, with little undercutting or slumped material at the base of the bank. At low flows, collapse or slumping of large blocks was the dominant process, occurring when the soil was thoroughly moistened after passage of the flood hydrograph. The flow and hydrograph characteristics, storm characteristics, time intervals between events, and antecedent soil moisture conditions were all shown to be important influences on bank erosion (Hooke 1979). Although approximately 90% of all channel changes occur due to major floods (Simons & Li 1982), Hooke (1979) showed that this effect was modified depending on soil moisture content. Twidale (1964) found that wet bank slumping was an important process causing banks to retreat, and that the soaking of a bank due to a high flood leaves the banks highly unstable.

Following bank failure, further degradation is often limited because the bank slope angle is decreased and more stable, and failed bank material forms a protective toe at the base of the slope. Failure often takes place on the recession limb of the hydrograph when pore water pressures are greatest in the banks, and the fallen material is then stable until the next flood event (Thorne & Osman 1988). Once the protective toe is removed by the flow, bank failure continues to a point at which the river no longer has the transport capacity to remove the slump deposits (Thorne *et al.* 1988).

Other factors are important influences on bank erosion. Rainsplash is an important erosive agent on bare bank surfaces (Bradbury *et al.* 1995), boat wave wash can have profound erosive effects (Nanson *et al.* 1994, Bradbury *et al.* 1995), and cyclic expansions and contractions such as heating/cooling, wetting/drying and freezing/thawing all play a role in bank instability (Haigh 1977). Vegetation has a large influence on channel patterns, bank stability and fluvial processes in general in a river (Gurnell 1995), and is often used as tool for river bank stabilisation (Gray & Leiser 1982; Thorne 1990; Abernethy and Rutherfurd, 1999; 2000a, 2000b).

3.5.2 Pore-Water Pressures on Bank Stability

This section (section 3.5.2) has been contributed by Dr. Bruce Abernethy who has conducted equivalent geomorphological investigations downstream of the Poatina Power Station (Appendix 17 of this report series – Downstream Poatina Geomorphology Assessment (Abernethy and Bresnehan, 2001)).

The soil water regime of a riverbank is highly variable. It fluctuates with both rain infiltration and recharge from and discharge to the channel as the stage rises and falls in response to passing flood waves. Pore-water pressure plays an important role in determining the strength of the soil. Any increase in pore-water pressure within the voids will reduce the grain to grain contact stresses, and hence the ability of the material to resist deformation. Conversely, negative pore water pressures will increase the contact stresses and hence the shear strength.

Under normal low-flow conditions, the pore-water pressure of bank material above the water table is negative. The presence of negative pore-water pressures, or suction, in unsaturated portions of stream banks contributes to an apparent strength of the material that can be visualised either as a friction angle or as a component of cohesion (Fredlund, 1987). For example, non-cohesive material can behave like a weakly cohesive soil in these circumstances, maintaining a bank angle that exceeds the friction angle. Slope stability analysis that incorporates the effect of soil suction has been the subject of recent detailed research (see Fredlund and Rahardjo, 1993), and is now being applied to riverbank stability problems (Casagli *et al.*, 1997; Simon and Curini, 1998; Casagli *et al.*, 1999).

Banks discharge water back to the channel during drawdown, the lowering of the water level in a river or impoundment. The special conditions of drawdown have been the object of a considerable literature (e.g. Morgenstern, 1963; Burgi and Karaki, 1971; Gill, 1990; Borja and Kishnani, 1992). Bishop (1954) and Skempton (1954) investigated effective stresses in an earth dam during rapid drawdown. However, the stability problems of natural riverbanks differ from embankment dams in that the natural setting is extremely variable with heterogenous sediments and complex geometries (Chugh, 1983). Drawdown related bank failure is discussed further in the next section.

Freeze and Cherry (1979) report that extensive laboratory and field tests indicate a range in the hydraulic conductivity of alluvial material of more than three orders of magnitude. The variations reflect the difference in grain-size distributions in individual strata; the bedded character of fluvial deposits imparts a strong anisotropy to the system (Freeze and Cherry, 1979). Variations in hydraulic conductivity can greatly modify groundwater flow, effective-stress fields, and slope stability (Reid, 1997).

In poorly drained banks, positive pore-water pressure can weaken a bank by reducing its effective strength (Bradford and Piest, 1977; 1980; Simons and Li, 1982). Failure mechanics for undrained banks are similar to those for drained banks with the addition that failure may result from an increase in pore water pressure. Even so, Padfield and Schofield (1983) show that where positive pore pressures do not greatly affect the factor of safety, the uplift pressures may modify the nature of the most critical failure mechanism.

3.5.3 Flow Regime and 'Drawdown' Effects

Rapid drawdown below reservoirs is often described as an important cause of bank instability, but there appears to be little evidence of accelerated erosion from this mechanism. Green (1999) has reviewed the literature on drawdown related bank failure, and the process has been referred to by several authors (Morgenstern, 1963; Twidale, 1964; Green, 1974; Higgins, 1980; Neuman, 1981; Springer, 1981; Thorne and Tovey, 1981; Mayo, 1982; Thorne, 1982; Springer *et al.*, 1985; Dahm *et al.*, 1988; Arnott, 1994; Budhu and Gobin, 1995). Rapid drawdown of river level leads to excessive pore water pressure within the banks, because of the falling watertable, causing them to cave (Higgins, 1980). The saturated bank also lubricates failure plains, and adds water to developing tension cracks (Simons and Li, 1982).

The stability of the bank under drawdown depends on; the height of the bank, the slope of the bank and its lateral extent, the proportion of the bank affected by the drawdown, the saturated and unsaturated strength of the bank materials, the permeability of the material and the degree of saturation which is related to the duration of peak flow (Mayo, 1982).

As described in the literature, drawdown failures are seen to involve slumping. Budhu and Gobin (1995) found that highly permeable sand bars in the Grand Canyon were subject to this type of failure on a regular basis. Springer *et al.* (1985) suggest that *"Drawdown failures can be recognised by* *large, cusp-shaped failure zones; headward scarps clearly defining the failure mass; accumulations of slump debris in the lower portions of the zone of instability*". Again, Hooke (1979) describes drawdown related slumping as involving "large blocks which topple forward but usually remain intact with the grass continuing to grow on the side".

In reality, drawdown is likely to contribute to many failure processes, and there is unlikely to be a single characteristic 'drawdown' failure type. For example, Springer, in his Masters thesis (1981) investigated the rate of river fall on stability of banks of the Ohio River. He considered the stability of a sliding wedge by analysing various factors that were thought to be important in stability. To assess the effect of varying a parameter had in his model of bank stability a parameter sensitivity factor was introduced. This is simply the ratio of the percentage change in the factor of safety to the percentage change in the varied parameter. Drawdown was represented by hydrograph shape, and was found to be of low importance in the failure mechanism (Figure 17).

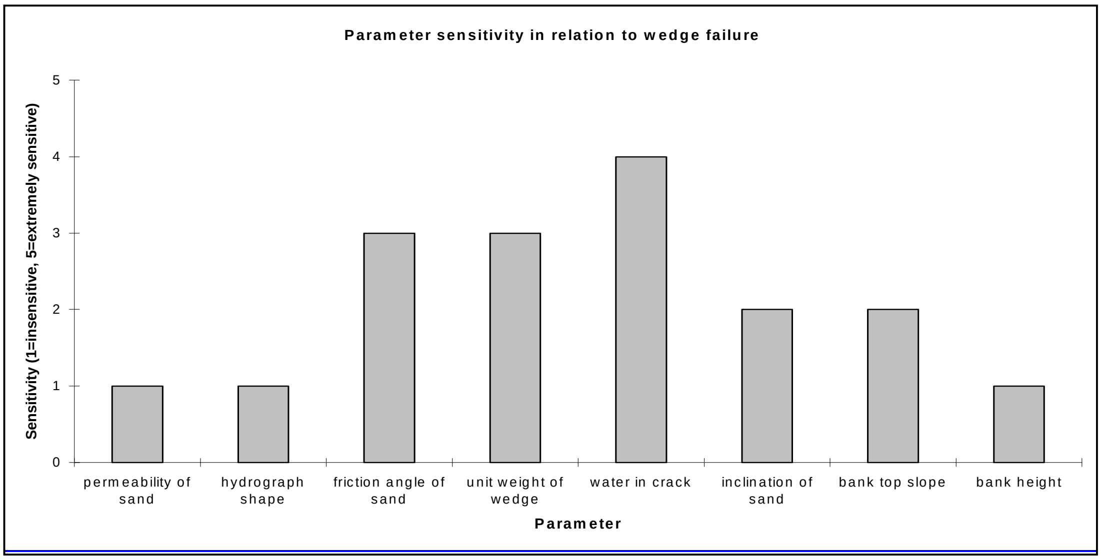


Figure 17. Sensitivity of bank to changes in model parameters, after Springer (1981)

Another effect of drawdown is seepage induced piping. The position of the ground water level within a bank depends on the rate of river rise, the peak discharge holding time and the soil permeability. Under conditions where river stage decreases faster than the rate of drainage of stored ground water, a seepage face develops between the river level and the exit elevation of the groundwater (Budhu and Gobin, 1995). If the exit hydraulic gradient of the soil water is sufficiently large, static liquefaction of the soil can occur (Budhu and Gobin, 1995). When water flows out of the bank face it can remove sediments grain by grain (Hagerty *et al.*, 1981). Piping is most common in coarse sandy sediments where there is a high enough hydraulic gradient out of the bank for particles to be entrained in the flow. Once these layers are washed out the overlying material collapses into the resulting void in either a wedge type or beam type failure. For net erosion to occur the river must be capable of removing any deposited material (Hagerty, 1991).

Rilling processes (rivulets, gullies) occur below the exit point as the bank stored water and its associated sediments flow down slope towards the river (Budhu and Gobin, 1995). Howard and McLane (1988) suggest that seepage contributes directly to slope erosion through the destabilising effects of the seepage forces, and indirectly through overland and channel flow. These same authors maintain that in a headwater channel being eroded by seepage-induced transport three zones occur. The top zone occurs above the water level in the bank and is characterised by dry or damp mass wasting caused by undermining of the bank. Proceeding down slope, a zone of seepage-induced slurry flow occurs, which is responsible for the undercutting of the bank. Down slope of the seepage zone, water flow occurs in surface channels largely unaffected by seepage.

Field observations, flume-based experimental work and modelling suggest that there is a stable geometry for seepage-affected slopes, with the seepage-affected portion of the bank tending to approximately one-half the angle of repose of the dry material in uniform non-cohesive banks (Taylor, 1948; Budhu and Gobin, 1996, Howard and McLane, 1988). For fine to medium sand this slope will be around 15^{o}. Upslope, in the zone of mass-wasting, bank slopes will be close to the angle of repose (Budhu and Gobin, 1996, Howard and McLane, 1988). This zone of mass-wasting has also been observed in a laboratory setting to develop cavernous overhangs due to strong capillary cohesion as the sapping face retreats headward (Howard and McClane, 1988). Experimental work has also shown that erosion rates due to seepage increase with increasing hydraulic head, decrease as the stable seepage slope is approached, and are limited by the rate of removal of sediment delivered to the downstream end of the seepage zone (Howard and McLane, 1998).

Thus, from a brief review of the literature, drawdown can contribute to various forms of bank mass-failure by surcharging and lubricating the banks, and by increasing seepage erosion. Features that we would expect to see as a consequence of more frequent drawdown events are:

- Increased frequency of rotational failures
- Increased incidence of seepage erosion from sandy units, and
- Lower bank slopes.

The magnitude of these effects depends upon the relationship between the filling and draining rates of the bank material. Lower bank slope should also be a limiting variable that will be reached and then stabilise.

3.6 Channel changes from analogous dams

We can focus on some of the possible changes in the Gordon River by considering the literature recording channel changes in similarly regulated streams. Once changes in other rivers have been identified, the unique characteristics of the Gordon can be used to 'filter' the list and arrive at predictions of bank response below the power station.

Many types of regulation are not analogous to the Gordon. For example, channel changes on the Parangana Dam on the Mersey River in Tasmania are of little value in this study as water from this dam is diverted out of the catchment, whilst flood levels have been little affected. Ideally we want to consider streams dams that have:

- augmented flow (about 20% in this case)
- a seasonal flow reversal (from high winter to high summer)
- reduced (or eliminated) peak flows, and
- constant moderate flows.

In regard to the Basslink proposal, we should also consider dams that increase rates of drawdown occurrence.

The first four changes, above, will be found in large irrigation dams. These capture winter flow and release the water in summer as a continuous high discharge. They also often buffer floods. Some of them have augmented flows from inter-basin diversions. Following are some descriptions of channel change from streams that have similar regulation patterns to the Gordon. In all of these examples we can assume that these large dams have reduced sediment supply by more than 95%.

Cudgegong River below Windamere Dam on , NSW (Benn and Erskine, 1994).

This river is a close analog of the Gordon. It is a bedrock confined, gravel channel. Regulation has eliminated floods and moderate flows, and greatly increased the duration of lower flows. Dam releases are incompetent to move the bed material, except where the channel has been constricted by bars or benches. The bed has not formed armour layers, but has instead deposited suspended sediment on the bed, partially in-filling pools.

Bars have formed at tributary junctions. The channel has also narrowed in places where benches have formed and then been colonised by vegetation. These benches are formed from sediment released from tributaries, and released during construction of the dam. Many of these changes occurred at different parts of the stream at the same time. Overall, changes were modest, but complex.

Missouri River downstream of Fort Peck Dam, Montana (Shields and Simon, 1999).

The Missouri is a meandering stream. Regulation by the Fort Peck dam has elevated low flows and depressed high flows. Low flow fluctuations also became greater (by a factor of six). The result of these changes has been a possible slight increase in width, and more than a two-thirds decrease in meander migration rates. Comparison of this decrease with other dams led the authors to conclude that reductions in peak discharges by dams generally produce a decrease in meander migration rates.

Goulburn River below Eildon Dam, Victoria (Erskine, 1996)

Eildon dam is a large carry-over storage providing water for irrigation. As such it reverses the flow seasonality, truncates high flows, reduces flood frequency, reduces the duration of low flows and increases the duration of moderate flows. This pattern of regulation has led to the following channel changes:

- Little bed degradation because of reduced frequency of flows competent to transport armoured gravel bed material
- Modest narrowing by deposition of benches, particularly near to local sediment sources such as tributaries
- Reduced migration rates.

Murray River below Hume Dam (Erskine *et al.*, 1994)

Regulation by the Hume dam is very similar to that described above for the Goulburn River. The resulting channel changes are also similar.

- Slight increase in channel width associated with long duration flows close to bankfull. This erosion developed as parallel retreat of the bank face.
- Effect on migration rates is not known
- Little degradation due to bed armouring, and reduced peak discharges.

Preliminary predictions of the response of the Gordon River to flow regulation are presented in the next section.

3.7 Predicted Channel Response for the Gordon River

The previous discussion has identified and discussed the processes potentially altered through flow regulation. These processes must be considered in the context of the Gordon River, and what is known about characteristics of the Gordon that will affect river response.

An understanding of the processes and especially rates controlling fluvial geomorphology in Southwest Tasmania is greatly lacking, and prevents the present investigations from being quantitatively related to natural rates and processes. There is a recent channel stability investigation (Nanson, *et al.*, 1995) that is relevant to the present work and provides a qualitative context within which the changes relating to flow regulation in the Gordon can be placed.

Nanson *et al.*,(1995) used dating techniques to investigate fluvial and environmental change in the Stanley River, a tributary of the Pieman River, in Western Tasmania over the past 17,000 years. Their work found that following the Last Glacial Maximum, the Stanley was a laterally active gravel load system. Between approximately 20,000 years before present and 3,500 years before present, drier climatic conditions resulted in less energetic flow regimes, which reduced the size of material transported by the river and allowed vegetation, including Huon Pine, to form dense cover on the banks and floodplains. In addition to dense vegetation stabilising the banks, fallen Huon Pines in the channel have contributed to long-term channel stability. Generational sequences of Huon Pines on the banks have been dated extending back 1000 – 2000 years and are cited as further evidence of channel stability.

The authors found that the establishment of dense riparian vegetation had the ability to reverse impacts on the channel during a regional increase in precipitation (between 8,000 and 5000 years bp) that must have resulted in a general increase in runoff. Nanson *et al.*,. (1995) conclude that during the late Holocene, declining runoff and vigorous riparian rainforest vegetation have combined to reduce channel capacities and limit channel migration in the lowland valleys of Western Tasmania. The process has a positive feedback mechanism where by increased channel stability promotes dense riparian vegetation which in turn, increases bank stability.

From this work the following points and assumptions pertaining to the Middle Gordon River prior to flow regulation can be made:

- Dense riparian vegetation was a major contributor to bank and channel stability;
- Rates of channel changes in the river were very low, largely as a result of stabilisation by riparian vegetation;
- Fallen trees, especially those species which decay exceedingly slowly (1000s of years) contribute to riverbank and channel stability through structural support and reducing stream power and boundary shear stress; and
- Stability provided by riparian vegetation *may* be sufficient to prevent changes to channel stability even under increased flow

Based on the preceding discussion and the flow characteristics of the Gordon River, some preliminary predictions as to the response of the river to flow regulation can be made. The following discussion provides a brief summary of the hydrologic changes that have occurred in the Gordon River due to flow regulation, and outlines the potential changes that might be expected in the Gordon given the present flow regime of the power station, characteristics of the river and evidence from other regulated rivers. This overview serves as a backdrop for the following sections of the report that describe in detail the existing condition of the Gordon River and the current erosional processes acting in the river based on the results of field investigations.

A detailed description of the pre- and post-dam hydrology of the study area is presented in Section 2.5, including a discussion of the propagation of flows downstream. The following dot points summarise the natural flow regime of the river, and some important alterations that have occurred due to damming. These dot points focus on the hydrology of the Gordon River at the point of regulation, the Gordon Dam.

- The pre-dam flow in the Gordon River at the power station averaged 86 m^3/s, with the hydrograph characterised by short, episodic high flow events occurring year round, though more frequently in winter.

- Post-dam flow from the Gordon Power Station averages 101 m^3/s due to the diversion of water into the Gordon catchment, with the hydrograph characterised by long periods of uniform flow interspersed with rapid fluctuations in water level
- Under pre-dam conditions, annual peak flows (1:1 Annual Exceedence Probability) were about 500 m^3/s with a 1:2 year high flow event of almost 1000 m^3/s.
- Peak flows from the power station are limited to 260 m^3/s, and there has been an increase in the duration of 170 m^3/s flows from about 10% of the time to almost 30% of the time, resulting in increased duration of high river stage.

Overall, these hydrological changes affect every aspect of flow in the Middle Gordon River: the magnitude, frequency, duration, timing and rate of change of flows in the river. These five critical flow components have been identified as being unique to the biological and physical integrity of a river's ecosystem (Poff, *et al.,* 1997) and it would be anticipated that the potential for change in the river would be great.

The Gordon River is a predominantly gravel bed river which is bedrock confined in many reaches and contains alluvial banks in the form of sand and cobbles in other reaches. Prior to regulation, the river would have carried a very low suspended sediment load typical of west coast rivers in Tasmania (Koehnken 1992).

We would predict the following changes in the river channel since the mid 1970s. However, all of the effects would decrease in magnitude downstream as tributary inputs progressively damp the effect of the dam. Recall that none of the tributaries are regulated in any way.

1. There will be minimal change to the bedrock channel reaches.
2. There will be minimal change to the gravel bed of the river. This is because the gravel bed of the river will be armoured by the former annual floods of 500 m^3/s or more. Such flows no longer occur. Furthermore, any armouring of the bed at the time of impoundment would be reinforced by the long duration medium flows that would winnow out fine material.
3. Continuing sediment supply from unregulated tributaries would deposit tributary bars in the Gordon River. The supply of sediment to the Gordon from tributaries could be increased because of tributary rejuvenation triggered by de-coupled flood flows.
4. Channel narrowing is unlikely, because of the diversion of water from other catchments into the Gordon River system results in larger volumes of water than would have occurred naturally, and from the continuous large volume releases out of the power station.
5. The presence of dense riparian vegetation and decay resistant rainforest species will inhibit channel widening, however if removed through inundation or water logging, channel widening is considered likely, where the bank material permits this response, for the following reasons:
    - Potential loss of riparian vegetation reduces bank stability and exposes alluvial deposits to direct attack.
    - Reduction in the sediment supply to below the sediment transport capacity of the river resulting in scour of the bank toe.
    - Increase in the duration of shear stress on the bank face due to an increase in the frequency of moderate flows (ie. flows are not dissipated on the floodplain).
    - Accelerated rates of drawdown, combined with long durations of high flows, will produce seepage induced erosion.
6. Meander migration rates (ie. rates of erosion of outer, concave banks) can only increase, assuming the pre-regulated river channel was highly stable and migration rates are considered to be virtually 'zero'.

Thus we would predict that the Gordon River would be wider, but with a more stable bed, as a result of regulation. In the regional context of geomorphic rates indicated by Nanson *et al.,* 1995, any rate of channel change measurable since damming the river in 1974 will be significantly greater than natural rates. Similarly, it would be expected that fluvial geomorphology changes associated with flow regulation in the Gordon would occur on time scales equivalent to those required for vegetation changes, loses and / or adjustments to occur.

It must be emphasised that the purpose of the present investigation is not to quantify the natural or present rates of geomorphic change, but to evaluate Basslink changes in the context of present rates and processes.

The potential river responses identified in the preceding discussion were used to focus the geomorphological investigations. The approach and methods used to address each potential river response are described in Section 4.

4 INVESTIGATIVE METHODS

The review of the literature combined with the predicted channel response of the Gordon River lead to the identification of characteristics and processes that were important to understand in the middle Gordon River. Investigating these processes involved five main tasks:

1. Examination of the past and present hydrology of the Gordon River to ascertain the changes to which the river is presently responding;
2. Field inspection to look for evidence of erosion processes;
3. Estimation of post-dam channel change using objective means;
4. Measurement of contemporary hydrological and erosion processes related to the present flow regime; and
5. Measurement of field properties of bank materials in order to develop models of bank behaviour.

Completion of these tasks was considered essential in being able to describe the current geomorphic condition and processes governing the Middle Gordon River, and in being able to then go on to predict Basslink responses. The techniques employed for each task are described below.

4.1 Hydrologic Modelling and Monitoring

Hydro Tasmania's in house hydrologic modelling capabilities were used to develop and run a number of hydrologic models associated with the project. Natural flows, historic power station operation and potential Basslink flows were modelled based on a reconstructed natural river flow time-series extending back to 1924 (Palmer *et al*, 2001). Statistical analysis of this information provides the basis for the pre-dam / present / Basslink river flow comparisons. Site specific hydrologic information, such as water discharge and river level, were modelled using a hydrologic model based on information obtained from 8 river stage recorders located throughout the study area, as well as river channel and bed slope information. Details of modelling work can be found in Appendix 2 of this report series (Palmer *et al*, 2001).

The projected changes to the hydrology under Basslink were modelled using the TEMSIM simulation model. A description of this model and its output are described in Appendix 1 of this report series – Scoping Report: Basslink Aquatic Environmental Project.

4.2 Field Inspection – Evidence of Erosion Processes

4.2.1 Geomorphic Zones

The present study is focussed specifically on identifying the potential impacts of Basslink on the Gordon River, so field based observations have been limited to the riverbanks and bed along the Gordon River and tributary junctions. The study area was divided into 5 zones, based on previously recognised geomorphological units (Roberts and Naqvi, 1978) but refined for the specific requirements of the present investigation. The units were primarily delineated based on hydrologic controls (confluences, gorges) with each zone reflecting similar hydrologic conditions, and successive zones reflecting the diminishing influence of the power station (Zone 1 = greatest influence; Zone 5 = least influence). The zones, location of start and finish in river kilometres, and boundary influences are shown in Table 7 and Figure 3.

Table 7. Characteristics of geomorphic zones established for this study.

Zone	Start	Finish	Linear River Length (km)	Mapped Riverbank Length* (km)	Boundaries influences upstream & downstream
1	Confluence Gordon R & Serpentine R (km 76)	Abel Gorge (km 72)	5	5.3	u/s: Power Station d/s: constriction
2	Abel Gorge (km 72)	Second Split (km 69)	3	5.6	u/s: Albert River d/s: constriction
3	D/S First Split (km 66)	Confluence Gordon R & Denison R (km 62)	5	5.4	u/s: constriction d/s: tributary inflow
4	Confluence Gordon R & Denison R (km 62)	Sunshine Gorge (km 57)	5	5.7	u/s: tributary inflow d/s: constriction
5	Shark Mouth Rapid (km 53)	Franklin R eddy (km 40)	14	17.0	u/s: constriction d/s: tributary inflow

*Based on GIS analysis of aerial photographs

Note that there are gaps between Zones 1 and 2, and between Zones 2 and 3, which are gorge sections and were logistically inaccessible. Aerial reconnaissance confirmed that these gorges are predominantly bedrock, so geomorphological change due to power station operation is unlikely and their exclusion from field study does not limit the conclusions of this study.

4.2.2 Field Observations

The following methods and techniques were used to investigate erosional processes in the Middle Gordon River.

4.2.2.1 Selective Mapping of Bank Features

During the first 6 months of the investigations (October 1999 – March 2000) the mapping of bank features in specific reaches of the river was completed. These areas generally corresponded to either highly active or inactive areas, or areas representative of specific characteristics of the river, such as geology. The mapping included the identification of bank materials, measuring bank slopes, qualitatively determining plant root density, identifying erosional / depositional characteristics (piping, rilling, alluvial fan deposits, tree fall), and determining the location of landslips and slumps. A hand held GPS was used to assist in this exercise. This exercise lead to the identification of key bank features associated with erosional processes in the study area.

4.2.2.2 Mapping of Riverbank Attributes

Between July 2000 and September 2000, a riverbank mapping exercise was completed for the entire study area. Previous observations had identified a number of bank attributes that are important to the overall geomorphology and stability of the riverbanks. These bank attributes were mapped on a reach-by-reach basis, with reach boundaries being determined by a significant change in one or more of the mapping categories. The exercise was completed over 10 days by the same two investigators to ensure consistency. The boat coxswain was also familiar with the mapping categories and provided assistance. Observations were typically made from a boat, with frequent landings to verify or further investigate initial observations. A hand held GPS was used to delineate mapping zones and document distinct geomorphic features. Photos were taken of many reaches as well as distinct geological features. The mapping categories and definitions are contained in Table 8.

4.2.2.3 Cobble Bar Mapping

A helicopter based survey of cobble bars was completed for Zones 1 through 4. The upstream two zones were completed during December 1999, with Zones 3 and 4 completed during September 2000. Additional observations of the bars were made throughout the study period. At most bars in these zones, a team of 2 or 3 people observed the typical material size, degree of sorting, clast shape, maximum cobble size, degree of imbrication, degree of cementation, and presence or absence of algal coatings.

4.2.2.4 Photo Monitoring

The study area was extensively photographed both from the air and ground. These photos have been used to document characteristics of the bank, and within the time scale of the study period, as a progressive record of erosion at selected sites. The entire photographic collection is catalogued and will serve as a record of the current condition of the river, and numerous sites will be selected as long-term photo monitoring points. The photos will be archived at Hydro Tasmania. The 1500m immediately downstream of the tailrace were only inspected from the air, or from the base of the tailrace, as this area is off limits to boats and helicopters due to safety considerations.

4.2.2.5 Tributary Assessment

An assessment of unregulated tributaries was an important component of the field observations. The identification and documentation of erosional processes in the unregulated tributaries provided a basis for comparison for investigations in the Gordon River. The Franklin, Denison, and Albert Rivers and Splits Creek were all visited by boat or on foot. Field activities included photography, descriptive notes, and measurements of erosion features. The Serpentine, Orange, Olga and Sprent Rivers were all investigated from the air due to the lack of suitable landing sites.

4.2.2.6 Field Consultation with Relevant Experts

During the twelve months of field work, Koehnken and Locher were accompanied by numerous geomorphological, hydraulic and bank stability experts in the Middle Gordon River and tributaries. These include Dr Ian Rutherfurd, who visited the field area repeatedly and is a co-author of the report, Dr. David Dunkerley (geomorphologist, Monash University); Dr. Kate Brown (geomorphologist, University of Tasmania), Dr. Bruce Abernathy (geomorphologist, SKM, Melbourne); Mr. John Styles (Dept. Civil and Environmental Engineering, University of Melbourne) and John Davies (geotechnical engineer, Hydro Tasmania.

Mr. Jason Bradbury, from Department of Primary Industries, Water and Environment also accompanied the investigators on numerous occasions as an official observer of the project. His role included providing a review of the project’s activities. Several scientific officers from DPIWE were consulted during a fieldtrip to the study area in March 2000, and following independent visits to the study area by Earth Sciences’ officers.

4.2.2.7 Field Consultation with other Basslink Investigators

From the initiation of the Basslink investigations, the interdependence of the various disciplines being investigated was recognised, and extensive consultation between investigators was conducted in the field, as well as the office. The geomorphology team completed joint field excursions with the vegetation investigators, and integrated investigations with the karst team. The co-location of several hydrological, biological and geomorphological monitoring sites allowed a cohesive understanding of the present status of the Gordon River.

Table 8. Description of categories used in bank mapping exercise.

Mapping Category	Option/qualifiers	Definition
BANK MATERIAL	Bedrock	Any type of bedrock, not differentiated
	Cobbles	Large gravel to cobble sized rounded to sub-rounded clasts in a sandy matrix with varying degrees of induration
	Alluvial	Any unconsolidated material not containing cobbles; includes colluvium
	Boulders	Angular predominantly boulder sized material derived from upslope or nearby
	Alluvial over bedrock	Composite banks containing more than one bank material type
	Alluvial over cobbles	
	Cobbles over bedrock	
Bank slope	Shallow	Approximately <20°
	Moderate	Approximately 20°-40°
	Steep	Approximately 40° - 70°
	Vertical	Approximately >70°
	Continuous/discontinuous	'Smoothness' of slope between high and low water marks, and along the bank
Percent Woody Debris	0 – 5%	Percentage of bank on a linear basis covered with woody debris
	5 – 25%	
	25 – 50%	
	50 – 75%	
	75 – 100%	
	Small	Majority of woody debris consisted of small material (<10 –20 cm diameter),
	Large	Majority of woody debris consisted of large material (>20 cm diameter)
Percent Buttressing	0 – 5%	Percentage of riverbank on a linear basis buttressed by woody debris
	5 – 25%	
	25 – 50%	
	50 – 75%	
	75 – 100%	
	Cobbles	Indicated if toe of bank buttressed or protected by cobbles
	Boulders	Indicated if toe of bank buttressed or protected by boulders
	Bedrock	Indicated if toe of bank is bedrock

Table 8 continued

Mapping Category	Option/qualifiers	Definition
Percent Tea Tree	0 – 5% 5 – 25% 25 – 50% 50 – 75% 75 – 100%	Percentage of fringing vegetation that consists of Tea Tree
Height to Green leaves	Estimated in metres	Estimated height between water level and continuous green leaves on river bank. Generally lower than high water mark as measured on banks due to overhanging vegetation. Affected by river stage
Level of **Recent** Activity	Low	Erosional activity limited to scour
	Moderate	Scour accompanied by limited piping, or undercutting or seepage erosion
	High	Scour accompanied by widespread piping, or undercutting or seepage erosion; recent treefall/landslip
Erosional/Depositional		Areas showing strong evidence of recent erosion or deposition noted

4.3 Estimation of Post-Dam Channel Change - Aerial Photo Interpretation

Recent aerial photos of the study area were obtained during December 1999 at a scale of 1:5000 during a period of low river flow. These were compared with similar low-flow 1974 (1:20,000) aerial photos from the study region by the Hydro's Survey and Geographic Services section using a Zeiss Planicomp P2 stereoplotter. The output of the project included a set of detailed maps for the entire study area showing the approximate location of the river channel, cobble bars, drip line (edge of vegetation), logs, sandy or rocky shorelines and submerged cobble bars and other major features from the two sets of photos. The absolute accuracy of the methodology is +/-5m in the x, y, and z directions, with a relative accuracy of +/- 1 m, without taking into account different water levels and vegetation at the time of photography . A complete description of the methodology employed is contained in Attachment 3, *Aerial Photography Interpretation Report*.

The 1974 maps reflect river conditions after the construction of the Gordon Dam, but prior to operation of the power station. River flow in the upstream reaches of the study area was low during this period, with flow restricted to approximately 5 m^3/s discharged via the diversion tunnel. At the downstream end of the study section, at the Gordon above Franklin River gauging site, river level was falling from 0.24 to 0.19 m during the aerial photography, which is equivalent to a flow of 19 to 18 m^3/s.

The 1999 photos were taken during a weekend shut down of the Gordon Power Station with no water discharged from the station and low tributary inputs. At the Gordon above Franklin River gauging site, water level was falling from 0.86 to 0.70 m, equivalent to flows of 35 m^3/s to 26 m^3/s. Therefore, flow in the upstream section of the study area (above the Denison River) was very similar during the two sets of photos, with greater tributary inputs during the 1999 photo run contributing to higher flows at the Gordon above Franklin site.

4.4 Measurement of Contemporary Hydrological and Erosion Processes

After initial reconnaissance of the study area, monitoring locations in fine-grained alluvial banks were identified which were judged to be representative of the river, and logistically accessible. At least one monitoring site was identified in each zone for the installation of erosion pins and scour chains. Monitoring locations are identified by distance (river kilometres) upstream of the mouth of the Gordon River. Field based investigations were concentrated on the upstream Zones 1 – 3, due to the greater apparent impact of power station operation in these regions, and the limited availability of field time due to logistical constraints.

4.4.1 Erosion Pins

An erosion pin is essentially a benchmark. It is usually a long metal stake, the head of which is taken to be a fixed reference and changes in exposed length are taken as measures of ground surface height changes (Haigh 1977). Erosion pins are one of the simplest, least expensive and most effective methods of monitoring changes in ground surface. Their use was pioneered by Schumm (1956), guidelines for their use have been well-described by Lawler (1978, 1993) and Haigh (1977), and there are numerous field studies which attest to their effectiveness (e.g. Twidale 1964, Hooke 1979, Bradbury *et al.* 1995).

In December 1999, 500 mm long, 10 mm diameter metal rods were installed in river banks of the Gordon in sets of 3 to 5 in a line perpendicular to the flow of the river. Repeated measuring of the length of pin exposed above the surface of the bank allows the quantification of net erosion or deposition at a site over time (Photo 1).

4.4.2 Scour Chains

Erosion pins only show net changes in ground surface over the period of time between measurements, whereas processes of scour and deposition may vary in the intervening period between measurements, and will not be reflected by the erosion pin measurements. To provide an indication of the maximum scour which had occurred between erosion pin measurements, scour chains (Leopold *et al.* 1964, Laronne *et al.* 1994) were placed near the erosion pins. The 1500 mm scour chain was inserted inside a metal tube with the cone end of the chain at the bottom, and two horizontal pins stopped the chain from sliding out when the tube was upright. The tube and inserted chain were hammered vertically into the bank so that 1 m of chain was in the ground, and then the tube removed. Upon removal of the tube, 1 m of chain was left vertically in the ground; half a metre of chain was still exposed, and this subaerial portion of the chain was left on the bank surface trending in the direction of river flow. During an event that causes bank scour, sediment removal from the bank would cause the upright section of chain to fall horizontal. Subsequent deposition of sediment after the flood event would cause the horizontal component of the chain to be buried. The depth of burial of the horizontal section of chain indicated the maximum depth of scour and fill that had occurred during the time interval between measurements. This is graphically illustrated in Figure 18 and shown in Photo 2.

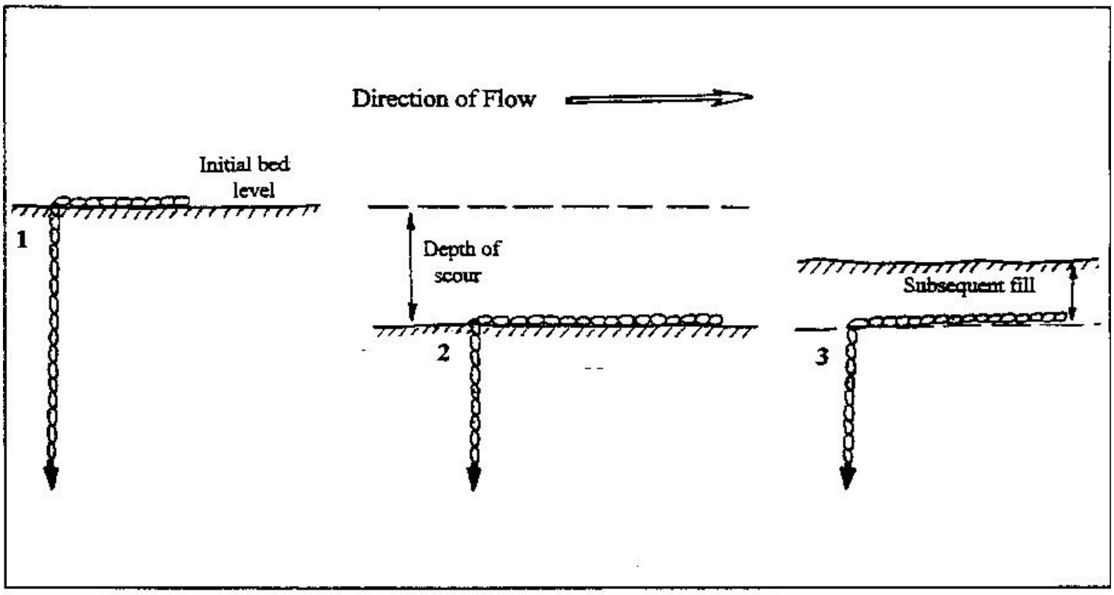


Figure 18. Maximum scour measurement using scour chains, after Laronne *et al.*, 1994.

4.4.3 Painted Cobble / Largest Cobble Measurements

In order to determine the size of bed load actively moving through the river under the present flow regime, thin (up to ~150 mm) lines ranging from 1 to 5 m in length were spray painted on cobble bars perpendicular to the direction of flow during low flow in the river. After a high flow event, both the painted pebbles/cobbles that had been transported downstream off the line and non-painted material deposited on the line were measured. The largest cobbles or boulders on banks were also measured in order to provide an indication of the size-range of bed load previously transported by the river. This investigation was intended to provide data relevant to the bedload being transported in the river, and not the stability of cobble bars.

4.4.4 Suspended Sediment Sampling

Suspended sediments were collected on two occasions from four sites in the middle Gordon River. The sampling coincided with high flow (22 August 2000, power station on) and low flow (27 September 2000, power station off) at above and below the Denison River and above and below the Franklin River. Suspended sediments were collected using a depth integrating sampler (USGS DH-48) from three points across the river at each sampling location. River discharge was measured at the time of suspended sediment collection using an Acoustic Doppler Current Profiler (ADCP). Sampling and current measurements were completed by Hydro Tasmania's Water Resources Group.

The establishment of a sediment budget for the study area was not possible during the investigations because of the importance of bed load transport in the study area, and logistical and safety issues associated with accessing and sampling the river under the wide range of flow conditions required to obtain a useful budget.

4.4.5 Surveyed Cross-Sections

A series of river cross-sections were surveyed in the study area, by the researchers investigating in stream biota, and the Resource Monitoring group of Hydro Tasmania. The cross-sections were not tied into AHD, but to local reference points or a hydrologic gauging station where possible. The cross-sections provided information about the channel morphology and nature of the substrate. These cross-sections were used in the hydrologic model and sediment transport model and provided information about channel form. In the future, these cross-sections will be a useful tool for assessing channel changes under the present flow regime, or Basslink. The cross-sections were used in the sediment transport capacity modelling.

4.5 Measurement of Field Properties of Bank Materials

Characteristics of bank materials were determined in order to develop models of bank behaviour. Information was used in numerical modelling of the bank's behaviour, and as a means of comparing the Gordon River banks with information available in the literature. The following techniques were employed.

4.5.1 Sediment Collections for Particle Size Analysis

Sediment samples collected from throughout the study area were dry sieved to obtain particle size distributions. Samples consisted of both surface and sub-surface material obtained through repeated augering. This work was completed as part of a University of Tasmania Honours Thesis (Brook, 2000). A summary of the particle size distributions is contained in Attachment 4 *Particle size distributions*. The grain size distributions from sites 70.6 and 61 were utilised in the bank stability modelling of the banks.

4.5.2 Piezometers

Because the initial time frame for the Basslink investigations was initially very short, and the quantity of probes required for the Gordon and downstream Poatina investigations were not commercially available, Hydro Tasmania's Water Resources Group custom designed and built the required probes.

A Honeywell differential pressure transducer producing a linear milli-Ohm change when a pressure is applied to it was used as the basis for the probe. Because this signal is too small for any standard logger to record it was amplified to produce a voltage proportional to the applied pressure. Interference from the barometric pressure was avoided by connecting a vented tube to the other end of the transducer which allowed it to vent to atmosphere during encapsulation and immersion in water.

The probes were powered by battery, and data were collected at 15-minute intervals by a multi-channel logger.

Two piezometer sites were established in Zone 2 (km 70.6, km 69) and one site in Zone 4 (km 61). Five piezometers were installed at km 70.6 and km 61, between low water level and approximately 25 m horizontally inland. The second site in Zone 2 (km 69) was underlain by quartzite cobbles which hindered drilling efforts. In March 2000, 2 probes were installed at this site within a few metres of the low water level. A third probe with a greater measuring range was installed at low water level in August 2000. The probes recorded water level at 15-minute intervals. Photo 3 shows the placement of piezometers on a bank at the km 70.6 site in Zone 2.

The collective record from these instruments provides a temporal and spatial indication of water movement in the banks and river. Local bank water behaviour was related to river flow patterns through the monitoring of river levels at 7 locations along the study area, and a hydrologic model developed by Hydro Tasmania Resource Analysis Group (Palmer *et al*, 2001).

The piezometers experienced some problems with drifting baselines, inconsistent baselines or complete malfunctioning. Infiltration of fine material into the bore holes appeared to alter the response time of the instruments. Periodically, probes that were not responding were removed and the borehole was flushed. Probes that failed were replaced.

The water surface profiles collected by the piezometers and the bank profiles that were surveyed at each piezometer site, were used in the bank stability modelling.

4.5.3 Penetrometer Measurements

Penetrometer readings provide an indication of the force per unit area required to puncture the surface of a river bank, and is an indication of the cohesion and strength of a bank. Measurements were completed in all zones in December 1999. These measurements were used in the bank stability modelling work.

4.5.4 Bank Stability Modelling

Bank stability modelling was completed using field derived information (particle size, bank slope, water level) and SlopeW, a slope stability analysis computer program. A simplified Bishop's method of slices for circular failure surfaces was used to determine the minimum factor of safety (Factor of Safety) for the critical slip surfaces that are structurally significant. In the case of the Gordon, the results of the model provide relative FoS's and not absolute FoS's as the actual failures on site are not limited to deep seated rotational slips, with smaller local slumps and seepage erosion common. A summary of this modelling work is in Attachment 5, *Gordon River Bank Geotechnical Stability Study*.

4.6 Summary of Investigative Methods

The investigative methods were selected, designed and implemented to provide information about the natural erosion processes operating in the Gordon catchment, how those processes have been modified due to the present flow regulation, and what changes may be expected under Basslink. These methods were selected based on considerable reference to the literature, consultation with experts, and consideration of field observations and data. Table 9 summarises the field based investigations used in each zone in the study area.

Table 9. Summary of the field based investigations used in each zone.

Zone & Location of Sites	Field methods employed in zone
Zone 1 1 site km 75	Erosion pins – 1 site Scour chains – 1 site Sediment collection Mapping of bank features Penetrometer measurements Photo monitoring Largest cobbles on bar measurements
Zone 2 4 sites km 71.3 km 70.6 (U/S piezometers) km 69 (D/S piezometers) Mouth of Albert R	Erosion pins - 3 sites Scour chains – 2 sites Piezometers – 2 sites Sediment collection Mapping of bank features Penetrometer measurements Photo monitoring Painted / largest cobbles on bar
Zone 3 1 site km 65	Erosion pins 1 site Scour chains 1 site Sediment collection Mapping of bank features Penetrometer measurements Photo monitoring Painted / largest cobbles on bar Suspended sediment monitoring
Zone 4 2 sites km 61 (piezometers) km 59.8 km 59	Erosion pins - 1 site Scour chains - 1 site Piezometers – 1 site Sediment collection Mapping of bank features Penetrometer measurements Photo monitoring Painted / largest cobbles on bar Suspended sediment monitoring
Zone 5 1 site km 47	Erosion pins - 1 site Scour chains - 1 site Sediment collection (few) Mapping of bank features (minor) Photo monitoring Painted / largest cobbles on bar Suspended sediment monitoring

4.7 Limitations of Study

This report contains the current understanding of geomorphological processes operating in the Gordon catchment and potential changes under Basslink. The study has been constrained by a number of uncontrollable factors. These include logistical constraints, a lack of available baseline information, and a relatively short time frame for the Basslink investigations.

The inaccessibility of the middle Gordon River is the major limitation to field based investigations in this region. Most of the study area is inaccessible by vehicle, boat or foot and requires helicopter access. Unfortunately, helicopter access is severely limited due weather constraints and to the lack of suitable landing sites on or near the river except during periods of very low-river flow requiring a shut-down of the Gordon Power Station. The optimal field season in Tasmania’s Southwest coincides with the drier summer months when daylight hours are greatest, although even during this period rain, low cloud and wind are common hindrances. However, shutting down the Gordon Power Station during the summer season is extremely difficult owing to Tasmania's dependence on the scheme for summertime base-load power generation. During the summer of 1999/2000 this hindrance was exacerbated by the drought conditions in the State which increased the dependence of the State on the Gordon scheme for power. This limitation was minimised as much as possible through the use of multiple helicopters and numerous field teams during every available opportunity for fieldwork.

The restriction of access to periods of low river flow has also limited the field observations of the river during rising stage, falling stage or high flow to helicopter based reconnaissance. This has resulted in a lack of high flow and drawdown related observations. The impact of this limitation has been reduced through the implementation of an extensive network of water level recording devices within the study area, and recurrent visits to established study sites, where progressive observations allow the inference of high river flow processes.

The time-frame available for completing the Basslink field investigations has been approximately 12 months between October 1999 and October 2000, with field access provided during eleven power station shut downs. The initial few months were dedicated to field reconnaissance and instrument deployment, which has reduced the time frame over which *in situ* data have been collected to approximately 7 – 9 months. During much of this time, the power station was constantly utilising three machines, resulting in little variation in river or bank water levels for extended periods. Piezometer failure was also a common occurrence, further reducing the time periods during which useful information was collected.

Ideally, an investigation such as this one would encompass summer and winter conditions, or at least 'wet' and 'dry' periods, but due to the drought in Tasmania, the majority of data collected reflects very dry conditions. This has had the benefit of allowing an in depth examination and analysis of the interaction of the power station with downstream environment, however it does not reflect the more typical interaction of the power station with an environment characterised by high rainfall. This limitation has been minimised through the use of historic river flow records where available.

There is a lack of 'natural' or 'present' baseline geomorphological information available for the study area, and the mapping of the geological units in the area is poor. Although the 'natural' status of the river is largely beyond the scope of this investigation, which has been directed to use the present as a base-line, where useful, the investigations have drawn heavily on work completed in the Stanley River (Nanson *et al.*, 1995), on observations from unregulated tributaries in the Gordon River catchment, and through the examination of pre-dam hydrographs and aerial photos for indications of the 'natural' condition. Establishing the 'present' baseline has been accomplished through the direct observation and measurement of the middle Gordon River during the study year.

The effect of the unusual hydrologic study year (Section 2.5.8) on the field observations and investigations has to be considered. Hydrologically, the study year can roughly be divided into four parts. During the first part, October 1999 to December 1999, the power station was operated in a typical manner, with infrequent use of three turbines and monthly average flows similar to long term averages. This provided the investigators the opportunity to observe the river under 'typical' regulated flow conditions. Between January and April 2000, the station was operated at the highest monthly flow rate in the history of the power scheme, which allowed the investigators to directly observe the impacts of very long-duration high flow events. Although this flow regime is very different from the anticipated Basslink flows (see Section 10.2), the response of the river to the prolonged high flows provided very useful insights about processes and rates operating in the river.

During July, August and September 2000, power station operation again returned to more typical patterns, which allowed the researches to test hypotheses developed during the first 9 months of the investigations. A 5-day Basslink simulation exercise was completed during this time period, 'bracketed' by typical power station operation. The final observations and investigations were completed during an extended shut-down of the power station, during which time the tributary inputs dominated river flow. This allowed the investigators to directly observe 'natural' processes normally masked by the present flow regime, providing additional information about the effects of regulation on the Gordon River. In conclusion, although the study year was very atypical when viewed from a yearly perspective, the segmented change in the flow regime allowed direct observation of the study area under a range of conditions, and was of benefit to the study.

5 GEOMORPHOLOGICAL DESCRIPTION OF THE MIDDLE GORDON RIVER

This section presents a description of each of the Geomorphology Zones in the Middle Gordon River. The descriptions focus on evidence of present erosion processes, and post-dam channel changes. In Section 5.8, unregulated tributaries of the Gordon (Franklin and Denison Rivers) are used as natural analogues for the study area as a means of putting the erosional features and channel changes in a regional context.

The evidence of present erosion processes is based on the field mapping exercises and has been summarised in a series of maps contained in Attachment 6. For each zone, maps showing the underlying bank materials; the level of recent activity and erosion features; and estimated percentage of tea tree present on banks are presented in Attachment 6. Other characteristics relevant to erosion processes (percent large woody debris (LWD), percent buttressing, height to continuous vegetation, bank slope) have also been compiled and were used for developing the 'risk maps' discussed in Section 7.7, but are not individually presented in Attachment 6. Whilst the information has been collected and synthesised as carefully and rigorously as possible, it must be recognised that much of the information is derived from boat-based observations of the river on a reach-by-reach basis. It has been necessary to generalise bank characteristics over distances of 10s of metres. Distinct erosional features, such as landslips or large recent tree falls have been mapped quite accurately, and the present maps can be used as a basis for future comparison.

Aerial photo interpretation has been used to assist in assessing pre-dam / post-dam changes and provide an indication of likely future trends under Basslink. Attachment 7 contains the results from the air photo comparison for the study area. The maps compare photos obtained in 1974 with December 1999 photos. Both sets were taken under low water conditions as described in Section 4.3. The 1974 photos show the Gordon River after construction of the dam had been completed, but prior to power station operation. Therefore, these photos show changes to the channel that may have occurred during dam construction, but do not show the impacts of power station operation.

A third set of maps showing features of cobble bars in Zones 1 – 4 is presented in Attachment 8.

This section describes how the middle Gordon River has responded to flow regulation. Section 5.1 looks at post-dam channel change based on aerial photograph comparison, and describes examines present erosion features in each Zone.

Subsequent sections (6, 7 and 8) discuss pre-regulation and post-regulation erosional processes and rates, for the river bed, cobble bars and bedrock banks (Section 6), alluvial banks (Section 7) and finally for cobble banks (Section 8).

5.1 General Description of Bank Materials and Erosion Features

Within the study area, a number of bank materials and erosional features have been identified and mapped, and are important to the discussions in the following sections. This section contains brief descriptions / definitions and examples of these common bank materials and features.

5.1.1 Bank Materials

Bank materials have been divided into three broad categories: bedrock, fine-alluvium, and cobbles. Examples are shown in Photo 4, Photo 5, and Photo 6. These units occur as homogenous banks and in combination with each other in the general stratigraphic sequence of bedrock overlain by cobbles or fine alluvium, or cobbles overlain by fine alluvium.

Bedrock type was not differentiated in the mapping exercise, but the common bedrock units include quartzites, schists, limestone and dolomite (refer to Figure 1 for general distribution).

The fine alluvial units consist of fine to medium sands and silt that have been found to be composed of 60% or greater quartz throughout the study area, with micas and feldspars contributing the majority of the remainder. Bedding is generally absent in the river bank exposures. Iron hardpan layers are occasionally present within the sands. Plant roots commonly penetrate this unit. Colluvium, which is present in all Zones and was frequently found overlying bedrock or boulders, was not differentiated from alluvium in the mapping exercise.

Cobble units are typically characterised by small to medium well-rounded cobbles in a sandy iron-rich matrix. The moderately to well-indurated unit is matrix supported in most exposures, and tends to form vertical bank faces. Plant roots were not observed to penetrate the unit.

The various bank materials are overlain by an organosol, defined as a soil dominated by organic material directly overlying rock or other units (Isbell, 1996). In the case of the Middle Gordon, the organosol overlies bedrock, cobbles or the fine alluvial deposits. Scour, inundation and water logging has resulted in the removal of much of the organosol below the high water level in the river resulting in the exposure of a degraded root mat (Photo 7). This unit is ubiquitous in the Middle Gordon River and was not included in the bank mapping exercise.

5.1.2 Seepage Erosion Features

Seepage erosion features that were commonly observed in the fine alluvial units of the Middle Gordon River and tributaries have been defined as slots, voids, pipes and sediment flows. These are not the only erosional features present in the Middle Gordon, but because of confusion in the literature regarding the terminology of seepage erosion, a summary of how these terms are used in this report is considered useful. Seepage erosion processes are described in Section 3.5.3.

Pipes, slots and voids are three terms used to describe a continuum of bank features associated with the movement of water, and sometimes sediment, out of the bank. Pipes tend to be isolated features which are typically small (<10 cm), but can be quite large (>50 cm) and frequently appear to be pathways developed along the route of old tree roots.

A slot is created when erosion (scour or seepage) of the fine alluvial bank has resulted in undercutting of the overlying organosol. The cohesiveness of the organosol prevents mass-failure, and instead, the soil and overlying vegetation ‘rolls over’ and creates a drape over the bank, rotating the vegetation towards the river.

On alluvial banks bearing medium to large trees, the tree root structures can provide support for the organosol, and instead of the vegetation draping over the alluvial bank a ‘void’ can form. Voids vary in size, from the narrow small slots previously described, to large caverns capable of fitting several people. Generally the larger voids are characterised by a uniform sloping floor. Bank toes below the voids vary, with some examples showing fairly uniform slope from the void to low water level, while others have a prominent slope break, increasing slope towards the waters edge. Rilling is common on the bank below the voids. The back wall of the void is steep, typically composed of orange sands. Plant roots are common near the roof of the void and decrease in occurrence down the back wall with increasing distance from the organosol. Pipes are sometimes present near the contact with the organosol. The roof is characterised by the spalling of sands from overhanging plant roots.

Sediment flows composed of material similar to the back wall of the void are sometimes present on the bank down slope of the voids. The material is generally wet and dissected by small channels caused by the draining of water from the bank.

These bank units and erosional features are used to describe the geomorphological characteristics of the study area in the following sections.

5.2 Zone 1: Serpentine R to Abel Gorge (5 km)

Zone 1 consists of the 5 km between the tailrace of the Gordon Power Station and Abel Gorge. Safety constraints pertaining to power station operating rules forbade the entrance of field parties into the 1 km immediately downstream of the tailrace during most field excursions. Limited geomorphic observations were made from a helicopter in this top part of Zone 1, but the mapping exercise, detailed investigations and hence the maps, begin at river kilometre 75.

The hydrology of this reach is dominated by operation of the power station with no significant tributaries entering between the tailrace and Abel Gorge. On an annual basis, less than 1.5% of the total flow is derived from natural flow entering below the power station. The greatest 'natural' contribution in this reach is about 5%, and coincides with periods of high rainfall and low power station operation (Figure 11).

The river has a steep slope in this zone, dropping in elevation from about 110 m at the end of the tailrace to approximately 70 m at the entrance of Abel Gorge. Most of this drop occurs in the upper 1500 m of the Zone (Abel Rapids), with a 10 m drop occurring between river km 75 (start of river based observations) and the entrance to Abel Gorge.

The upstream inaccessible Abel Rapids consists of a steep bedrock controlled channel, with rock walls below high water level being devoid of vegetation. Several cobble bars are present in this area that appear from the air to be located in deeper pools within the bedrock channel.

Table 10 shows the distribution of bank materials in Zone 1 as a percentage of river bank length. Below site river km 75, approximately 60% of the channel length is bedrock controlled, with most of the remaining banks consisting of fine alluvial (and colluvial) material (35%). Cobble banks are limited to the lower reaches of the Zone, immediately above the entrance to Abel Gorge and make up about 5%.

Table 10. Distribution of Bank Materials in Zone 1

Bank Material	Percentage of Bank Length in Zone 1
Cobbles	5
Fine alluvial	11
Alluvial and cobbles and/or bedrock	32
Bedrock	48
Bedrock and cobbles	4

Bank toes are devoid of vegetation, creating a distinct Plimsoll line on the bank where vegetation begins (distinct line with no/little green vegetation below and abundant green leaves above). The Plimsoll line fluctuates between approximately 1 and 4 m above low water level (power station off), with the higher levels found upstream of hydraulic controls (Abel Gorge, Albert Rapids).

Along bedrock reaches, vegetation is consistently present above the high water mark. In areas where the high water level exceeds the height of the bank or mid-stream outcrop, vegetation and the associated root-mat or organosol has retreated to above the high water stage (Photo 8). The presence of small rainforest species above the Plimsoll line suggests that the reduction in high flows due to power station regulation has permitted the growth of vegetation in a previously uncolonised zone of the bank.

Alluvial sand banks in Zone 1 are generally located between 500 m upstream of the confluence with Piguenit Rivulet and the entrance to Abel Gorge. Medium to fine – sands comprised between 60% and 90% of the bank samples analysed (Brook, 2000). In four samples analysed mineralogically, quartz accounted for >80% of the fine-sand fraction in two samples, and contributed 60 – 80% in the other two. The remaining 20 – 40% of the sample consisted of micas and feldspar (plagioclase), with minor chlorite and rutile (Brook, 2000).

The alluvial banks show differing characteristics depending on the presence or absence of tea tree. Tea tree bearing banks show evidence of scour resulting in the exposure of tree roots (Photo 9) and adventitious roots (Photo 10), indicative of long-periods of inundation (adaptation for direct uptake of oxygen from water). The underlying sands comprising the bank toe are typically low-angle (<16°) with little evidence of erosion or deposition. The absence of leaf litter on the sand toe indicates the bank is 'swept clean' during power station operation. Scour of the bank toe is discussed in more detail in Section 7.4.3, and Attachment 9 *Sediment Transport Capacity Analysis.*

Non-tea tree bearing alluvial banks generally show greater signs of seepage erosion, with pipes, slots and voids near or at the high water level common in Zone 1 (Photo 11).

Generally the larger voids are characterised by a uniform sloping floor. Measured bank slopes within Zone 1 varied between 8° and 32°, with the steeper slopes associated with bedrock of similar slope located at shallow depth below the alluvial deposit. Bank toes below the voids vary, with some examples showing fairly uniform slope from the void to low water level, while others have a prominent slope break, increasing slope towards the water's edge, which may indicate scour of the toe is occurring. Tree fall is common in these areas.

Sediment flows were present during some field excursions, and absent during others. The deposited material was generally wet and dissected by small channels caused by the draining of water from the bank. Water was observed exiting slots and voids 24 hours after power station shut downs, however no sediment movement from the slots or voids was observed.

The few cobble banks present in Zone 1 have near vertical faces, and have similar vegetation patterns to bedrock – organosol retreat where high water level exceeds the height of the cobble bank, and mosses and ferns present above high water level where cobble height exceeds high water level (Photo 12). The cobble banks vary in degree of induration and permeability. Water was observed exiting the cobbles in a number of locations both within the zone of river water level fluctuation, and higher up near the contact with vegetation. A slip in the 3 to 4 m high cobble bank above the entrance to Abel Gorge resulted in the exposure of a fresh vertical cobble face and the deposition of cobbles at the toe of the bank (Photo 13).

Zone 1 contains numerous cobble bars of varying height. At river km 75, the crest of a high cobble point bar has been colonised by vegetation (Photo 14). The flanks of the bar are armoured, with algae present in the zone between high and low water level. Further downstream, lower cobble bars that are submerged during high water are devoid of vegetation, generally armoured, and show varying degrees of imbrication. In general, clast sizes on the bars tend to be bimodal, with large cobbles up to 30 cm forming an armoured layer over and under gravel sized material. Cementation of some bar surfaces was observed, with the cementation breached on the flanks of the bars and on some surfaces where channels have formed. Algal coatings are also common. One bar, located in the first 'pool' of the study area (between 412200mE and 412400mE) differs from the other bars, in that it is not cemented, composed of generally more angular material, and although armoured, is overlain by sands and gravels.

There is evidence of small amounts of sand and small gravel moving through the system, occurring as drape deposits in back bar environments, but there is little overall deposition except for fines in a backwater immediately upstream of Abel Gorge.

Abel Gorge is situated between the downstream end of Zone 1 and the beginning of Zone 2. The inaccessibility of this steep boulder controlled gorge section prevented field observations in this region.

Based on the aerial photo comparison, the most prominent changes in the river in Zone 1 between 1974 and 1999 have been the widespread expansion of vegetation and the alteration of cobble bars.

The expansion of vegetation has occurred within two environments, the steep bedrock sections, and the downstream alluvial reaches. Field visits have determined that each of these environments is reflecting different processes.

Although not evident from the comparative photos, the additional colonisation in bedrock areas has occurred in a consistent zone immediately above the present high water level. Field visits have documented the presence of a range of rainforest species of varying young ages on the steep bedrock and boulders. The colonisation of this area is attributable to the reduction in flows greater than present power station operation in this Zone, which has allowed the establishment of vegetation in portions of the bank previously subjected to very high-energy flows.

In alluvial areas, the apparent expansion of vegetation typically coincides with tea tree stands that show signs of scour around the roots. There are no small tea tree within the stands, and in general it does not appear to be an expanding vegetation community. The expansion of vegetation observed in the air photos may reflect a previous increase in vegetation corresponding to the operation of only two turbines in the Gordon Power Station. The construction of the power station and reduction of high flow events may have promoted the expansion of vegetation in these areas. The implementation of a third turbine, which has the effect of increasing water level heights by 0.7 m at site km 75, may now result in scour of previously unaffected zones.

A minor portion of the observed expansion of vegetation may be due to the reduction in high flows that has allowed the expansion of the tea tree canopy, but not the colony. This alone cannot account for the up to 20 m difference observed between the drip lines on some of the photos, but could account for some of the smaller changes.

Cobble bars have expanded, generally in a longitudinal direction in most areas below river km 75, with one new cobble bar present in the reach, between 412200mE and 412400mE (Zone 1 map, Attachment 7) on the 1999 photos. As previously discussed, this bar has a different appearance from the other bars in the zone, in that it is composed of generally smaller clasts (up to 15 cm) and has sand and gravel deposits overlying an armoured surface.

5.2.1 Summary of Zone 1

To summarise, Zone 1 is characterised by a predominantly bedrock controlled channel with short alluvial sections. The alluvial banks show signs of scour where tea tree are present, and scour and seepage erosion, concentrated along the high water level, where tea tree is absent. Tree fall is common in seepage erosion areas. Bank toes are devoid of vegetation, and there is a prominent Plimsoll line. Vegetation has increased on the high bedrock banks and on some alluvial banks based on aerial photo comparisons. Cobble bars are armoured, and in some cases cemented, and one new cobble bar has been deposited between 1974 and 1999 in the first 'pool' in the study area below Km 75.

5.3 Zone 2: Abel Gorge to the 'Splits' (3 km)

Zone 2 is delineated at the upstream end by Abel Gorge and at the downstream end by the Second Split. The Albert River enters the top of the Zone, discharging into a large pool. The river drops approximately 10 m over the length of the zone.

Hydrologically, Zone 2 is dominated by power station operation, with the flow from the Albert River (59 km^2 catchment) and direct inflows from the Gordon catchment below the Gordon and Serpentine Dams contributing approximately 6% of the total yearly flow. Similar to Zone 1, the greatest 'natural' contribution to flow occurs during spring, when rainfall is high and power station usage is limited. During these periods, the contribution of non-power station derived water can account for up to about 20% of total monthly flow.

Compositionally, Zone 2 has a greater proportion of alluvial banks than Zone 1, with 76% of the banks classified within this category (Table 11). Bedrock in the Zone only accounts for about 5% of the banks, and is generally located in two areas; the downstream end of the large river bend near river km 71, and in the 500 metres upstream of the Second Split. Cobbles are present as both low and high banks, and distributed throughout the Zone.

Table 11. Distribution of bank materials in Zone 2

Bank Material	Percentage of Bank Length in Zone 2
Cobbles	8
Fine alluvial	76
Alluvial and cobbles and/or bedrock	9
Bedrock	5
Bedrock and cobbles	2

As in Zone 1, there is a prominent Plimsoll line throughout the zone, with virtually a total lack of vegetation between low water level and the Plimsoll line. Erosional features on banks are generally confined to the area between low and high water. The Plimsoll line varies between about 1.5 and 3 m, with higher levels associated with the bedrock constriction near river km 71 and upstream of the Splits.

5.3.1 Bedrock Banks

Zone 2 is largely underlain by dolomite rock (Attachment 6). Bedrock banks are similar in appearance to Zone 1, with retreat of the organosol common where high water level exceeds the height of bedrock. On higher bedrock banks, high water level is marked by the presence of mosses and ferns (Photo 15). Bedrock outcrops are commonly separated by alluvial 'pockets' that display a high level of erosion activity, and suggest that the bedrock promotes backwater and eddy effects.

5.3.2 Alluvial Banks

The sedimentology of the alluvial banks in this zone differ from Zone 1 with a higher proportion of fine-sand and silt sized material (<63µm) within the banks (Brook, 2000). Auger samples collected from near river km 71 contained the highest proportion of fine sand and silt of samples analysed from the entire study area, comprising up to 95% of the sample. Samples collected from near the downstream end of the Zone (km 69) contained relatively more medium sand. Mineralogically, the fine sand component of the samples collected from river km 71 contained 60 – 80% quartz, with 15 – 25% micas.

Similar to Zone 1, there were significant differences in the morphology and erosional features of banks supporting stands of tea tree as compared to those where tea tree was absent. The tea tree areas show signs of scour resulting in the exposure of individual tree roots, but little evidence of undercutting or piping, and slots and voids are absent. Large stands of tea tree are present in the 500 m downstream of the mouth of the Albert River, and in the middle of the Zone upstream of the start of bedrock outcrops. In the sands underlying the tea tree, there is a high density of fine roots, producing an inherent cohesion in the material. The presence of extensive fine-root networks in these sands is in sharp contrast to the sands associated with slot or void development and sediment flows, where coarse roots are present (even common) near the roof of the void, but decrease downslope. The tea tree banks are typically present in depositional areas (backwater between 5 266 400 mN, 410 300mE and 5 266 500 mN, 410 300mE) and as 'pockets' interspersed along banks where voids, slots and sediment flows are present (cf. between 5 266 400 mN, 410 150 mE; and 5 266 300 mN, 410 000 mE).

In the non-tea tree bearing alluvial banks there is widespread piping, 'slot' and void development, with sediment flows observed below many of these features during some power station shutdowns. Rilling is common on the lower banks. The characteristics of the voids and slots are similar to Zone 1, with generally low angle bank toes abutting steeply sloping void-back-walls beneath an organosol drape. Voids in this zone were the most extensive and largest documented within the entire study area, with a cavern capable of fitting several people identified near the Second Splits (Photo 16).

In addition to sediment flow deposits below voids and slots, saturated banks near km 71 were prone to plastic down-slope mass-movement, especially following disturbance such as investigators walking on the banks. Piezometer casings in the banks were tilted towards the river during the mass-movement, and several erosion pins were lost between site visits, presumably by falling into the river following downslope movement.

5.3.2.1 Tree Fall on Alluvial Banks

Both old (no green leaves or small branches present) and new fallen trees were common in the alluvial sections of this zone, as shown on the Zone 2 map in Attachment 7 (aerial photo comparisons). Very recent tree falls, occurring within the previous 24 hours, were observed on a number of the field excursions. A common tree fall pattern consisted of a large individual tree toppling down-slope towards the river, with smaller neighbouring trees taken out on the way down.

One large tree fall that occurred within 24 hours of power station shut down was extensively investigated on 6 March 2000, and the site was revisited on subsequent field trips. The large celery top pine was situated approximately 1 m above the high water level of the river. The bank had been visited prior to the tree fall and identified as an erosionally active area based on the presence of seepage erosion features. The initial scarp created by the tree fall (Photo 17) was delimited on one side by a large, seepage void, suggesting that the void contributed to the destabilisation of the bank. The initial scarp was subjected to additional undercutting during high flow in the Gordon, leading to additional tree collapse (Photo 18; Photo 19). The fallen trees were not mobilised by river flow, and the large woody debris was trapping and buttressing sediment derived from upslope processes as well as deposited from the river).

5.3.3 Alluvial Deposits Overlying Basal Cobbles

Many of the alluvial banks in this reach contain basal cobbles, of varying thickness overlain by medium to fine grained silty sands. Where river level exceeds the height of the cobbles, the over lying alluvial bank displays similar characteristics to alluvial banks lacking cobbles, with the difference that cobbles buttress the bank toe. In areas containing cobble banks higher than high water level, the cobble faces and overlying soils have a vertical profile (Photo 5, Photo 20). The faces of these exposures are typically well weathered and support vegetation above the high water mark. When landslips and slumps occur in these areas, they are characterised by the fresh exposure of cobbles and overlying soils, a deposit of cobbles at the toe of the slip, and re-colonisation of the overlying soils with ferns. Photo 21 shows an example of a slip in a high cobble bank in Zone 2 (left bank between 5 266 400 mN, 410 100 mE and 5 266 300 mN, 409 800 mE). Weathered vertical cobbles are evident on the left side of the photo, bordering the slip, and the initiation of revegetation is evident on the slip face above high water mark. During the course of the study year, additional slips occurred in this reach, Photo 81) with similar vegetation and cobble deposits along the toe, and high angle bank faces. Five landslips were documented during the field mapping exercise, with 3 of the 5 being relatively recent (fresh cobble and vegetation deposit at toe, little recolonisation of soils) and the remaining appearing older and partially revegetated.

5.3.4 Cobble bars

There are approximately 12 cobble bars present in Zone 2, with most bars composed primarily of rounded cobbles 5 – 8 cm in length. Larger cobbles, measuring approximately 18 to 30 cm are also common. Bars tend to be armoured, imbricated, with varying amounts of cementation on surfaces. Breaching of the cementation on the flanks of the bars and along the bar surface where channels have formed is common. Active head-cuts (incision of the downstream end of the bar) were observed on a few bars. These features are prominent on the bars immediately upstream of the Splits. Superimposed on the large cobbles are gravels and pebbles which are transported under the present flow regime. Vegetation is present on some of the bars, and shows signs of scour, with exposed tree roots common.

5.3.5 Change to River Channel Since Regulation

The air photos and field mapping demonstrate that tree fall in the middle Gordon River is most prominent on alluvial banks, with fewer fallen trees associated with cobble banks, and almost none on bedrock banks. Overall, the 1999 photos show a greater number of treefalls. Most of the individual fallen trees that are apparent in the 1974 photos are still present in the 1999 photos, indicating that the flow of the river is insufficient to transport these large trees down stream. In areas where there was considerable tree fall in 1974, there continues to be tree fall (cf. Zone 2 aerial photo comparison Attachment 7, between 409 200 mE, 4009 300 mE).

Retreat of the drip line has been documented in limited reaches of Zone 2 in the 1999 photos. These are indicated on the aerial photo interpretation (Attachment 7), and are typically confined to alluvial banks on one side of the river where bedrock, extensive cobble bars or backwater areas are found on the opposite bank. A notable exception to this is found in the ≈500 m section of the river between 409 200mE and 409 600mE presented in on the Zone 2 map (Attachment 7) where significant changes to the drip line have been noted on both banks.

Vegetation has retreated from the upstream end of some in-stream cobble bars due presumably to scour during high flow and inundation of soils and roots for extended periods (cf. Zone 2 between 5 266 400 mN and 5 266 400 mN; 409 600 mE and -409 700mE). Other vegetated bars show little difference in the aerial photos, although in the field, indications of scour in the root zone are evident. (Zone 2 bar between 5 266 500 nM and 5 266 600 mN; 407 900 mE and 408 000 mE).

Vegetation has increased in backwater areas that are inundated during high flow (cf. backwater near the two previously indicated islands, between 408 9900 mE, 409 100 mE). Vegetation has also increased in gorge areas above the main river channel, presumably due to the much lower incidence of very high flows in these narrow strictures (cf. 407 300 mE, 407 400 mE).

There has been no large scale change to the cobble bars in Zone 2 in terms of number or location. No new bars have emerged, and no bars have been lost since the initiation of power station operation. Differences between the two sets of photos are most pronounced at the upstream end of the section, where extension of bars at their downstream ends appears to be common. (Attachment 5, Zone 2).

Loss of bar material is limited to the upstream end of a broad bar just downstream of the 'pool' near the Albert River (between 5 266 300 mN and 5 266 400 mN), and to the apparent breaching of a bar immediately upstream of the Splits (between 408 000mE and 408 100 mE).

Due to the similarity in flow conditions during both sets of aerial photography, it is unlikely that these differences are attributable to water level differences between the two sets of photos. The uniformity with which the bars are elongated at the downstream end suggests deposition has occurred and the differences are real. The growth of bars at the upstream end of Zone 2 might also be the result of less efficient transport of sediment introduced by the Albert River through the system.

5.3.6 Confluence of Gordon and Albert Rivers

The confluence of the Albert River is shown in detail on the Zone 2 map in Attachment 7. The confluence is subject to power station induced river level fluctuations on the order of 2 metres, with power station on conditions leading to a back up of water within the Albert. The confluence is characterised by alluvial banks, with high (>4m) cobble banks approximately 100 m upstream on the left bank of the Albert R. Between the mouth of the river and the high cobble banks, the left bank of is part of the divide that separates the Albert from the Gordon. The banks show extensive evidence of scour, undercutting, tree fall and seepage erosion on the Albert River side (Photo 22). The bank materials appear similar in characteristics to the finer, micaceous sediments of the nearby km 71 site, although no sedimentological or mineralogical analyses have been completed. On the Gordon River side of the 'divide', the bank consists of a shallowly sloping sandy toe abutting a steeply sloping vegetated bank. The right bank of the Albert at the confluence is a low laying backwater area that is subject to deposition of fines.

The cobble banks in the Albert River show evidence of recent slip failures, with fresh surfaces exposed, collapsed vegetation and cobbles deposited at the bank toe (Photo 20). Precarious vegetation overhangs suggest additional collapse is imminent.

Opposite the cobble banks, the lower lying alluvial banks are undercut, and show evidence of seepage erosion. There is abundant both old and new tree fall along the banks. A small vegetated remnant of the left bank of the river showing signs of scour is present approximately 150 m upstream of the confluence (410160 mE, 5265930 mN), demonstrating the degree of erosion in the river (Photo 23).

The aerial photo comparison of the mouth and lower Albert River (Zone 2 map, Attachment 7) show major changes to the lower 500 m of the river. Above this no significant changes were identified, although tree overhang and shadow limited the comparisons.

In the lower 500 m, the channel has widened extensively, with increases in width of up to 30 m evident, equivalent to a 3-fold increase in channel width. The greatest widening is found at the mouth of the river, and upstream of the high vertical cobble bank (approx. 100 m upstream of confluence). The cobble banks have experienced less retreat overall than the adjacent upstream or downstream alluvial banks. Explanation of the processes creating this significant channel change at the mouth of the Albert River is provided in Section 6.1 *Planform Changes*.

5.3.7 Summary of Zone 2

In summary, Zone 2 is characterised by extensive exposures of alluvial banks that have been subjected to scour and seepage erosion. Tree fall is common, with many fallen trees immobilised since at least 1974. Numerous landslips in high cobble banks are present in the zone, and several occurred during the study period.

Despite the very active localised erosion and channel change processes documented, the river planform has not changed significantly in the past 25 years. In limited pockets, typically bounded by bedrock both upstream and downstream, bank retreat or vegetation colonisation has occurred. Although the planform of the river has not changed, the morphology of the bank faces has been significantly altered, with the loss of vegetation and subsequent scour and seepage erosion reducing the angle of the banks. The cobble bars in the upstream section of the Zone have grown appreciably, mostly at the downstream ends. Bank materials in Zone 2 are finer and more micaceous than in the other zones.

The lower Albert River has experienced significant channel widening of up to 30 m. Fine alluvial banks have undergone the greatest retreat, and show signs of scour and seepage erosion. Cobble banks have retreated relatively less than the alluvial banks.

5.4 The Splits

Dividing Zones 2 and 3 are the spectacular gorges known as The Splits and Snake Rapids. The approximately 2 km long reach is bedrock controlled, and the Gordon River drops about 20 m through the section. The area between the Splits is largely inaccessible even by helicopter, except for a small area near the confluence of Splits Creek that was visited and mapped. Note that, as stated in Section 4.2.1, because the gorges are predominantly bedrock and not prone to geomorphic change due to power station operations, the lack of access was not viewed as a limitation to this study.

The Plimsoll line was high in this area (3-4 m), due to the narrow bedrock (quartzite) controlled channel. Vegetation patterns on the bedrock resemble the upstream Zones, with no vegetation present below the high water mark, with a rapid transition to abundant vegetation.

The Splits Creek enters in a locally broader area, which coincides with a less resistant, highly weathered schistose strata. The Creek banks are alluvial, and the confluence is characterised by scour, seepage erosion features at high water level, and tree fall.

Snake Rapids, downstream of the First Split is also bedrock controlled, with vegetation present above a distinct high water mark. The Orange River enters the Gordon at the top of the rapids. Field observations of the Orange River have been limited due to the abundant tree fall and log jams near the mouth which are not evident on the 1974 aerial photos. The bed load of the river is characterised by angular cobbles. A small sand bar is present at the confluence and there is undercutting of the bank at the mouth of the river.

5.5 Zone 3: Downstream of Snake Rapids to confluence of Gordon and Denison Rivers (5 km)

Zone 3 consists of the 3.5 km long straight river reach between the end of Snake Rapids and the confluence of the Denison River. The grade of the River is lower in this Zone than in Zones 1 or 2, with a drop of about 2 m occurring over the reach.

Hydrologically, the system has been augmented by the inflow of the 60 km^2 Orange River catchment and pickup from the 14 km between the dam and the mouth of the river. Non-power station derived flow averages about 10% on an annual basis for this Zone, which is almost double that for Zone 2. The natural flow contribution can be about one-third of the total monthly flow during wet periods of low power station usage.

The river widens below Snake Rapids, and the Plimsoll line is generally lower and less pronounced than above the Splits.

Bank materials in the zone display greater variety over short distances than in the upstream zones. Stratigraphically the area appears to be bedrock (primarily limestone) overlain by cobbles and alluvium, which have been dissected to varying degrees. The abundant bedrock outcrops within the river suggest that much of the channel is bedrock controlled. Table 12 shows the distribution of bank materials in Zone 3.

Table 12. Distribution of bank materials in Zone 3

Bank Material	Percentage of Bank Length in Zone 3
Cobbles	6
Fine alluvial	44
Alluvial and cobbles and/or bedrock	5
Bedrock	44
Bedrock and cobbles	2

Bedrock vegetation patterns are unchanged from the upstream zones, with delineation created by the lack of vegetation.

Similar erosional features are present in the alluvial banks of this Zone (piping, sediment flows, undercutting, scour), however, where as in Zone 2, river reaches of 10s of metres in length were characterised by voids and seepage erosion, in Zone 3 these features are present as discreet occurrences that were easily mapped as bank point features rather than a widespread condition.

Vertical cobble banks tend to be weathered and well colonised with algae and mosses above high water level in contrast to the more recently exposed faces observed in Zone 2.

Cobble bars are less common, and characterised by bi-modal clast size distributions. Large (45 to 60 cm) angular clasts, are dispersed amongst smaller (3 – 20 cm) more rounded clasts. The large angular clasts appear to be derived from nearby limetsone or dolomite units (Photo 24). Similar to the upstream zones, sand and gravels are present. The bars are armoured, though not strongly imbricated. Cementation of the bank surfaces is not common. In areas where algae coatings are present, the bars appear to be stable.

The aerial photography comparison showed similar trends for Zone 3 as for the upstream zones, with decreased vegetation on low lying instream islands, and increased vegetation on bedrock outcrops above high water level, most notably in Snake Rapids.

The 1999 maps show a large increase in the number of fallen trees located near the mouth of the Orange River and downstream of Snake Rapids. The confluence of the Denison and Gordon Rivers has been modified, with erosion of banks and tree fall.

The two sets of photos suggest that the submerged portion of cobble bars have narrowed since flow regulation of the Gordon commenced.

5.5.1 Summary of Zone 3

Zone 3 is composed of approximately half alluvial banks and half bedrock banks and is characterised by similar erosion features as the upstream Zones 1 and 2, however the ‘scale’ of the features is diminished. Erosion features are more typically present as discrete features rather than extensive zones. The Plimsoll line is lower in this zone than upstream.

Tributary confluences appear to have undergone noticeable changes since 1974, with tree fall apparent downstream of the junction of the Orange River with the Gordon River.

5.6 Zones 4: Confluence of Denison and Gordon Rivers to Sunshine Gorge (5 km)

The 5 km reach below the confluence of the Denison River is designated as Zone 4, which terminates at the entrance to Sunshine Gorge. The Denison is a major tributary that greatly affects the hydrology of the area. An additional change to the river in this stretch is the presence of major outcrops of the Gordon Limestone forming extensive high cliffs along the river.

Hydrologically, the entrance of the Denison produces a major shift in the origin of flow in this section of the river, with about 30% of flow derived from unregulated sources on a yearly basis, a 3-fold increase as compared to Zone 3. This is close to pre-dam conditions, when about 34% of the flow in this section was derived from below the dam site, although of course the pattern of discharge has changed considerably (Figure 9 and Figure 11). On a seasonal basis, the contribution from non-power station sources exceeds the power station inflow during August – October, and contributes between one-third to one-half of the flow for an additional five months of the year.

The distribution of bank materials is presented in Table 13, which shows that there is a high incidence of cobbles or bedrock overlain by alluvium. Within short reaches of the river bank materials tend to vary frequently.

Table 13. Distribution of bank materials in Zone 4

Bank Material	Percentage of Bank Length in Zone 4
Cobbles	1
Fine alluvial	31
Alluvial and cobbles and/or bedrock	41
Bedrock	13
Bedrock and cobbles	13

This major hydrological change is reflected in both the Plimsoll line and distribution of erosion features. Whereas in Zones 1 and 2 the Plimsoll line is a very well defined feature and many erosion features are concentrated at the same level, in Zone 4 the high water mark is more diffuse, and erosional features are more widely distributed over the bank. The Plimsoll line generally varies between 1 and 2 m in height, and varies spatially due to a large number of bedrock controls.

Bedrock banks and outcrops display similar attributes as in the upstream zones, with no vegetation below high water level (Photo 25). Within the Gordon limestone at least one cave system has been identified which is affected by water levels in the Gordon River. A separate Basslink karst investigation (Deakin *et al*, 2001) has been completed and should be referred to for further information.

Surface samples from several alluvial banks in the zone contained predominantly fine to medium quartz rich sands, with a 5 – 10% micaceous component (Brook, 2000). Alluvial banks show evidence of undercutting, piping, scour, and seepage erosion although at a smaller scale and distributed over a range of heights rather than concentrated at the high water mark. Tea tree colonised banks and cobble bars show evidence of scour of the organosol, but no undercutting, slots or voids. Tree falls appear to be less common than in Zone 2. Although vegetation is sparse below the high water level, plants are present and limited recruitment was documented (Appendix 6 of this report series – Gordon River Riparian Vegetation Assessment (Davidson and Gibbons, 2001)).

There is a marked increase in the deposition of sands on point bars and in local backwater areas. A distinct pattern of deposition of sands and woody debris on point bars is first observed in this Zone, and persists for the remainder of the study area. At the start of an inside bend, the point bar tends to be moderate in slope, vegetated by tea tree above high water, devoid of woody debris and displays ripple marks in recently deposited sands. Downstream through the bend the amount of woody debris deposited on the toe of the bank increases in both size and abundance. The downstream end of the bend is characterised by large accumulations of large woody debris, and steeper alluvial banks showing greater erosional activity. Tea tree predominates above high water through most of the point bar, with a reduction towards the downstream, more active end.

High cobble banks are not common in this Zone, but where present show similar characteristics as in Zone 3. Recent landslips in the cobbles are not common, and the vertical bank faces appear weathered and are covered with mosses above high water. Cobbles are commonly found at the base of the alluvial banks, and a greater proportion of bank toes appear to be protected or buttressed by cobble deposits as compared to Zones 1 or 2.

Vegetation on cobble bars show signs of erosion in some places, but there is also recruitment evident on some bars. This is the first observation of recruitment of species in the study area, and is described in Appendix 6 of this report series (Davidson and Gibbons, 2001).

Cobble bars are characterised by rounded to sub-rounded material typically 3 – 30 cm in size, although angular cobbles up to 50 cm in size are present. The bars tend to be armoured, and slightly imbricated. Cementation is absent. On the crest of one bar an extant algal mat appears to be contributing to the stability of the bar. Sand and gravel deposits are common and vegetation is present on the higher portions of the bars.

The aerial photo comparison shows generally minor changes in Zone 4 between 1974 and 1999. The loss and gain of vegetation on bars and banks is minor compared to changes recorded upstream. An exception to this is on the lateral bar located at 402220 nE, 5272950 mN where a significant loss of vegetation has occurred. There has been an increase in tree fall on the right bank of the Gordon River downstream of the confluence with the Denison, whereas the 1974 photos indicate considerable tree fall on the opposite bank. Bank retreat has occurred in localised pockets, such as downstream of the Denison confluence (403750 mE, 5269625 mN).

The photos suggest that the submerged portions of the cobble bars have been narrowed. In the 1974 photos, large lateral lobes are shown that are absent in the 1999 photos. There have also been changes to the bar at the confluence of Harrison Creek, with a downstream migration of the creek's channel.

5.6.1 Summary of Zone 4

The hydrology of Zone 4 is significantly different from the upstream Zones due to the inflow of the Denison River. Evidence of seepage erosion and scour is present, but erosion features continue to decrease in size and occurrence with distance from the power station. This is the first zone where recruitment as well as erosion of vegetation is apparent on in stream islands below high water. Banks are devoid of vegetation between the low water level and the Plimsoll line, although the Plimsoll line is more diffuse in this zone than upstream.

The comparative aerial photo analysis indicated generally small scale changes between 1974 and 1999, with narrowing of the submerged portion of cobble bars a common feature. Changes to vegetation are generally less pronounced. Localised exceptions to this are downstream of the confluence of the Gordon and Denison Rivers where tree fall has been concentrated, and the significant loss of vegetation on one cobble bar upstream of Harrison Creek.

5.7 Zone 5: Olga R to Franklin River (14 km)

The longest and most distal geomorphic zone from the power station begins below Sunshine Gorge and Sharks Mouth Rapid and ends at the confluence with the Franklin River. The Olga River, a major tributary of the Gordon, enters between the end of Zone 4 and beginning of Zone 5, below Sunshine Gorge. Neither Sunshine Gorge nor the confluence of the Olga River were visited due to the lack of safe landing sites. The Sprent River, another large tributary enters approximately 5 km upstream of the Franklin River mouth.

Hydrologically, the input of 'natural' waters accounts for about 40% of the total flow on a yearly basis, and 9 out of the 12 months, non-power station derived flows contribute 30% or more of the total flow as measured at the Gordon above Franklin site.

The slope of the river is lower in this Zone, with a total drop of only a couple of metres over the 12 km stretch. The area between the Sprent and the Franklin is the steepest within the Zone. Plimsoll lines are generally lower in this zone, and more diffuse with distance downstream.

Aside from the bank mapping exercise, limited ground reconnaissance of Zone 5 was completed for this study. During the initial investigations, it was quickly recognised that there is a lower impact from power station operation on this section of the river, and given the limitations on access to the study area, the upstream zones were determined to be the highest priority for field investigation.

Zone 5 differs considerably from the upstream zones in that it is confined to the Gordon Limestone. Steep limestone cliffs with seeps border many river reaches, with dissolution features common (Photo 26). Bedrock outcrops at the base of alluvial deposits is also common. Similar to Zones 3 and 4, cobbles are present more commonly as beds (<1 m thick) underlying alluvial sands rather than as high vertical banks. A summary of the bank materials is presented in Table 14.

Table 14. Distribution of bank materials in Zone 5

Bank Material	Percentage of Bank Length in Zone 5
Cobbles	8
Fine alluvial	25
Alluvial and cobbles and/or bedrock	29
Bedrock	23
Bedrock and cobbles	15

The Sprent River delta, a geomporphic feature on the Tasmanian Geoconservation Database is located within this zone, and consists of large rounded boulders in a deltaic deposit at the mouth of the Sprent.

A diffuse Plimsoll line is present, throughout Zone 5, and although largely devoid of vegetation, the banks in this Zone support mosses and ferns below high water level in limited areas.

Alluvial banks are similar to Zone 4, in that erosional features are more limited in extent and distributed over a wider range of the bank. Depositional areas within Zone 5 contain muds as well as sand, which is not commonly present in Zones 1 - 3.

Cobble bars are less common in Zone 5, and were not systematically investigated except for the largest clast / painted bar analysis described in Section 6.2.

Small changes were found between the 1974 and 1999 aerial photographs. Unlike tributary confluences in the upstream zones, the Olga confluence showed little change. The mouth of the Sprent shows both the loss and gain of vegetation, and the high cliffs opposite the Sprent also show an increase in vegetation.

The in-stream bars have been modified similarly to Zone 4, with narrowing of the lateral lobes, and some loss or gain of vegetation.

5.7.1 Summary of Zone 5

Zone 5 is furthest from the power station, and the size and extent of erosional features on the alluvial banks is small compared to the most upstream zones. Most of Zone 5 has bedrock or cobble deposits along the bank toes with fine-alluvium overlying the stable deposits. The Plimsoll line is generally lower and more diffuse as compared to upstream zones and there is a greater occurrence of fine-mud deposits on the banks. In limited areas, ferns and mosses are present below the Plimsoll line. Few changes have occurred between 1974 and 1999 based on aerial photo comparisons.

5.8 Comparison of Middle Gordon River with the Denison and Franklin Rivers

An important component of these investigations was the identification and investigation of natural, unregulated rivers that could be used as analogues for the Middle Gordon River. The erosion features and processes in the unregulated tributary rivers of the Gordon River were used to help understand how the Middle Gordon River has responded to regulation. The Denison and Franklin Rivers were chosen for this exercise, as they are the largest tributaries of the Gordon, with catchment sizes of 664 km^2 and 1664 km^2 respectively. The Gordon River catchment above the confluence of the Franklin Rivers is 2981 km^2, so the Denison accounts for about 20% of the area. The Franklin catchment is about 50% of the size of the Gordon above the Franklin.

Both sub-catchments experience similar rainfall rates and patterns as the remaining Gordon catchment, and hydrographs from the rivers are similar in appearance to the Gordon prior to regulation, characterised by short high flow events occurring year round, although more common during winter. The underlying geology of the Denison River catchment is similar to the geology of the upstream study Zones 1 and 2, with the river bisecting the resistant quartzose ridges of the Prince of Wales and Nicholls Ranges. The underlying geology of the lower Franklin River is the Gordon Limestone, the same geological unit as underlying Zone 5.

Similar soils (Tarvydas, 1978) and vegetation (Appendix 6, (Davidson and Gibbons, 2001)) have been documented in the Gordon, Franklin and Denison catchments. All three rivers are generally confined within bedrock controlled channels characterised by rapids, gorges and falls.

Boat based reconnaissance of the Denison and Franklin Rivers was completed in July 2000 by the members of the geomorphology team who conducted the Gordon riverbank mapping. In the Franklin, two 2 – 3 km sections were investigated, one beginning at the confluence of the Jane and Franklin River; and the second covering the 3 km upstream of Big Fall. In the Denison, one 3 km river stretch was investigated immediately downstream of the confluence of the Maxwell and Denison Rivers. River flow was a low winter base flow, as there had been little recent rainfall. Additional helicopter based observations were made a various times during the study year, when access to the Franklin and Denison rivers was possible.

Differences and similarities in bank features were noted between the Franklin and Denison Rivers, as well as between the tributaries and the Gordon River. The Franklin River showed evidence of transporting medium to coarse sand, with accumulations on bars and banks common. Sediment deposits in the Denison were much finer grained with mud drapes common in depositional environments. The accumulation of abundant organic material, mainly tree litter, accompanied sediment deposition in both rivers. Both tributaries showed evidence of high water at a range of levels on the banks (undercutting, slots, voids).

Visually the most striking difference between the tributaries and the Gordon River is the presence of vegetation to low water level in the tributaries. Mosses and ferns were extremely common in the riparian zone, covering the banks, woody debris and trunks of trees (Photo 27, Photo 28). Only high-energy environments, such as the toes of cobble point bars, or environments experiencing considerable deposition, such as some inside bends, did not support mosses and ferns to the water's edge. In these areas, the floral community was present a short distance upslope (Photo 29). Vertical cobble banks were also colonised by mosses in the tributaries (Photo 30).

The river banks of the tributaries commonly contain mud deposits and accumulations of organic material. A notable environment for the accumulation of material was amongst tea trees, where the roots appeared to be efficient at trapping material.

Tree fall and the occurrence of large woody debris in and on the banks of the tributaries is very common in the Franklin and Denison Rivers (Photo 31). Large woody debris is a common component of the banks, providing structural support, trapping sediments and creating small 'terraces' near the rivers' edge. The presence of the large woody debris and multi-generational Huon Pines on the river's edge is consistent with the channel stability processes documented in the Stanley R (Nanson, *et al.,* 1995), and suggests long-term channel stability of the rivers.

The erosional features observed on the tributary banks were the same as those documented in the middle Gordon River; undercutting, scour, seepage erosion, and tree fall. Undercuttting was observed at a range of heights on the tributary banks, with the presence of vegetation on the scarps of undercuts suggesting many of the features were not recent (Photo 28). Cohesive organosols created voids in some recently undercut areas, and sediment flows were apparent over a range of heights on the banks. In the Denison and Franklin rivers, these common erosional features were distributed over a height range of several metres on the banks. Downslope of voids or undercuts, the bank toe was vegetated with mosses and ferns.

The abundance and size of erosional features appeared to be lower in the tributaries, although this is a qualitative judgement, and zones of extensive disturbance were present in the tributaries. Major disturbances were observed at the confluence of the Denison and Maxwell Rivers where there was extensive undercutting, bank collapse and seepage erosion, and in the Franklin River where a large tree fall had exposed the bank to undercutting, and scour, creating large voids (Photo 32 and Photo 33).

Comparison of the Middle Gordon River with the unregulated tributaries provided good insights about which Gordon River bank characteristics have been affected by flow regulation.

Denudation of the lower bank in the Gordon River, between low water and the Plimsoll, line is a prominent difference between the tributaries and the Middle Gordon. Mosses and ferns are present, though not common in Zone 4, and increase in occurrence downstream through Zone 5 (Photo 34). These Zones generally have a lower, less pronounced Plimsoll line, and the unvegetated bank toes resemble some of the banks in the Denison River (compare Photo 29 with Photo 35).

The lack of mud and accumulations of organic matter on the banks is another major difference between the Gordon and tributaries. The Gordon banks have a 'swept clean' appearance, whereas the tributary banks do not. Tea tree environments in the Gordon are characterised by exposed tree roots due to scour, a lack of mosses, the presence of adventitious roots (able to extract oxygen from water and caused by prolonged inundation), and lack of deposited material between roots. This is in stark contrast to the depositional environments associated with these trees in the tributaries.

Similar erosional features are present in the Middle Gordon and tributaries. A major difference, however, is the distribution and abundance of these features on the banks. In the Gordon, active undercutting and seepage erosion features are confined to and concentrated at the power station controlled high water level. In the tributaries, these features occur over a wide area of the bank. The tributaries and Gordon River Zones 4 and 5 had similarities in terms of the size of undercuts slots or voids, although the features in the Gordon have a more constrained distribution over the bank.

Similar 'relict' erosion features are present above present power station controlled high water level in the Gordon River, suggesting that similar processes operated in the Gordon prior to regulation over a range of high water levels. For example, the undercutting shown in Photo 36 is located at Sharks Mouth rapids (below the Olga R) approximately 7 m above present low water level.

In Zone 2 of the Gordon, tree fall is much more common than in the tributaries (qualitative assessment), but downstream of the Denison the density of tree fall is similar to the tributaries (qualitative assessment), and has not increased over the river as whole since regulation, based on aerial photo comparison, with the exception of a few localised pockets that tend to be associated with tributary confluences. Large woody debris in both the tributaries and Gordon is common and appears to play similar roles in the buttressing of banks.

5.9 Summary of Existing Geomorphic Condition in the Middle Gordon River

The following summary points can be made on the geomorphic condition of the Middle Gordon River based on the field observations and comparative aerial photo analysis.

- Bank materials exert a primary control on bank morphology in the Middle Gordon River, with alluvial banks more susceptible to modification than the bedrock or cobble banks.
- Bank toes and lower bank faces are devoid of vegetation in the upstream zones of the study area. In the lower Zones 4 and 5, there is a gradual reappearance of vegetation on the bank faces. This is in stark contrast with unregulated tributaries where the vast majority of entire bank faces are vegetated to low water level.
- Alluvial banks in the Middle Gordon River have been modified through scour and seepage erosion. Undercutting and sediment flows are concentrated and generally confined to the high water level of the regulated flow, whereas the bank toes show signs of scour. This is a marked difference between the Gordon River and tributaries, where erosional features are distributed over a range of bank heights.
- Erosional features are more common, more extensive, and more 'extreme' in Gordon River Zones 1 and 2 where flow from the power station dominates total flow and water level fluctuations are greatest. There is a gradual decrease in occurrence and 'intensity' of erosional features in the Gordon River with distance downstream. A major change occurs below the confluence with the Denison River where unregulated flow becomes a major component of total flow.
- Banks vegetated with tea tree, which have the ability to withstand extended periods of inundation have generally not been affected by seepage erosion due to the stability provided by the root system, but scour of the roots is widespread. In comparison, tea tree stands in tributary streams are typically depositional environments, with fine sediments and organic material trapped by the roots.
- Tree fall is common on banks showing seepage erosion features, and is widespread in Zone 2.
- Vertical cobble banks are prone to slip failures that retain the vertical bank slope.
- Overall, the impacts of flow regulation appear to decrease with increasing distance from the power station as the proportion of regulated flow to total flow diminishes and water level fluctuations associated with power station operation decrease.

The following Sections (6, 7 and 8) discuss pre-regulation and post-regulation erosional processes and rates, for the river bed, cobble bars and bedrock banks (Section 6), alluvial banks (Section 7) and finally for cobble banks (Section 8).

6 CURRENT PROCESSES AND RATES – RIVER BED, COBBLE BARS AND BEDROCK BANKS

Section 5 provided a description of the present geomorphic condition of the Gordon River. The aim of this section is to synthesise the hydrological information (Section 2.5) with the results of the field investigations and discuss the major geomorphological processes presently controlling the bed, bars and bedrock banks of the Gordon River. The section is divided into four sub-sections, and begins with a discussion of planform changes in the study area. Section 6.2 discusses processes affecting the cobble bars and section 6.4 contains a synthesis of what is known about the bed of the Gordon River. Bedrock river banks are discussed in Section 6.4. The next two major sections (Sections 7 and 8) will consider current processes and rates for alluvial sand and cobble bank materials.

6.1 Planform Changes

This discussion focuses on planform changes in the middle Gordon River since the implementation of the Gordon River Power scheme, utilising the results from the aerial photo comparison and field observations, and is intended to provide an overview of recent (last 25 years) changes only. The evolution of the Gordon River in geological time is beyond the scope of this report.

The comparative aerial photo interpretation demonstrates that in the past 25 years there have not been large scale changes to the planform of the middle Gordon River, with changes limited to apparent narrowing or widening of the drip line in limited areas, and minor changes to the channel near some cobble bars (Attachment 7).

Based on the results of the bank material mapping exercise, it is not surprising that the Gordon River channel appears to be very stable. Approximately 34% of the riverbanks in the study area are composed of bedrock or bedrock overlain by cobbles, with another 30% of the banks being alluvial deposits underlain by bedrock or cobbles. These resistant banks constrain channel changes over the time period examined. Alluvial banks make up about 36% of the banks in the study area, however, with the exception of Zone 2, the alluvial banks generally occur as short pockets between bedrock controlled reaches. Although changes have occurred within some of these pockets, the bedrock controls dictate the planform of the river.

Narrowing of the drip lines is largely confined to bedrock banks that exceed the Plimsoll line in height and is the result of the colonisation of banks by vegetation down to the present, constant, high water level. Zone 1, the Splits, Snake Rapid, Sprent River and Sunshine Gorge are areas where this process is common. Drip lines have also narrowed in bank areas adjacent to cobble bars (cf. Zone 2), where a reduction in maximum river flows has allowed the expansion of vegetation. Neither of these processes has affected the river channel, as they are confined to the banks above the present high water level.

A comparison of drip lines in alluvial areas suggests that channel widening has occurred in limited stretches of Zone 2, and in few instances, in the downstream alluvial reaches of Zone 1. In Zone 2, approximately 40 occurrences of widening of the drip line were deemed to be ‘significant’ as defined in the aerial photo analysis (a difference between the 2 aerial photo data sets was evident because of a change in terrain). Most of these affected areas were less than about 50 m in length with a retreat in drip lines of up to 10 m. If an average length of 25 m is used as an estimate, then the drip line on 1000 m of river bank have been significantly altered in the past 25 years in Zone 2. This is equivalent to 10% of the mapped banks in Zone 2, or 1% of the entire study area. Tree fall commonly accompanies these areas. Field observations (Attachment 6) indicate that these zones are generally steep banks that show evidence of undercutting, scour and tree fall. Slip failures are apparent on vertical cobble bars.

The aerial photos do not indicate preferential erosion of outside bend banks, but rather channel widening along generally straight reaches (see Zone 2 Map, Attachment 7). Natural meander migration rates are believed to be exceedingly low in Southwest Tasmania (Nanson, *et al.*, 1995) and the aerial photo analyses shows no evidence to the contrary, although the short 25 year timescale must be recognised as a limitation of this comparison.

The Albert River displays considerable change with channel widening evident for several hundred meters upstream from the mouth. The alluvial sections are most affected, with the vertical cobble banks appearing to be more resistant (Attachment 7, Zone 2 map). Field observations suggest that the channel widening has been caused largely by backwater effects associated with operation of the Gordon Power station. The lower reaches of the Albert are inundated during power station ‘on’ conditions, and subject to rapid drawdown during power station shut-downs, or reduction in power output, similar to the Gordon River. This leads to notching and undercutting at the constant high water level, and seepage erosion on saturated banks where vegetation has been lost, similar to the processes occurring in the mainstem of the Gordon (Photo 22).

Additional modification of the Albert is linked to the decoupling of flow regimes in the Gordon and Albert River. Historically, when the Albert was in flood, the Gordon would also be in flood and both rivers would experience high water levels and high current velocities at the same time. The Gordon would provide some back-water effects to the Albert near its mouth. Now, flooding in the Albert either coincides with power station ‘on’, or power station ‘off’, and never with a Gordon River flood. During power station ‘off’ periods, the base level of the Gordon will be lower than under previous flood conditions, and the lower Albert will have greater flood energy slope, because of the absence of backwater effects. During power station ‘on’ storm events, the situation may be similar if the Albert flood is greater than a 1 in six-month flood event (max flow from power station is equivalent to 1 in 6 month event pre-dam flood). Although additional hydrological analyses of pre-dam flood events in the Albert and Gordon Rivers would be required to quantify the mechanisms leading to the extensive channel widening, it is evident that a combination of seepage erosion and changes to the hydrograph of the lower Albert have had significant effects on the river.

The mouths of some other creeks and rivers (creek upstream of the Splits on south bank; Orange R; Splits Cr) that are subject to inundation during power station ‘on’ have similar attributes to the Albert River mouth, although on a much smaller scale. No upstream investigations have been completed in these creeks.

In summary, the planform of the Gordon River has not changed significantly in the 25 years between 1974 and 1999. Small changes have occurred on some alluvial banks, where retreat of the drip line and tree fall indicate channel widening. These changes are most common in Zones 2 of the study area. The lower Albert River has undergone significant channel widening.

6.2 Cobble Bar Processes

The comparative aerial photo analysis indicates that the location and sub-aerial exposure of existing cobble bars at low water has not been altered in the Middle Gordon River between 1975 and 1999, and that one new bar has been deposited during the past 25 years in Zone 1. Changes to the bars present in 1974 have been generally limited to the submerged portion of the bars which have developed a more ‘streamlined’ shape, with a narrowing of the wide central portion of the bar and sometimes a loss of lobes extending from the bar into the channel (Attachment 7). In some instances, most notably in Zone 2 downstream of the Albert River the downstream end has been extended through deposition and or re-shaping. This deposition is likely to be related to sediment supply from the Albert River.

The new cobble bar that has been deposited is located in Zone 1, downstream of a long, steep bedrock section. The bar is atypical of the bars in the area, reflecting post-dam deposition. Its placement and composition suggests that the sediment is derived from the catchment below the power station, with deposition occurring in the first quiescent pool in the Middle Gordon River.

In general, the surfaces of the cobble bars in the study area are armoured (river flow has winnowed away smaller material, leaving behind large clasts that 'trap' finer material below, Photo 37), have varying degrees of imbrication (alignment of long-axis of cobbles on surface of bar in a downstream direction, Photo 38) and in Zones 1 and 2, tend to be cemented (Photo 39).

Where the crests of bars exceed the current power station controlled high water level, colonisation by mosses and larger vegetation has occurred (Photo 14), and the bar surface is stable.

On bar surfaces below the level of power station controlled high water, bed-load transport is the predominant process acting on the bar surface, and in general the surfaces are stable. The topic of bed-load transport is discussed in more detail in the next section. An exception to this is on the cemented bar surfaces located in Zones 1 and 2, where cemented surfaces have been breached and channels have been incised (Photo 40), and in some cases, head-cuts have formed.

In contrast to the bar surfaces, the flanks and submerged portions of the cobble bars do not appear to be immobile. The aerial photo comparison shows a narrowing, and in some cases an elongation of the submerged portion of the bars. The 1974 photos commonly showed lateral rounded lobes on the bars, which are lacking in the 1999 photos. Field observations also support more activity along the flanks of the bars. No algal coatings were apparent on the margins of most bars, and at several sites in Zones 1 and 2, the movement of cobbles along the channel margin has lead to undercutting of the cemented bar surfaces (Photo 39, Photo 41).

6.2.1 River Bed Processes

Bed materials in the middle Gordon River were investigated as part of the habitat assessment for the instream biota project (Appendix 7 of this report series – Gordon River Macroinvertebrate and Aquatic Mammal Assessment (Davies and Cook, 2001)). Davies and Cook (2001) found that below the Denison River and particularly below the Olga River, the middle Gordon is composed of long reaches of open water with a fairly uniform cobble – boulder substrate, with sand deposits lateral to the channel. Bands and bars of bedrock form short rapids. Above the Denison, the substrate is similar, with an increase in boulder and cobble rapids (Davies and Cook, 2001). The common features of a cobble substrate with lateral sand deposits as expressed on a point bar are shown in Photo 42.

No systematic investigation of the Gordon River bed was completed as part of the geomorphology investigations. However, observations made while wading in the river during the extensive field work, support the following characteristics. The bed of the river is mobile, as evidenced by the frequent rolling of cobbles under foot when wading in the river under low flow. Sands are trapped beneath the cobble surface layer, as small sand plumes are visible when the bed is disturbed.

The infiltration of sands into void spaces of cobble bars has been identified as an important process in some rivers (Beschta and Jackson, 1979; Petts, 1988; Sear, 1993), that can lead to a loss of macroinvertebrate habitat. The 'locked' and cemented nature of many of the bar surfaces in the study (especially in the upstream zones) area result in a scarcity of void spaces on the bars. This process is not believed to be significant in the Gordon. The investigations into instream-biota in the Gordon River did not identify this processes as significant in the study area (P. Davies, pers. com).

Cobble bar surfaces were used to investigate bedload transport in the Middle Gordon River. In December 1999, the 20 largest clasts present on the surface of cobble bars were measured as an indication of the maximum size of bedload historically transported by the river. At the same time, lines were painted perpendicular to river flow direction on some of the same cobble bars. In March 2000, after 75 days of high power station usage (Figure 19) the bar surfaces downstream of the painted lines were searched for painted clasts. The size and distance of any painted material recovered was recorded (Zones 2 – 4). This provided an indication of what size material the river system is presently capable of transporting.

The painted bar experiment in Zone 5 was not revisited until September 2000, reflecting a much longer time period making direct comparison of the results with the other sites difficult. Results from the two investigations are presented in Table 15, and Figure 20.

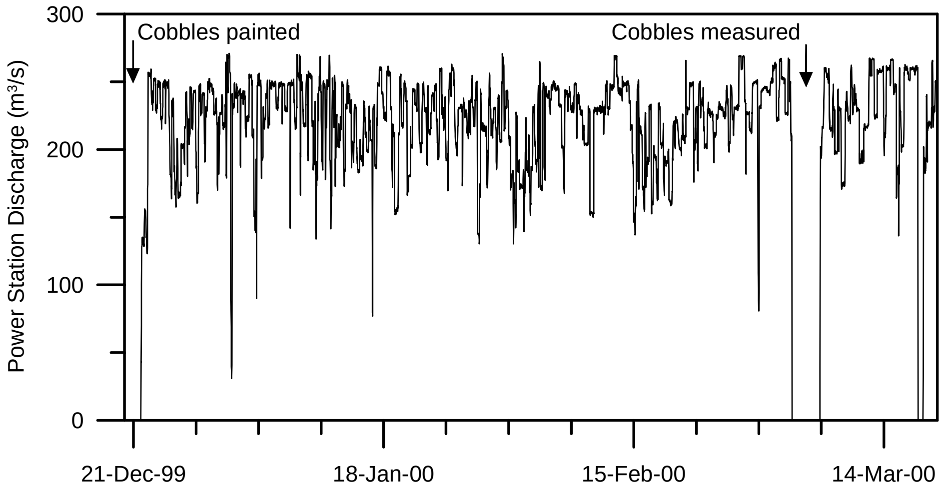


Figure 19. Power station discharge during painted cobble experiment

Although the bars were exposed to 75 days of high flow, Figure 19 shows that the entire period consisted of one long power station 'on' event, with flows generally fluctuating between 150 m^3/s and 250 m^3/s.

Table 15. Comparison of clasts mobilised before and after flow regulation.

Zone	Average/Median length of B-axis of mobile material	
	Pre-dam (Largest clasts on bars)	Post-dam (Mobilised by p/s flow)
2	27.6 (u/s Splits)*/25.8 cm	2.48/2.24 cm
3	28.5/26.0 cm	3.85/4.16 cm
4	18.5/11.7 cm	2.36/2.17 cm

*5 other cobble bars from Zone 2 ranged in average B-length axes of 11.3 cm – 28.5 cm.

The intermediate axis of the clasts (B-axis) is used for comparison in this exercise. The measurements show a large difference between the largest clasts present on the bars and the size of material currently mobilised under power station 'on' conditions. Because the vast majority of flow in Zones 1 and 2 is controlled by the power station, the difference between the two sets of measurements presumably reflects pre-dam / post-dam differences in high flows. Whereas the river transported clasts with B-axes greater than 25 cm in Zones 1 – 3 prior to regulation, maximum power station flow is now mobilising material generally <5 cm in the B-dimension. This suggests that the bed of the river, and surfaces of many cobble bars, are not mobile under regulated flow.

The painted cobble results from Zone 2 (Figure 20) show a rough trend of increased distance traveled with decreasing clast size. Photo 43 shows one of the painted lines in Zone 2, and demonstrates the size range of material that is mobile (flow is towards the right) and immobile under present flow conditions. Shadow deposits composed of sand and gravels deposited downstream of large cobbles and boulders are common on the bar. The larger clasts on the bar are immobile under the present power station flow conditions.

A qualitative comparison of the graphs for Zones 2 – 4 suggests that the bar in Zone 3 had larger material moving greater distances than the other sites. This bar is situated 200 m below the steep Snake rapids, and 1 km below the entrance of the Orange River, a source of bed load. Photo 44 and Photo 45 show the general character of the bar and a painted line at the end of the experiment, providing an indication of the quantity and size of clasts mobilised during the experiment. The bar consists of mobile small platy cobbles and immobile large sub-angular boulders. Gravels and sands are present as shadow deposits (lower right of photo). Photo 46 shows the movement and partial burial of an individual clast (near calipers) relative to the painted line (upper right).

The painted lines in Zone 4 were placed on two very different environments of the cobble bar (location at 5272200 mN; 402350 mE; Photo 47, Photo 48). The 'inner' bar is on a gently upward sloping area with the crest of the island between it and the main river flow. The 'outer' bar, is located downstream of the vegetated portion of the island, on the flank facing the main channel of the river. The inner bar site showed less than 1 m movement of material compared to the outer bar where larger clasts moved up to 10 m. Photo 49 is a close-up of one of the inner bar lines at the conclusion of the experiments, showing movement of pebbles and deposition of sands. There is a coating of dead algae on the larger cobbles.

The outer bar painted line was almost indistinguishable at the end of the 75 day period due to the deposition of sands on the bar (Photo 50). The sands were not evident at the beginning of the exercise (Photo 48) and may be related to the very high discharge from the power station between December and March as compared to the several months prior to December.

The results from Zone 5 reflect 9 months of variable river flows (cf Figure 15; hydrology during study year) and a greater number of events as compared to other sites. Photo 51 shows the general nature of the bar and the location of the painted lines (1 red, 2 faint yellow ones beyond red one) in December 1999. Photo 52 shows the remnant of line in September 2000 and some of the larger material that has moved short distances over the nine-month period. The graphs in Figure 20 indicate that the size of the transported material is greater than at any of the other sites (note y-axis scale is greater for this plot), and the photos show a lack of small gravel and sand on the bar. This site was the most distal bar investigated, and reflects the greatest input of unregulated flow. Between the initiation of the painted bar exercise and the final measurements in September 2000, several high flow events occurred, most notably one in the beginning of May 2000. These higher flows are presumably responsible for the movement of larger material. This result suggests that the mobility of the bed increases with distance from the power station as the contribution of unregulated flow increases.

In the Middle Gordon River, there was a distinct lack of fine material (muds) deposited on the bars and banks of the rivers during power station shutdowns. The presence of muds increased with distance downstream of the power station, but large mud banks appeared to be confined to Zone 5. This was in major contrast to observations made in the Franklin and Denison Rivers, where a veneer of mud coated most banks and many plants in the riparian zone.

The lack of fines deposition in the Middle Gordon is probably partially due to sediment trapping in Lake Gordon, but is likely to also be caused by the decoupling of the sediment supply from transport in the river through regulation of flow. During the long power station shutdown in September – October 2000, mud deposits were present on riverbanks following rainfall events indicating that this material is delivered to the Gordon, but its deposition is prevented by the regulated flow regime. A similar situation was observed with the deposition of organic material on the banks. Even during the first two weeks of power station shutdown, considerable leaf litter was deposited in the riparian zone (Photo 53).

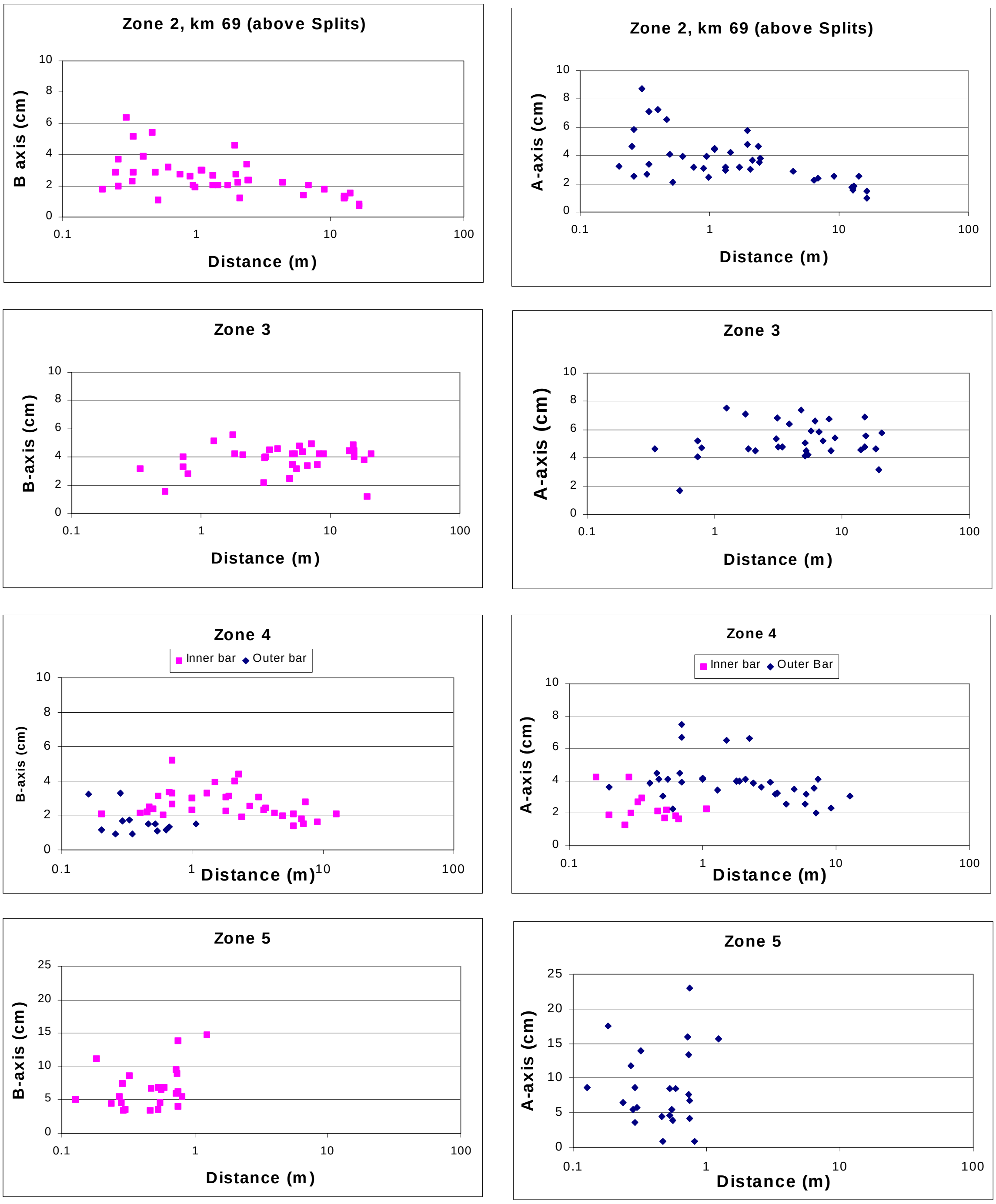


Figure 20. B-axis length and distance transported of material mobilised during power station operation. Zones 2 – 5 measured in March 2000 after approximately 80 days of power station operation, Zone 5 (note change in y-axis) measured in September 2000, after approximately 280 days.

In summary, bedload transport in the Middle Gordon River upstream of Sunshine Gorge is largely limited to sand and gravel under the present flow regime. The armoured bed and cobble bar surfaces are generally stable, as the flow is insufficient to move the large surface clasts. As input from unregulated tributaries increases leading to higher peak flows, the size of bedload material transported also increases.

6.3 Summary of River Bed and Cobble Bars

The observations and experimental results from these investigations suggest that flow regulation of the Gordon River has lead to the following changes to the river bed and cobble bars in the study area:

- The number and location of cobble bars in the study year has not altered between 1974 and 1999, with the exception of one new bar being deposited in Zone 1;
- Bar crests and surfaces above the present high water level are immobile, and have been colonised by vegetation;
- Bar surfaces that are inundated at high water are largely immobile, and characterised by algal coating, cementation, armouring and imbrication;
- Some cobble bars in Zones 1 and 2 are being incised by the formation of channels, and head cutting is occurring at the downstream end of several bars;
- The flanks and submerged portion of bars are active, and have been modified between 1974 and 1999, with a narrowing of bars due to the loss of lateral lobes;
- The reduction in high flows due to flow regulation has greatly reduced the size of bed load transported under the present high flow conditions;
- The present bed load of the river is limited to predominantly sand, gravels, and small platy cobbles; and
- The discharge from the power station may be a factor in the supply of sand to the river, with higher water levels resulting in greater sand transport.

6.4 Summary of Bedrock Banks

The middle Gordon River flows through a number of distinct geological units, and the river channel is commonly bedrock controlled, ranging from riffles, to rapids to major gorges. The extent of bedrock exposures along the banks of the middle Gordon River is estimated to be 44%, with approximately half of the bedrock exposures associated with gorges and rapids extending up to several kilometres, and the other half occurring as outcrops with the ‘zones’. Examination of much of the bedrock river channel has been limited to aerial reconnaissance due to difficulties of riverine access. Areas such as the 1500 m immediately below the power station, Abel Gorge, the Second and First Splits, Sunshine Gorge and Snake Rapids are all largely inaccessible by boat, chopper or foot. The presence and status of karst bedrock in the study area is described in Appendix 5 of this report series (Deakin *et al*, 2001).

The typical appearance of bedrock riverbanks and mid-stream outcrops is clean, sometimes polished rock exposed up to the high water mark with sparse to dense vegetation present above this point. Mid-river bedrock outcrops that lie below the high water mark, such as areas above Abel Gorge (Zone 1) and Snake Rapids (Zone 3) are devoid of vegetation (Photo 8).

Changes in the rate of bedrock erosion through physical erosion or chemical weathering is beyond the scope of this investigation, as it is unlikely to be related to flow regulation at a discernible scale.

Bedrock banks in nearby rivers such as the Denison and Franklin typically have vegetation and soils present in the riparian zone of the bank. This suggests that regulated flow has resulted in the loss of vegetation, especially mosses and ferns up to the Plimsoll line in the Middle Gordon. Davidson and Gibson (2000) have suggested both rotting of roots and inundation resulting in the loss of ability to photosynthesise as contributors to the denudation. Scour during high water levels results in the loss of root-mat related soil cohesion.

The aerial photo comparison has shown that there has been a loss of vegetation below high water level, and an increase in vegetation above the present Plimsoll line. The vegetation team has documented a narrowing of the riparian zone in the middle Gordon as compared to tributary streams, with denudation affecting the lower riparian zone and encroachment by rainforest species accounting for the reduction of the upper riparian zone (N. Davidson, pers. com.).

7 CURRENT PROCESSES AND RATES - ALLUVIAL SAND BANKS

This chapter summarises common features on sandy alluvial banks (Section 7.1), and discusses erosional processes (Section 7.2), and stabilising factors (Section 7.3) affecting the banks. A summary of what is known about the rates of processes affecting sandy alluvial banks is presented in Section 7.4, with a final synthesis of the present working hypothesis on sandy alluvial bank instability and final summary in Sections 7.5 and 7.6, respectively.

It is estimated that about 35% percent of the study area consists of sandy alluvial banks, with the most continuous stretches located in Zone 2 (76% of Zone 2). 'Composite' banks, that is cobbles overlain by sands are estimated to account for about 10% of the study area. Refer to Section 5 for a more detailed description of the riverbanks.

7.1 Summary of Sand Bank Features

A description of common erosional features on fine alluvial banks and discussion of seepage erosion is contained in Section 5.1. This section provides a brief summary of that material, and begins to relate the features to flow conditions in the river.

A typical profile of a sand bank several meters back from the water's edge is presented in Photo 54. An organosol overlies a zone of white to grey sands which grades into the dominant unit, an iron-rich (orange) sand. A likely explanation for this relationship is the *in situ* chemical leaching of iron staining from the sands immediately below the vegetation layer, due to the presence of organic acids derived from the vegetation.

Photo 55 and Photo 56 show additional examples of these sandy alluvial riverbanks, with white sandy shallowly sloping bank 'toes' protruding into the Gordon River at low flow. The bank below high water level is devoid of live vegetation, though woody debris is common. Below high water level, the banks have a 'swept clean' appearance, with no accumulations of small organic matter, or mud.

Near the Plimsoll line, the white to grey sands are overlain by a truncated fibrous organosol. At the contact between the units, the organosol is partially eroded from below, and 'slots' and 'voids' are created. The draping of the peat over the sands is attributable to the continued strength of the remnant root-mat, even after loss of overlying vegetation. With distance from the power station, the Plimsoll line and the contact between the organosol and underlying sands becomes less sharp, due to greater variability in water levels and presence of vegetation below high water level.

Within voids, the roof consists of the degraded organosol – sand contact, with extensive exposure of plant roots of varying sizes. Sediment spalling from the roof is common during low water levels. Void floors tend to be similar in slope to the bank toe down-slope of the void, generally <16°. The back walls are sub-vertical, have exposed plant roots near the roof, and the orange colour of the steeply exposed material indicates that the void has intruded the soil profile below the leached layer (Photo 54). Pipes sometimes extend beyond the back wall, and pipe lengths in excess of 2 m have been measured. Foam lines indicative of high water were observed over a range of heights on the steeply sloping back wall of the voids (Photo 57a&b),

Following periods when all three turbines in the power station have been in use, producing the highest power station induced water levels, sediment flows are common on the bank toe downslope of the voids, slots or pipes (Photo 58). These deposits have been recently deposited (since the last fall in river level), are derived from within the void/slot/pipes and are commonly 'softer' and wetter than the underlying stable white sands. They are the results of liquefaction of the bank face following a reduction in river level. Frequently the deposited sands are orange in colour (derived from the unleached unit of the soil profile) and the contrast between the deposit and white sand toe causes the deposits to be visually prominent. Similar depositional features consisting of white sands are also present (Photo 59).

Alluvial banks lacking seepage erosion features tend to be colonised by tea tree, with trunks and roots (though no green leaves) extending below the Plimsoll line. These banks are characterised by exposed tree roots, with no mosses or ferns growing on the tree trunks, and no fine or organic material deposited within the tree roots as is common in the tributaries.

Another common feature of the basal sand unit is the presence of rills, which occur on the sediment flows, down slope of the sediment flows, and on banks devoid of sediment flows. These erosional features are associated with the movement of water out of the bank and down the face of the bank, either by discharge of water from the base of the peat, or through the riverbank as seepage.

These erosional features were found to be widespread in geomorphic Zones 1 – 3, correlating with the region displaying the most prominent Plimsoll line. The base of the exposed and eroded organosol appears to coincide with the highest high water indications on the banks, caused by the operation of 3 turbines in the power station, and can vary in height along a reach as the Plimsoll line varies. In Zone 2, where the features are most common, it is estimated that 25% of the banks show evidence of slots, voids or sediment flows.

Generally, the extent and size of the features decreases with distance from the power station, with a notable decrease below the confluence of the Gordon and Denison Rivers, and another below Sunshine Gorge and confluence of the Olga. Aspects of the dewatering structures (pipes, small sediment flows, eroded organosol – sand contact) are also present above the power station induced high water mark along the Gordon below the Denison and in the Franklin and Denison Rivers. It is likely that they are a characteristic of the contact between underlying sands and overlying organosols. From a comparison of these areas, it is apparent that the upstream features are confined and intensified at the present high water mark, whereas downstream and in tributaries, they occur over a greater range of stage height. Photo 60 and Photo 61 compare seepage features in the Franklin and Gordon Rivers.

These observations are consistent with the range of river levels documented throughout the study area based on observations of the height of the Plimsoll line. Close to the power station where little non-power station derived flow is present, high water levels are the most constant, and erosional features are concentrated and focussed along the high water mark. Below the Denison, where for nine months of the year the 'natural' catchment contributes greater than one-third of the flow, there is a greater variability in river level height reducing the energy focused at one level of the banks.

No evidence of overland flow on the organosols was found in the study area. The high permeability of the unit results in the rapid transfer of water into the underlying sand layer thus preventing overland flow.

Backwater channels are common on alluvial banks and were investigated and well described by the karst team (Deakin *et al*, 2001). These are important geomorphic features close to the river, but it was determined in these investigations that they are not influenced by power station operation so were not investigated further. Although the backwater channels were commonly located in areas displaying seepage erosion features, they were also common in areas devoid of seepage features, and it was concluded by the investigators that there is no linkage between the channels and bank face seepage erosion.

7.2 Processes of Erosion in Alluvial Banks

7.2.1 Pre-flow Regulation Processes

Prior to flow regulation in the Middle Gordon River, erosion processes in the river would have been similar to those presently observed in the Denison and Franklin Rivers. Photographs of the Middle Gordon River prior to the initiation of water release and regulated flow from the Gordon Power Station show riverbank vegetation between the low and high water levels, similar to that present in Gordon tributaries (Jarman and Crowden., 1978) In 1978, the near river vegetation was described as follows:

> "Foreshore communities are comprised mainly of herbfields and sedgelands. A narrow bank of Leptospermum riparium scrub occurs higher up the bank adjacent to the forest communities" (Jarman and Crowden., 1978).

The *Leptospermum riparium* (tea tree) was identified as being in a zone of periodic inundation.

In the tributaries, the mosses and ferns in the riparian zone protect the alluvial toe from scour and trap fine sediment and organic rich material. It is likely the same processes operated in the Gordon. The presence of dense vegetation has been suggested a major contributor to long-term river channel stability in Western Tasmania (Nanson, *et al.*, 1995).

The presence of 'relict' undercutting high above the present high water level which are similar in characteristic to those observed in the tributaries today, suggest that erosion processes operated over a greater range of water level heights in the past, with no one water height preferentially attacked.

The common erosional and depositional features in the Middle Gordon River, truncated eroded organosols, concentrated pipes/voids/slots, sediment flows, scour and rilling, can all be related to the present regulated flow regime of the system. Regulated flow is an integral element in the development of this distinct bank morphology as these features are less common but still present with distance from the power station. Various aspects of the flow affect different erosional processes, and the following sections describe the present understanding of these processes and how they are linked to the current hydrology of the system.

7.2.2 Present Erosion Processes: Inundation, 'Notching' and Scour

Figure 13 shows fluctuations in river stage as a function of power station operation. The plot demonstrates that due to flow regulation, river level is maintained at constant high levels for extended periods. These constant and consistent high flows have killed the vegetation through inundation and water logging, leading to the denudation of the bank below high water level (see Davidson and Gibbons, 2001).

The loss of vegetation and consistent high water level has lead to scour of the bank near high water level producing a 'notch' near the level of 3-turbine power station operation leading to degradation and retreat of the organosol. This process is probably related to the high surface velocities in the river which lead to increased shear stress. This is supported by the visual contact of the two units coinciding with present high water level, as indicated by foam lines and debris in trees (Photo 57a&b).

A similar phenomenon has been observed on the Murray River where long periods of high regulated flows lead to the parallel retreat of the bank face at an angle, leading to undercutting and collapse above (Erskine *et al.*, 1994). Scour features apart from the retreat of organosol layers and notching of the sand banks include the exposure of plant roots, high angle bank faces and more typically, the exposure of roots on tea trees on low lying banks near the river's edge (Photo 62). Additionally, the loss of vegetation affects the drainage of water from the banks, which is discussed in the next section.

Rates of bank toe scour in the Gordon are discussed in Section 7.4.

7.2.3 Seepage and piping

High pore water pressures are present in the saturated banks during power station operation. Following the rapid decrease in river level after a period of power station operation, pore water pressures remain high. If the pore pressures and groundwater surface gradients are sufficiently high, sediments are entrained in the exiting groundwater and transported out of the bank. The drainage of this stored bank water along with natural ground water is responsible for the deposition of sediment flows, rilling, and mass-movement of material down slope. In the middle Gordon, seepage erosion involving sediment flows is most notable at the level of high water on the bank. Similar to the other processes, it has its greatest expression in the zones of the river where power station operation dominates hydrology, and the rate and magnitude of river level fluctuations are high. Because seepage erosion appears to be an important bank erosion process in the middle Gordon River, specific investigations into the movement of water into and out of the banks were completed and are described below.

7.2.3.1 Water Movement through Banks

Water level probes (piezometers as described in Section 4.5.2) were installed in three banks in the middle Gordon River in sandy alluvial banks (Zone 2 Sites 70.6, 69 and Zone 3 Site 61). Site 69, immediately upstream of the Splits was composed of sands overlying a 1 – 3 m layer of cobbles which limited the effectiveness of drilling and resulted in only 2 near river probes initially being installed at this site. As these probes primarily recorded river level (river level exceeded bank height during power station operation) the collected information was not used for this analysis.

Site 70.6, situated on the right bank in Zone 2 is an 8 m high alluvial bank with cobbles at the base. Site 61 is located on the left bank of the Gordon below the confluence with the Denison River, has a bank crest about 7m above low water level, and is also underlain by cobbles at river level.

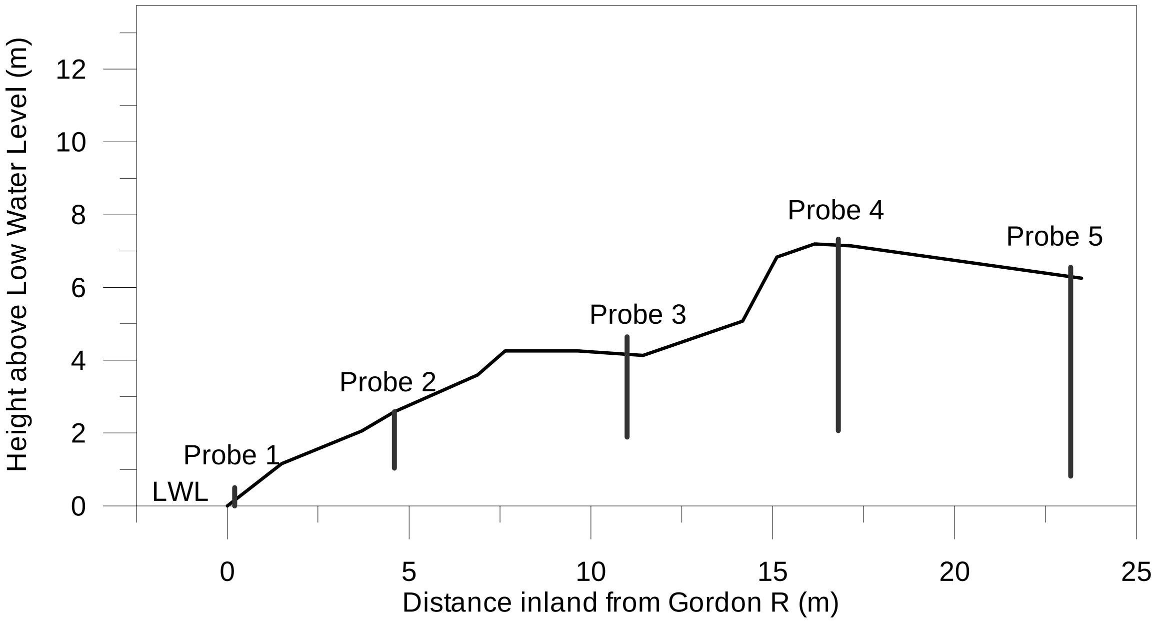


Figure 21. Schematic of Zone 2 (Site 70.6) river bank showing placement of water level probes.

The upstream site (70.6) has a water level range of approximately 4 m, where as the downstream site experiences water level fluctuations of about 2 m.

A series of 5 probes were deployed at each site, ranging from the low water level to between 20 to 25 m inland (Figure 21). Both sites are composed of medium to fine sands with an overlying organosol. The piezometer data was used to examine the rate of bank filling and draining water surface slopes under a range of power station operations. As discussed under 'Methods' (Section 4.5.2) there were some problems associated with the piezometers, resulting in drifting or inconsistent baselines, and probe failure. The data selected for the following analyses are considered to be free of major errors, however, minor instrument drift of a few centimetres may be present in the data.

7.2.3.1.1 Bank Filling

Filling episodes following power station shutdowns of various duration were examined at both piezometer sites. Figure 22 and Figure 24 show time series of one of these events, with water levels in the bank superimposed on the bank profile. Probe 5 at each site failed during this period limiting data to 18 m inland from the river. These graphs reflect conditions between 7 March 2000 and 14 March 2000, and hydrographs showing discharge from the power station and river level in each zone are presented in Figure 13. Flow during this period exceeded 200 m^3/s for most of the time. In each of these graphs, 'low water' denotes the position of the groundwater surface immediately prior to the beginning of river level increase at the site. The groundwater surface is indicated for 12 hours following 'Low water' and on a daily basis for 8 days.

Figure 23 and Figure 25 show water level at the most distal probe (Probe 4) at the Zone 2 and Zone 4 sites during several filling events. In Figure 23, filling events following a 16- hour and 24 - hour shutdown are compared with the filling event depicted in Figure 22. All of these filling events reflect very high discharge from the power station.

Figure 25 compares bank filling in Zone 4 following the 48 - hour shutdown with filling following a 16-hour shutdown under high flow conditions. The third event depicted in the graph shows bank filling associated with variable power station usage, rather than near maximum discharge.

In Zone 2, Figure 22 and Figure 23 show a rapid increase in bank water levels during the first 24 hours of high flow, with filling continuing at a reduced rate as river water level is approached. Water levels increase by about 1.5 m during each event, with approximately ½ of the maximum water level height achieved in the first 24 hours of filling. Occasional inconsistencies between river water levels recorded by Probes 1 and 2 resulted in sloped river water surfaces in Figure 22.

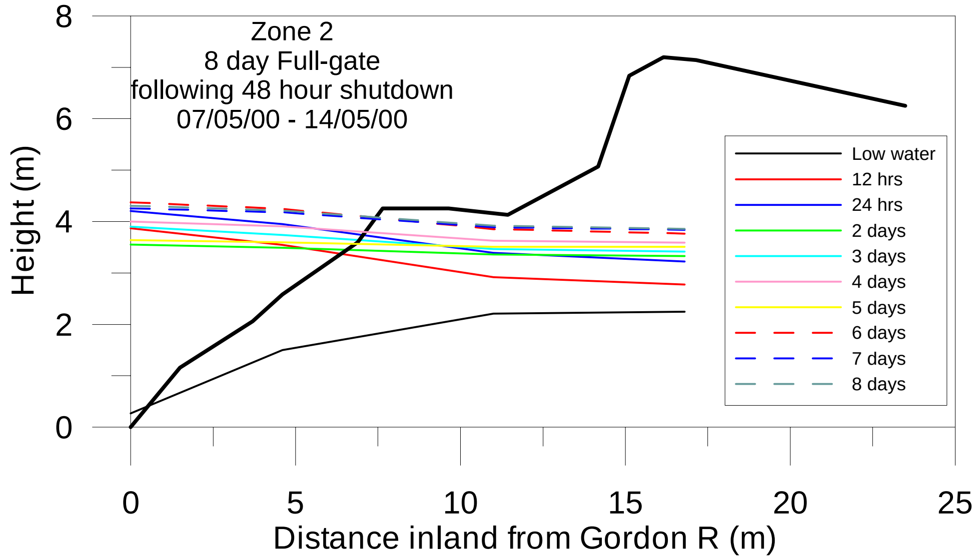


Figure 22. Time series showing 8-days of water level in Zone 2 bank during a 10-day high discharge event following a 48 hour power station shutdown. The times indicate time since river level began increasing at site. Probe 5 (23 m) malfunctioned during this period.

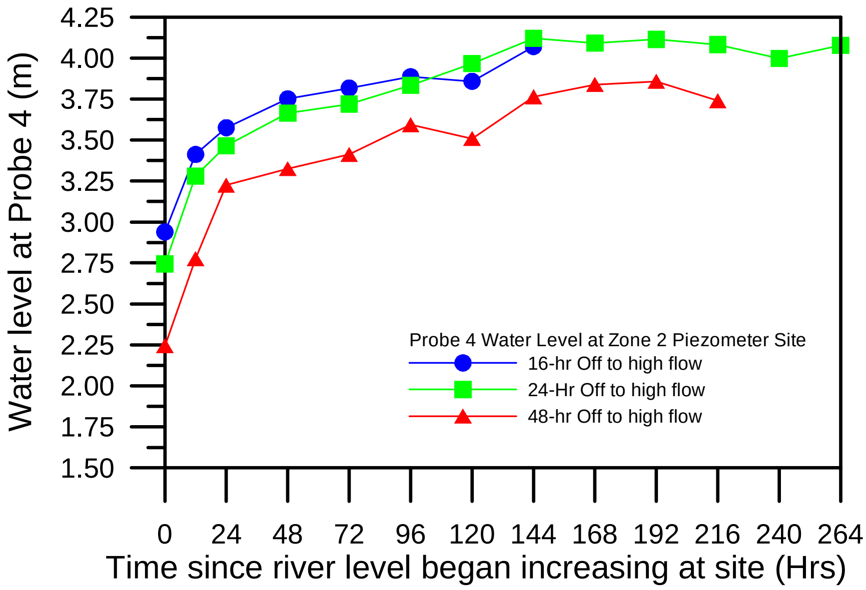


Figure 23. Comparison of Probe 4 (17 m from bank) water level during different 'filling' events at Zone 2 piezometer site.

The main difference between the curves in Figure 23 is the starting point of water level in the bank which is directly related to the length of the previous shut down. The 48-hour shut-down resulted in the lowest in-bank water levels, which were about 0.5 m lower than the 24 hour shutdown, and 0.75 m lower than the 16 hour shut-down. Due to this lower starting level, 48-hours of bank filling following the 48-hour shut down were required to achieve the same water height as 12 hours following a 16-hour or 24-hour shut-down.

Similar trends are apparent at the Zone 4 piezometer site, although water level increases in both the river and banks are only about half those documented in Zone 2.

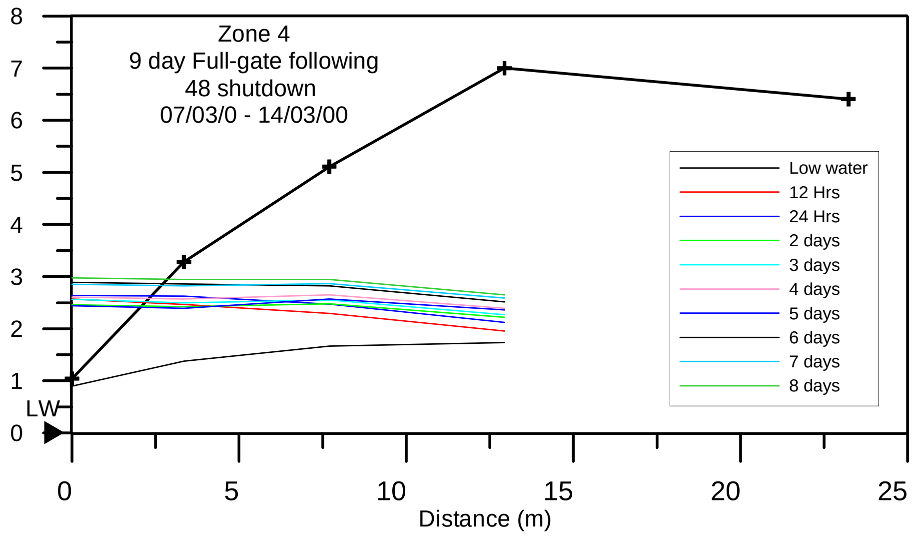


Figure 24. Time series showing 8 days of water level in Zone 4 bank during a 10 day Fullgate (high flow) event following a 48 hour power station shutdown. The times indicate time since river level began increasing at site. Probe 5 (23 m) malfunctioned during this period

Water level in the bank increases rapidly during the first 24 hours followed by a reduced rate of increase. The comparison of filling events in Figure 25 shows the water level at Probe 4 following a 16-hour and two 48-hour power station shutdowns. The 48-hour shutdowns reduce water levels in the banks by up to 0.5 m greater than the 16-hour shutdown, and result in much slower filling of the bank. Following the 48-hour shutdown, 48-hours of high flow was required to raise water levels to the starting point of the 16-hour shutdown event.

The third event depicted in Figure 25 is a 48-hour shut down followed by variable power station operation between 20 August 2000 and 2 September 2000. Hydrographs for the river and bank probes for this period are shown in Figure 26. During this period, minimal rainfall occurred, with a total of only 16 mm recorded at Strathgordon over the two weeks. Unregulated tributaries (Collingwood R., Franklin R. at Mt Fincham) for which discharge data is available show a low winter baseflow.

The 48-hour shutdown and associated decrease in river and bank water level is indicated by ‘A’ and the plateau in level in Probes 2 and 5 is due to the water level in the bank falling below the installed depth of the probe. During the short duration power station on and off events (‘B’= 6 hour on, 6 hour off), the filling of the bank is reduced compared to the full-gate events (Figure 25). During this period the power station was on and off roughly equivalent periods of time. The increase in water level in the banks indicates that the banks fill more rapidly than they drain.

The area denoted as ‘C’ on the plot shows a period when the power station was operating with 2 turbines at full-gate. Although the river level and water level in probe 2 remain constant, levels in probes 3 – 5 are observed to increase. The rise is likely to be attributable to instrument drift. No other piezometer records show an increase in back-bank water levels following a decrease in river levels. If the increase is due to the influx of groundwater (although there was only minor precipitation during this period) these conditions could lead to the discharge and/or seepage of water from the bank to the river above the river level.

After 72 hours of variable operation, which included 12-hour on and off periods and a 24-hour maximum discharge ('D') the water level at Probe 4 is roughly equivalent to 12 hours of full-gate operation following a similar 48-hour shut-down (Figure 25). The two curves converge after 5-days, but the variable power station usage curve decreases again owing to reduced discharge from the power station on 26 August ('E'). The subsequent 5 days of alternating 3-turbine and 2-turbine power station discharge resulted in continued filling of the bank ('F'). By the end of the 10-day data set, bank water levels are within 0.25 m of river level, similar to the 10 – day power station full-gate on event shown in Figure 25.

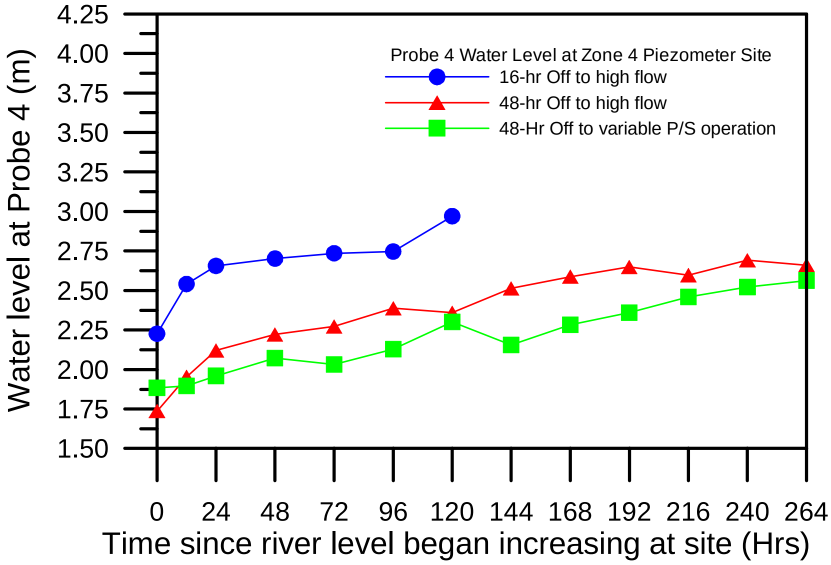


Figure 25. Comparison of Probe 4 (17 m from bank) water level during different 'filling' events at Zone 4 piezometer site .

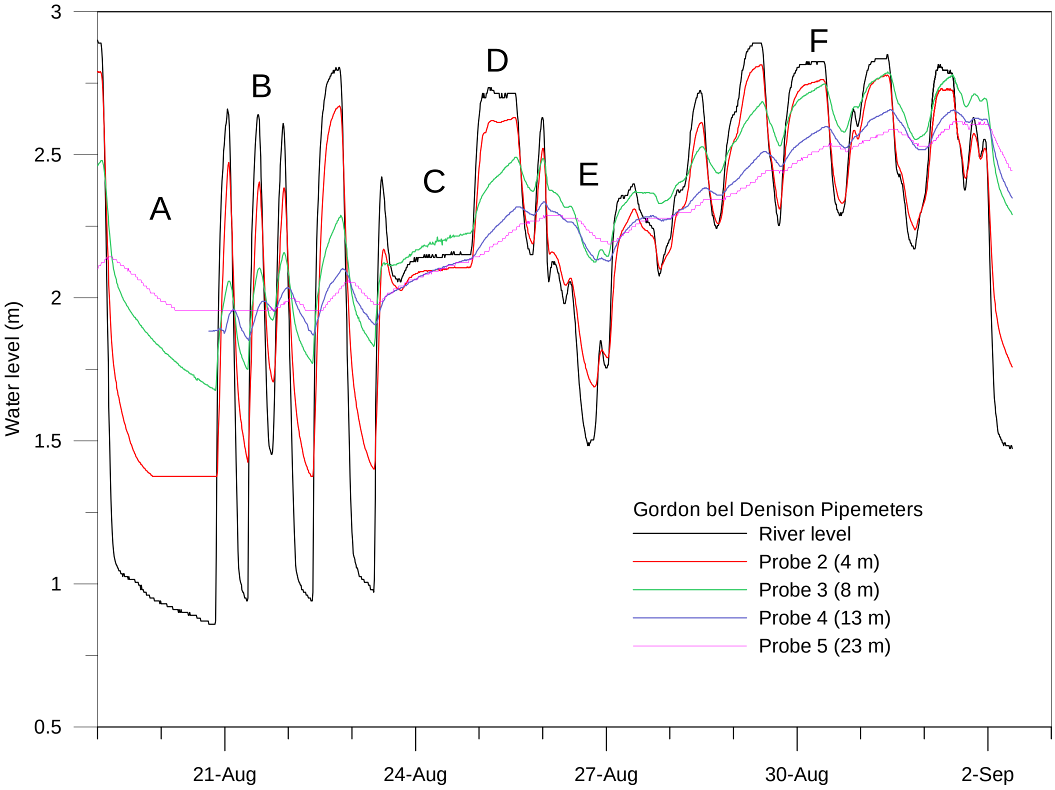


Figure 26. River level and water level in piezometers at Site 61 during variable power station operation (Gordon Below Denison)

7.2.3.1.2 Bank Draining

Seepage erosion occurs as water drains from the banks. A number of shut-down events, associated with varying lengths of previous power station operation are presented in Figure 27 and Figure 28 for Zone 2 and Zone 4, respectively. In each graph, the maximum water level is shown prior to draw-down at the site. Water levels corresponding to 1, 2 4 and 8 hours after the initiation of river level decrease at the site are indicated.

The graphs are consistent with the 'filling' events previously discussed, in that water level fluctuations are much greater at the Zone 2 site, and the level of the groundwater surface in the bank increases with increased duration of power station operation.

The piezometers in Zone 2 indicate that following periods of power station shut-down, the difference in water level in the bank and in the river is about 3 m, in the absence of local precipitation. This maximum difference occurs within about 6 hours of power station shutdown. Differences of 2 m continue to be present 72 hours following power station shutdown. In Zone 4, the variations are considerably lower, with the maximum difference between water level in the bank and the river being 1.7 m, also at about 6 hours following shutdown, and reducing to 0.82 m after a 72 hour shutdown. The rate of change is also considerably different, with the Zone 2 site experiencing a river level decreases of 1 to 1.5 m between 1 and 2 hours following power station shut down, as compared to a decrease of only 50 cm at the downstream site during the comparable period.

The shut-down events show that for isolated power station 'on' events up to 24-hours in duration, the groundwater surface slopes into the bank, and during the first few hours of draw-down, water surface slopes continue to be into the bank. River level in Zone 4 remains higher longer as compared to Zone 2, probably due to the influx of Denison River water which had been 'dammed' by high flows in the Gordon River.

Table 16 summarises river water level and in-bank water slope changes following draw down events in Zone 2. The 'Partially Saturated to Off' case reflects draw down following an 18-hour maximum discharge event, and the 'Fully Saturated to Off' reflects drawdown following a 10-day maximum discharge event.

Table 16. River level and water slope changes associated with drawdown events in Zone 2. Time indicates time since water level began decreasing at the site. The water slope is shown as the height difference between Probe 3 and Probe 2. Negative water surface slope values indicate water surface slopes into the bank.

Partially Saturated to Off				Fully saturated to Off			
Time (hours)	River level (m)	Change in River Level (m)	Water surface slope (P3-P2)	Time (hours)	River Level (m)	Change in River Level (m)	Water surface slope (P3 – P2)
0	4.43		-0.16	0	4.31		-0.04
1	4.39	-0.04	-0.16	1	4.30	-0.01	-0.03
2	3.39	-1	-0.04	2	3.46	-0.84	0.03
3	2.47	-0.92	0.08	3	1.98	-1.48	0.16
4	1.63	-0.84	0.12	4	0.97	-1.01	0.19
5	1.12	-0.51	0.12	5	0.52	-0.45	0.19
6	0.78	-0.34	0.12	6	0.36	-0.16	0.19
7	0.62	-0.17	0.12	7	0.29	-0.07	0.18
8	0.62	0	0.11	8	0.27	-0.02	0.18

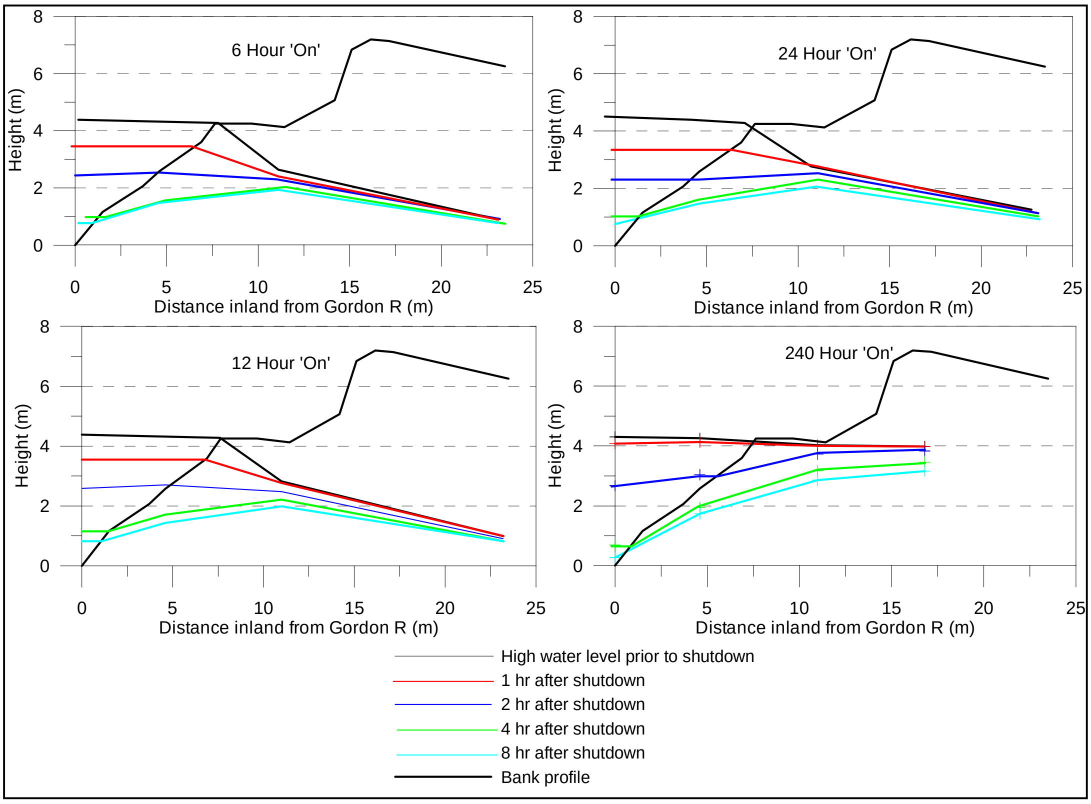


Figure 27. Water level during draw-down events in Zone 2 bank following varying power station operating durations. There are no data for the 23 m probe during the 240 'on' due to probe failure.

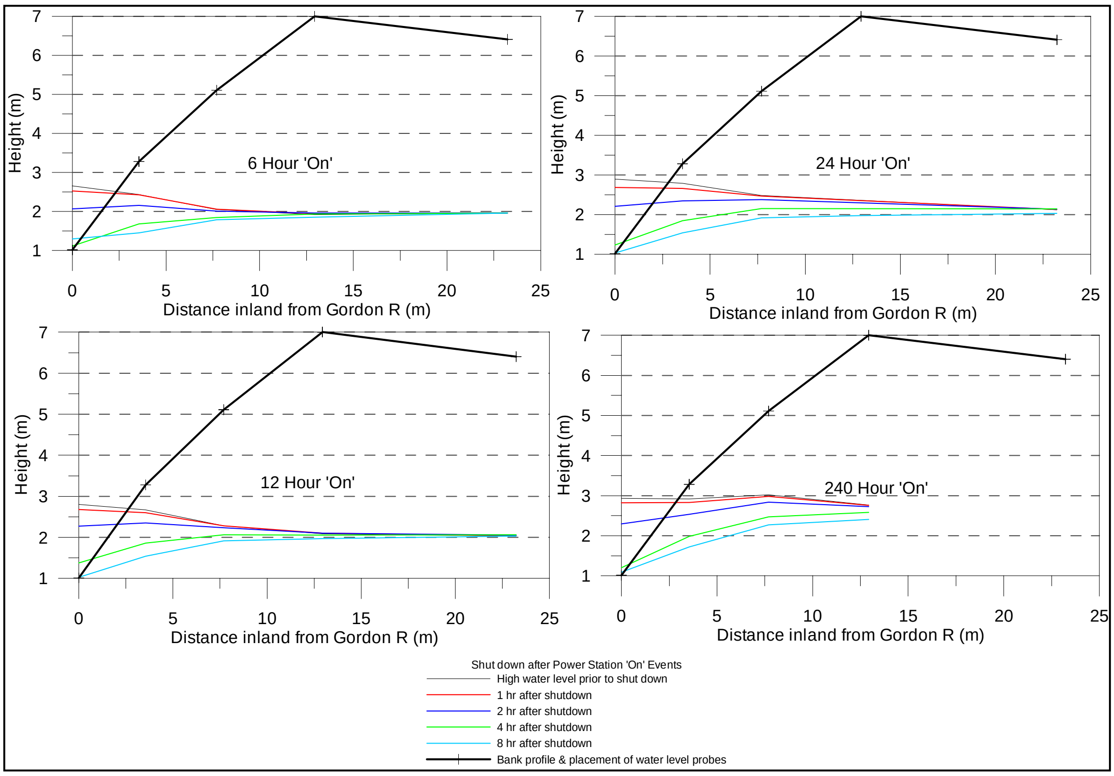


Figure 28. Water level during draw-down events in Zone 4 bank following varying power station operation durations

The table shows that for the first 2 hours of draw-down, river level decreases more slowly for the fully saturated case. This is probably due to the draining of upstream backwaters and banks which would contain a greater volume of water following 10-days of maximum discharge as compared to 18-hours. The saturated bank case results in higher rates of water level decreases (1.48 m in 1 hour) and higher water slopes (0.19) as compared to the partially saturated banks. These maximum conditions occur between 3 and 6 hours following draw-down.

An important aspect of these results is that maximum water slopes are not associated with the initiation of draw-down when river water levels are high. Because seepage erosion in the form of sediment flows is most common near high water levels on the banks following extended periods of maximum discharge from the power station, the results in Table 16 suggest that maximum water surface slopes are not required for the process to occur. Maximum water surface slopes are associated with the lower bank, where bank slopes are lower and show rilling, but not sediment flows. The low bank angles and absence of sediment flows suggests the lower bank has adjusted more to these drawdown conditions.

In summary, river level can affect water levels in the banks to distances of 20 m or more inland, and banks drain more slowly than they fill. Where river level fluctuations are greatest, the rates of rise and fall of bank water levels are highest. Near-river bank water levels respond quickly (hours) to changes in river level, with the more distal portion of the bank requiring days to achieve equivalent levels. Following a drawdown event associated with a power station shut-down, maximum differences between river level and bank water level occur within 3 to 6 hours.

7.2.3.2 Bank Morphology and Seepage Erosion

Typically, sandy alluvial banks in the middle Gordon have a denuded shallowly sloping toe, up to a sharp slope break near high water level (3 machines operating). Seven sand bank toes measured in Zone 1 had slopes between 5° and 32°, with an average of 23°. In Zone 2, banks averaged 14° (4° to 25°, n=13), and in Zone 3, the average was 19° (10° – 36°, n=4). These slopes were observed to either extend up into the void space created by the overhanging root-mat and beyond the contact with the vegetation, or terminate at a much higher angle at the sand wall at the back of the voids. The first morphology was more common in areas of ‘slots’, where discrete voids were limited. The second expression was frequently accompanied by individual pipes extending back and up from the steep back wall. These areas were likely to have large trees present on the bank, with the large roots providing structural support for the void.

Below low water level, bank slopes increased slightly. In Zone 2, eight paired measurements yielded average above low water level slopes of 14° (range 5° – 25°), with below low water level slopes averaging 17° (range 12° to 28°).

Theoretically, banks controlled by drawdown induced seepage will continue to reduce slope until a stable ‘seepage slope’ is obtained, roughly estimated to be ½ of the angle of repose for the material, and generally between 13º and 17º (Taylor, 1948, Howard and McLane, 1988; Budhu and Gobin, 1996). Some bank toes in Zone 2 are similar to these values, whereas banks and toes in Zones 1 and 3 exceed this angle. This suggests that either the river is not in equilibrium or other factors are contributing to final bank slope. Scour of the bank toe, which produces steeper slopes can also explain the steeper slopes. It must be recognised that the numbers of measurements are very limited.

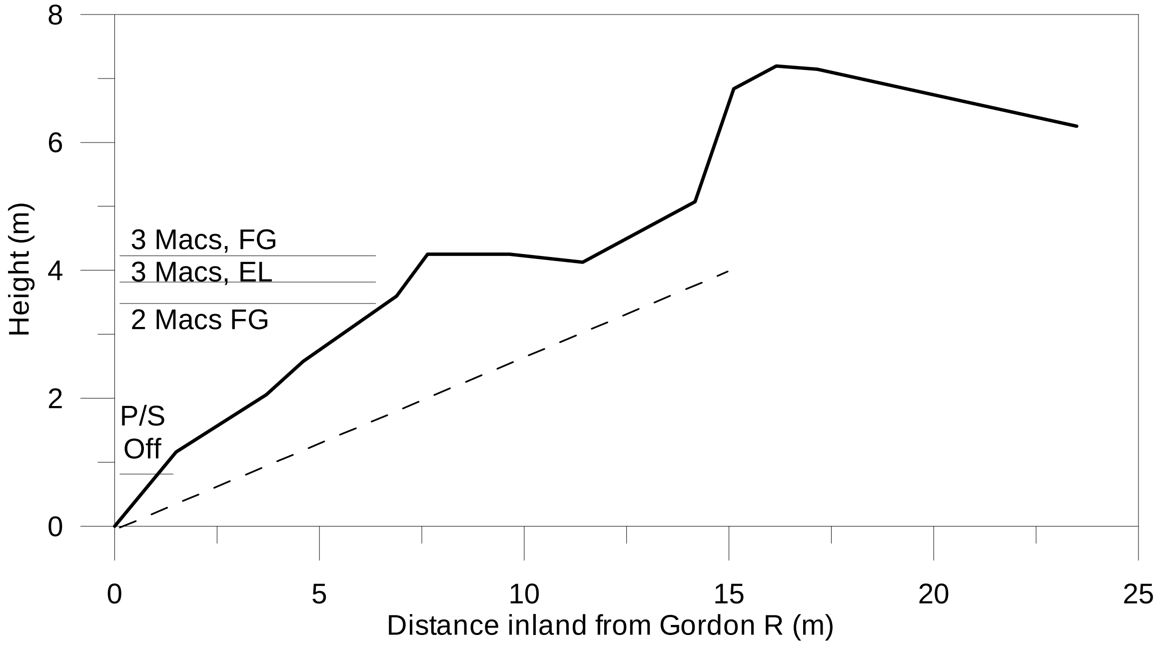


Figure 29. River bank profile from Zone 2 piezometer site (river km 70.6) with water levels associated with different power station usage. A hypothetical stable seepage slope of 15° is shown as dashed line. Mac = machine (turbine); FG = Full-gate (maximum discharge capacity); EF = Efficient load

A bank profile of the Zone 2 pipe-meter site (km 70.6) and river levels corresponding to common power station operating regimes is shown in Figure 29. Also shown is a theoretical stable seepage of 15° derived from the literature. This is assumed to be the slope the bank would assume if seepage erosion were the only process controlling bank slope.

Bank features correspond to common river level heights, with a bench present at highest high water level (3 turbines operating at maximum capacity). Above the bench, there is a section of bank with slope similar to the stable seepage slope, which joins a steeply sloping ‘angle of repose’ section 15 m from the river bank. This area of the bank reflects the change between sub-aqueous and sub-aerial processes controlling bank slope.

Other slope breaks are evident at the 2 turbines operating at maximum capacity water level (~3.5 m), and at low water (power station off level). The slope of the lower toe is steeper than the theoretical seepage angle, and Photo 63 shows the presence of a large log buttressing the toe of the bank, and tea tree growing on the lower slope. Photo 3 shows the same site in detail.

Where present, voids on the bank face are typically located between what is interpreted to be the 2-machine maximum discharge level and 3-machine maximum discharge levels and caused by seepage erosion of the bank near high water level.

On bank faces, pipes are observed directly exiting banks, usually in the vicinity of large tree roots, or entering the back or ceilings of void spaces. These pipes are differential flow paths that appear to have two roles in the transport of water from the banks. Piping features that exit the bank below the high water mark are presumably active during shutdown related bank dewatering, and provide a mechanism for the rapid lowering of the water table near the front of the bank. Pipes that exit at or above the high water mark are probably active during periods of high water flow and local precipitation. Because operation of the power station results in an elevated local water table, precipitation that cannot be stored in river bank will exit above or at the high water level. The lack of evidence for surface water flow on the banks of the rivers supports the sub-rootmat transport of rain derived water. These ‘drains’ may play an important role in controlling the water level within the banks during periods of high rainfall. The pipes are typically associated with the root networks of large trees, with exit holes commonly occurring between roots.

In summary, the following points summarise the movement of water through the banks, and the relationship between water movement and seepage erosion:

- River level can affect water level in the banks to distances of 20 m or more inland;
- Near river water levels in the banks respond rapidly to river level fluctuations, while further inland water levels can take many hours (days) to respond;
- Bank slopes are generally slightly steeper than predicted theoretical slopes for free draining bank faces; and,
- Seepage features are located at water level heights corresponding to 3 turbine power station operation.

7.3 Stabilising Factors and Slope Stability Analysis

7.3.1 Role of Vegetation

Vegetation has been recognised as limiting the mass failure of river banks through a variety of processes including buttressing, root reinforcement, transpiration and surcharge (Abernethy and Rutherfurd, 2000; Rutherfurd *et al*, 1999). The presence of large trees on banks provides a stabilising influence near the trunk and can increase the apparent cohesion of the bank by up to 200% (Abernethy and Rutherfurd, 2000). At depth in the bank, the large tree roots provide anchors and buttress the banks. In a regional sense, the presence of dense vegetation on riverbanks has been postulated to be the major processes contributing to long-term river channel stability in Western Tasmania (Nanson , *et al.*, 1995).

In the middle Gordon River, there is a strong correlation between the presence of tea tree in the riparian zones and bank stability (Attachment 6, Tea Tree maps). Because tea tree can withstand long-periods of inundation, it has survived on the banks below the high water level (see Appendix 6 of this report series (Davidson and Gibbons, 2001)). A similar stabilising influence is observed on banks where the tea tree has been lost, but the root mat is still present. The fine roots stabilise the sand, allowing drainage of water, but preventing the movement of material. Clusters of tea tree, such as shown in Photo 63, provide stable oases within otherwise highly active bank faces (for example to the right of tea tree in Photo 63 there is a greater abundance of woody debris, and a more active bank face).

The riparian tea tree communities in geomorphic Zones 1 – 3 differ from colonies of trees in the tributaries in that they show signs of scour around the root mat, instead of the accumulation of organic material and fine sediments common in the Denison and Franklin. The Gordon communities also show no recruitment or new colonisation below the high water level (Davidson and Gibbons, 2001). It is predicted that in the long term, the riparian tea tree communities and associated root mats will be lost through scour, exposing the now protected banks to additional erosional attack (Davidson and Gibbons, 2001,). The time frame for the loss of vegetation may be on the order of decades to a century if the individuals are healthy (N. Davidson, pers. com).

7.3.2 Buttressing by Large Woody Debris and Boulder/Cobbles

In river channels, large woody debris can both increase and decrease local bank erosion (Rutherfurd *et al.*, 1999). Erosion can be increased through the redirection of flow onto the bank, or decreased by deflecting flow away from the bank. Large woody debris can also contribute to bank stability by locally decreasing flow velocities and thereby decreasing scour, by trapping suspended sediments, and by directly protecting the banks and especially bank toes from scour (Thorne, *et al.*, 1995)

In the middle Gordon, the presence of large woody debris was associated with banks with low to moderate erosional activity. However, the presence of the fallen trees is also taken to be evidence of past bank erosion. Buttressing of the banks by large woody debris is a major contributor to bank stability in areas subject to seepage erosion. Large woody debris, especially parallel or sub-parallel to river flow direction promotes the trapping of sediments delivered to the bank through upslope seepage erosion processes (Photo 64). Large woody debris provides a localised stable point above which a stable seepage slope can develop. This results in a stepped-bank in places, with woody debris acting as risers, and deposited sands the runners.

Unconsolidated cobble and boulder deposits provide protection for the toe of the bank by reducing near bank velocities and directly protecting the toe. Boulders are present in areas downstream of the Able Gorge and Albert River, and downstream of Sunshine Gorge. Cobble deposits are widespread (Attachment 6, Bank Materials maps), associated with virtually all riffles and rapids as well as alluvial banks in runs (Photo 65).

7.3.3 Bank Stability Modelling

Bank stability modelling of two banks in the middle Gordon River was completed using *Slope-W* and field derived geotechnical and hydrological data (Attachment 9, Davies, 2000). *Slope-W* is primarily used to predict and assess the susceptibility of slopes to rotational failures. Though these types of failures are not the primary erosional processes controlling banks in the middle Gordon River, the modelling was used to determine the relative stability of each bank under varying power station operating regimes. Therefore, results are comparable within each site, but not between sites. A report detailing the methodology and results is attached to this report as Attachment 9.

The model predicts ‘Factor of Safety’ (FoS) values for each scenario. FoS values greater than one indicate bank stability under the imposed conditions, whereas values less than one indicate instability.

The Zone 2 piezometer site (river km 70.6) and the Zone 4 piezometer site (river km 61) were modelled under the range of power station conditions shown in Table 17. For each scenario, the bank water profile reflecting the greatest difference between river level and piezometer 3 was used (located at 11.0 m and 7.7 m from the river’s edge for sites 70.6 and 61 respectively). These probes were chosen as providing the best indication of near river bank water slopes given the morphology of the banks. Two model runs were completed for each case. The first used the field derived geotechnical data, and the second applied a 20% reduction to the friction and cohesion values used in the model, thus providing very conservative results. The modelled Factor of Safety (FoS) results for each scenario is also presented in Table 17.

Table 17. Modelling scenarios used in *Slope-W*. Site 70.6 is located in Zone 2, Site 61 is located in Zone 4. Progressively higher run numbers reflect progressively smaller river level fluctuations, or shorter duration high flow events.

Site	Run No	Power Station Operation Scenarios	FoS reflecting 20% strength reduction
70.6	U1	Max. discharge to off (High prior usage)	1.24
70.6	U2	Max. discharge to off (Moderate prior usage)	1.35
70.6	U3	6 hour full-gate on to off (following 2 previous 6 hour on, 6 hr off cycles)	1.38
70.6	U4	24 hour full-gate on to off (low prior usage)	1.43
70.6	U5	Max. discharge to efficient load	1.45
61	D1	Max. discharge to off (High prior usage)	1.18
61	D3	6 hour full-gate on to off (following 2 previous 6 hour on, 6 hr off cycles)	1.19
61	D2	24 hour full-gate on to off (low prior usage)	1.20
61	D4	Max. discharge to efficient load	1.26

For each site, the 'Power Station Operation Scenarios' reflect a range of bank water level conditions. The Full-gate to off with high prior usage subjects saturated banks to large and rapid changes in river water level, whereas the Maximum discharge to Efficient Load case reflects comparatively small changes to river level.

The results from both sites show similar trends. Drawdown following the extended use of the power station at maximum discharge produces the lowest FoS, with FoS increasing with shorter duration power station usage. The FoS results show a consistent reduction in bank stability with increasing bank water gradient following drawdown, as shown in Figure 30, where the FoS is plotted against the difference between river level height and water level height in probe 3 for the upstream site.

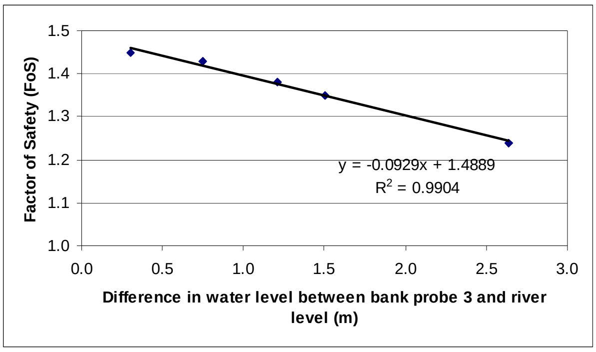


Figure 30. FoS as a function of difference between bank water height at probe 3 and river level

The range of FoS values is greater at the upstream site where water level fluctuations are greater. The model predicts a decrease in bank stability of 14.5% between the most stable (Full-gate to Efficient Load operations) and least stable (Full-gate to off, high prior usage) cases, whereas only a 6.5% reduction is predicted at the downstream site for the same range of conditions.

The modelling results support the field observations, that banks in the upstream zones that are subjected to the highest range of water level fluctuations are the least stable, with stability increasing downstream as water level ranges decrease, and the input of unregulated inflow increases.

7.4 Rates of Erosion Processes on Fine Alluvial Banks

Determining the rates of erosional processes affecting the fine alluvial banks in the middle Gordon River is a difficult task, given the episodic nature of the processes observed during these investigations and for reasons as were discussed in Section 3.3. The main mechanisms of assessing rates in this study were aerial photo comparisons, monitoring of erosion pins and scour chains, observation, and measurements of sediment transport.

Although no direct evidence for the Middle Gordon River exists, it is considered that the natural rates of change for Southwest Tasmanian rivers have been exceedingly low over the past few thousand of years, largely due to the presence of dense riparian vegetation (Nanson, *et al.*, 1995). This does not imply that river banks are not active as evidenced by erosion features in the Denison and Franklin Rivers, but that river channel stability is high. Against this setting, any rates measurable on the time scale of the power station operations can be considered to be 'high' though unquantifiable. The intent here is not to assess current rates with respect to natural rates, but to establish current rates as a baseline for assessing Basslink changes.

7.4.1 Aerial Photos

Comparison of the 1974 and 1999 aerial photos demonstrates that changes to the planform of the river have been minimal in the past 25 years, indicating that the rate of large scale river planform change is low. Channel widening has occurred in limited areas of the river, most notably Zone 2 where widening of up to 10 m has occurred. Preferential erosion of outer banks is not evident, and there is no evidence of meander migration.

Aerial photo comparisons show more fallen trees in the 1999 photos as compared to 1974, especially in Zone 2. In the field, many of the treefalls that were identified as having fallen during this period appear to be very old, lacking small or medium branches or leaves and having a weathered appearance quite different from newly fallen trees observed during the study year. It is possible that these older falls are the result of similar erosional processes to those currently observed, but associated with the initial operation of the power station using 2 turbines only. It also has to be recognised that between 1974 and 1978, prior to power production at the power station, river flow in the upper Gordon River was very low due to the filling of Lake Gordon. It is possible that the continual low river levels and drying out of the sandy banks during this period contributed to bank instability and tree fall. Although only a qualitative observation, recent tree fall appeared to increase during October 2000 when the Gordon Power Station was shut-down for several weeks.

Since the 1999 photos were taken, numerous (~10) trees have fallen in Zone 2. Most (6-7) of the falls were first observed during the two power station shut-downs in March 2000 (Figure 15) following long durations of maximum discharge power station usage. When first observed, these trees still contained green leaves, and showed no signs of submersion and are assumed to have fallen during the shut-down. Seepage erosion features, including sediment flows were prominent in Zone 2 during these shut-downs. As outlined in Section 2.5.8, the long-duration maximum discharge operation of the power station in the summer of 2000 was a unique flow event, and it is theorised that the rapid draw-down following prolonged very high river flow resulted in extensive seepage erosion.

Combining the above observations suggests that tree fall in the Middle Gordon may be related more to episodic events (initiation of regulated flow; long-shut downs; high flows for extended periods) rather than occurring at a continuous rate. This suggests a rapid response to changed flow conditions in the river followed by longer more quiescent periods.

7.4.2 Erosion Pin and Scour Chains

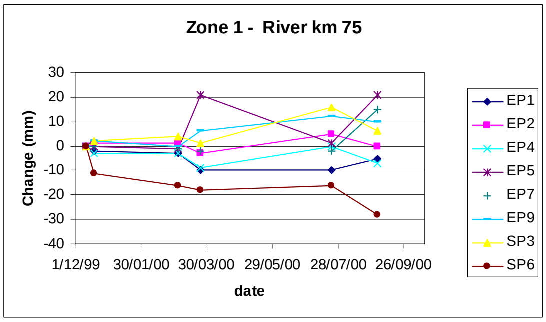
7.4.2.1 Placement and Monitoring

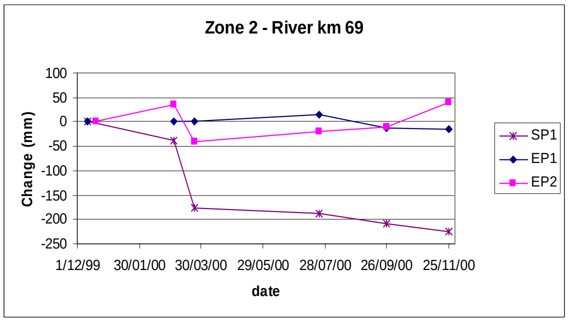
Erosion pins and scour chains, monitored throughout the study year, show a variety of responses. Erosion pin and star picket (used as large erosion pins) results from banks not showing seepage features from each Zone (sites 75, 69, 65, 60 and 47) are shown in **Figure 31**. Due to logistical realities, sites 65, 60 and 47 were less frequently measured than the more upstream sites.

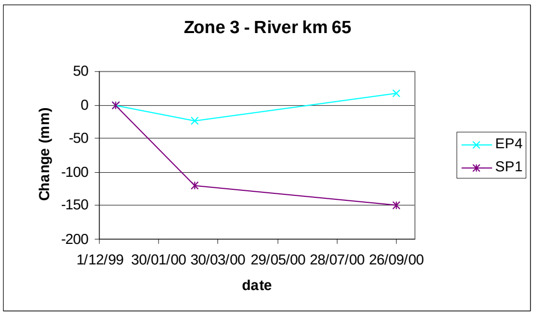
Additional monitoring sites were established on banks displaying seepage features in the study area, but the banks were found to be subject to down-slope mass movement when saturated. This was exacerbated by disturbances such as walking on the bank while measuring the pins. Because the pins were moving down-slope and changing angle relative to the bank, they are not reliable indicators of the relative importance of scour and deposition. These banks are further discussed in section 7.4.4.

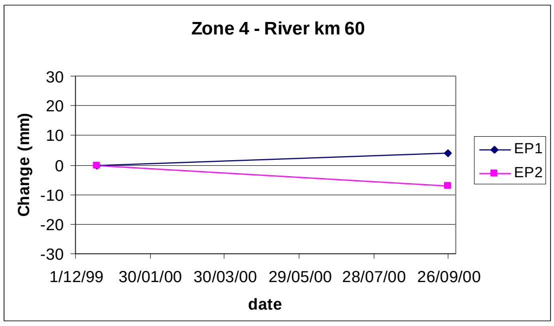
The erosion pins and star pickets at the Zone 1, km 75 site were all place in locations along the sub-vertical colluvial river bank behind a cobble bar. The pins in Zone 2 were placed in a transect on a sandy shallowly sloping bank toe at the downstream end of a cobble point bar, with the star picket near low water level, and the pins upslope. In Zone 3, the star picket was located near the low water level of a sandy bank toe, while the erosion pins were installed approximately 30 m downstream on and near a seepage feature. The Zone 4 site is on a sandy shallowly sloping alluvial deposit overlying bedrock. The star picket at the Zone 5 site was also placed at the downstream end of a cobble point bar, with 3 erosion pins forming a transect upslope and across the slope break (EP1-3), and down slope and upslope of a large nearby log (EP4 & 5 respectively).

The contact between the bank and the pins was frequently irregular, especially where deployed in the organosol, introducing potential irregularities in the results. Because of this and the necessity of having several different people collect the results during the study period, a qualitative assessment of error bars on the measurements is about ±0.5 cm. Because the number of measurements are limited, and only one year of data has been collected, the following discussion is intended as indicative only.









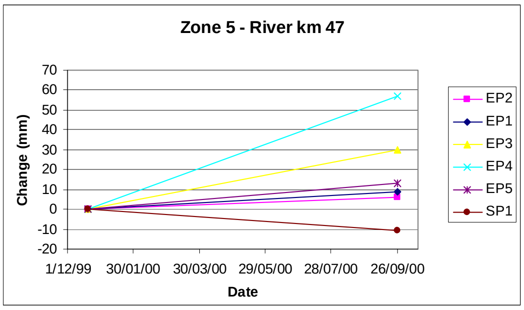


Figure 31. Erosion pin monitoring results. SP 1 is located on the bank toe near low water level; EP 1 is located lowest on the bank, with pin numbers increasing upslope. Positive 'Change' on y-axis indicates deposition whereas negative 'Change' indicates erosion.

7.4.2.2 Rates of Erosion and Deposition on Non-Seepage Banks

The results from Zone 1 do not show consistent deposition or erosion with the exception of SP6 which was located in a high tree fall area of the bank and shows erosion. The changes at all other pins were small. Five of the eight pins showed relative bank movement over the study period of within 10 mm of the starting position. The scour chain situated at this site shows a similar behaviour, with the gradual exposure of one link during the study period.

The star picket near low water level in Zone 2 shows continual scour throughout the study period, with the greatest changes associated with the period of prolonged full-gate power operation at the power station. EP2, situated highest on the bank, also shows scour during this period, but net deposition between the other measurements. EP1, located between the star picket and EP2 shows little change with time. A scour chain located near EP1 showed minor scour, with an increase of one-half of one link exposed during the study period. The chain also commonly had a dusting of sand on it.

Although 4 erosion pins had originally been deployed at the Zone 3 site, 3 that were situated in, above and down-slope of an active seepage feature were lost during the course of the investigation, along with a scour chain. The remaining pin, EP4 was located within a log buttressed area of the bank, next to the active seepage void, and experienced erosion and deposition. The star picket SP1, along with a scour chain, located on the toe of a sand deposit, showed considerable erosion, with three scour chain links being exposed during the study periods.

The Zone 4 site was only visited twice during the study period. Net changes were less than 10 mm overall, with the downslope pin (EP2) showing minor erosion, and the upslope one minor deposition. The scour chain located downslope of the two pins did not record any change during the study period.

The Zone 5 site was also only measured twice during the study year. The star picket located on the bank toe shows net erosion, while the erosion pins show little change or net deposition. Three of the pins showed about 10 mm or less change over the study year. EP3, located upslope from the star picket showed deposition. EP4, which is located on a small terrace downstream from the star picket showed the largest net deposition, and suggests sediment is being trapped on this small woody debris buttressed feature. EP5 was located on another log-created terrace upslope from EP4 and showed little change.

Overall the erosion pin and scour chain results show scour of bank toes, with fluctuating changes upslope. Scour rates ranged from about 1 cm over the year to greater than 20 cm in Zone 2. Signs of scour are ubiquitous on the banks, with roots exposed where vegetation or remnant organosols persist below high water level. The data suggest that the long duration high flow event increased scour significantly in Zones 1 - 3. The very limited erosion pin data from Zones 4 and 5 suggest that scour rates are lower these Zones as compared to the river upstream of the Denison.

Compared to pre-dam conditions, rates of bank scour have increased. Using the Denison and Franklin Rivers as analogues, under pre-regulation conditions in the Gordon there would have been limited scour of the banks due to the presence of vegetation. Vegetation reduces bank scour by lowering the near bank water velocity, directly protecting the bank from exposure, and trapping fine sediment. None of these processes are presently operative on the banks of the Middle Gordon below high water level except for large woody debris. The magnitude of these changes are explored in the next section.

7.4.3 Changes in Bank Scour Potential with Regulation

The toe of the bank (the point of maximum curvature on the bank face) is the most important control on bank erosion rates (Thorne, 1982). Frequent low flows and infrequent floods in the Gordon River have been replaced with constant moderate discharges. The result of this change for erosion rates is explored in Attachment 9 in which sediment transport modelling is compared for regulated and natural flows, and summarised here. Sediment transport capacity modelling establishes the theoretical sediment load that a river could transport if an infinite supply of sediment was available. It does not take into account stabilising influences such as vegetation, or large woody debris, and should be considered an indication of the potential of the Gordon River to scour the bank toe.

The sediment transport capacity at the bank toe was calculated at three gauged sites in Zone 1 (Km 75); Zone 2 (Km 69), and Zone 4 (Km 61). The method involved converting an hourly discharge record for these gauging cross-sections into a stage duration record, to a shear stress record, and so to a sediment transport record. This provides an indication of the potential for bank scour under natural and present flow regimes. Figure 32 shows the results of this analysis, and indicates that the regulation of the river has resulted in an increase in sediment transport capacity in Zone 1, but little or a negative change at the downstream site. The negative values should be viewed cautiously, as the majority of sediment transport capacity in the natural regime was predicted to have been in large flood events. However, it is likely that sediment supply would have limited the actual sediment transport rate to well below the sediment transport capacity during these events. This would reduce the natural time averaged sediment transport rate relative to that under the present regime. This flood dominance in the natural regime increased with distance downstream due to tributary inflows, and was maximum in Zone 4, where the greatest decrease in sediment transport capacity was predicted.

The increase in scour associated with power station operation does not contradict predictions for reduced sediment transport capacity. The loss of riparian vegetation on the banks has exposed the bank to direct attack, resulting in more scour, even though the overall sediment transport capacity may have decreased.

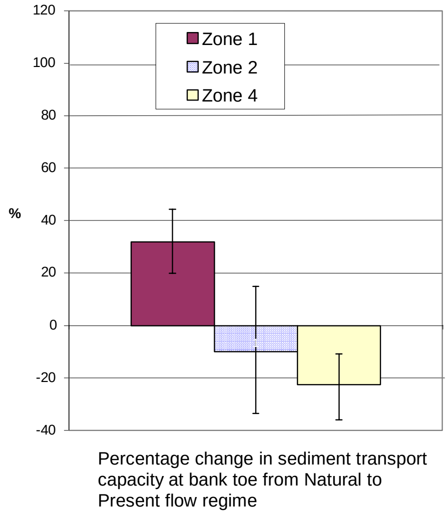


Figure 32. Percentage change in bank toe sediment transport capacity, Natural to Present operation

7.4.4 Rates of Sediment Flows

Erosion pins and scour chains located down slope of active seepage erosion zones exhibiting sediment flows recorded very high levels of activity. At these sites, (Zone 2, river km 71.3; Zone 3, river km 65) erosion pins have been observed to move down slope within a sediment flow (Photo 66), and be removed from the site. In these environments, erosion pins do not provide relevant information, as the pins are moving and the mass-movement of the top several cm of the bank is delivering sediment to the river during low flow, rather than scour and deposition affecting bank surfaces.

On the opposite river bank from the Zone 2 (upstream of the Splits) erosion pins described in Section 7.4.2, very active seepage features are present on a bank subjected to water level fluctuations of between 4 and 4.5 m. A scour chain was installed on the surface of an active sediment flow in December 1999. When visited in March, the chain showed scour of 24 cm (11 new links exposed; Photo 67), followed by approximately 20 cm of deposition from newly deposited sediment flows derived from a void upslope. This is interpreted as reflecting the scour of the previous sediment flow during the continuous use of the power station during the intervening period, followed by an episode of seepage erosion associated with drawdown. The results from a star picket located at the toe of the same bank showed fluctuating results of deposition and erosion on the scale of 2.5 cm to 5 cm over the study period, with a net deposition of 3.0 cm. The amount of sediment derived from upslope largely controlled the results. In March, net deposition was recorded whereas in November, following use of only 2 turbines, erosion of 2 cm was recorded, coinciding with only a small upslope sediment flow. Similar to the erosion pin results at other sites, the March 2000 scour chain results showed the greatest erosion and deposition, however the data set is limited due to the failure of relocating the chain on several occasions.

Qualitative assessment of the 'volume' and 'intensity' of seepage erosion observed during power station shut-downs indicates that the process is much more active following full-gate power station usage. Initial reconnaissance of the study area completed in October 1999 (See Figure 15) did not identify sediment flows as a major erosion process. This trip followed an extended period of power station operation utilising only 1 or 2 turbines. The greatest presence and volume of sediment flows was observed during the March shut-downs, when the power station had been used at maximum discharge for several months, which was a unique flow event in the history of the river.

Similar to the Spring of 1999, fieldtrips during early July 2000 observed little seepage erosion, although later in the month and in August, following more frequent and extended 3 - turbine operation, seepage erosion was again widespread. The final fieldtrips occurred during the beginning of a long power station shutdown in September 2000, before which power station usage was limited to 1 or 2 turbines, and seepage erosion was again less prominent.

The rate of seepage erosion observed during this study appeared to be related to the amount of time the power station was run using three turbines, prior to rapid drawdown. Due to the inaccessibility of the river, it was not possible to observe whether seepage erosion occurred during intermediate drawdown events, such as a reduction in power station operation from 3 turbines to 2 turbines, or from 3 turbines maximum discharge to 3 turbines efficient load. It is likely that because these intermediate events would produce a shallower water table slope towards the river, the exiting groundwater would have less capacity to entrain and transport sediments.

The rate of seepage erosion will also ultimately be affected by the down slope stability of the river bank, bank toe and angle of the seepage face. If large woody debris is located downslope of an active seepage face, the buttressing and trapping of sediments will allow the local slope to approach a stable seepage angle and reduce the sediment flows. If no down slope buttressing exists, and the flow associated with the next power station 'on' event scours the previous sediment flow, the processes will continue unchecked until a stable seepage slope is created over the length of the bank extending from low water level to high water level. The theoretical slope of this surface in non-cohesive material is about 15^{o}. If no buttressing is present and the bank toe experiences continual scour, then the continual steepening of the bank will promote on going seepage erosion, as the stable seepage slope is never attained. In this way, the creation of voids and bank undercutting that leads to tree fall becomes a feedback mechanism. As woody debris accumulates on the bank, seepage related erosion and scour are reduced.

Preliminary field measurements strongly suggest that flow regulation has increased seepage erosion rates in the Gordon. Compared with tributaries, where there are limited discrete occurrences of seepage erosion, such erosion is common and rapid in the upstream Zones 1 and 2. This is due to the higher rate of river level decrease associated with power station shut down as opposed to unregulated river level decreases, and the lack of stabilising vegetation on the lower banks. These processes becomes less pronounced with distance from the power station as heights and rates of river level fluctuations decrease.

7.4.5 Sediment Transport Measurements

The painted cobble experiment demonstrated that sand and gravels are the predominant size classes transported under the present flow regime, and transport volumes are low. Qualitative field observations suggest that more extensive sand deposits were present on bars during the March 2000 shutdowns following maximum discharge from the power station. This is probably related to increased bank erosion rates due to the higher flows, as this period had very low tributary inputs.

The 'largest cobble on bar' measurements compared to the painted bar results show that the size of bed load transported by the river under high flow has significantly decreased since damming of the river.

Suspended sediment measurements were completed under high and low flow conditions at four sites in the river: Gordon River Above and Below the Denison River, and Gordon River Above and Below the Franklin River. Three depth integrated suspended sediment samples were collected at each cross-section under each flow condition (Table 18). Under high and low power station controlled flow, suspended sediment concentrations are very low, especially at the above and below Denison sites where power station derived flow predominates.

These low suspended sediment loads suggest that even with tributary inputs, the suspended sediment load is very low. This implies that prior to regulation the sediment load of the river was also very low (which is consistent with other West Coast rivers), and indicates that although scour has increased since flow regulation, it has not significantly altered the suspended sediment load of the Middle Gordon River.

Table 18. Depth integrated suspended sediment results

Site	Flow	L.Bank (mg/L)	Centre (mg/L)	R. Bank (mg/L)
Gordon above Denison	High	<1	<1	<1
	Low	2	NA	NA
Gordon below Denison	High	<1	<1	<1
	Low	2	<1	NA
Gordon above Franklin	High	3	3	2
	Low	1	5	3
Gordon below Franklin	High	2	<1	2
	Low	<1	1	6

NA= NOT AVAILABLE

7.4.6 Summary of Rates of Fluvial Geomorphic Changes Post-Dam

The observations and investigations relating to erosion rates of sandy alluvial banks can be summarised by the following points:

- There is circumstantial evidence that episodic erosion has accompanied marked changes in the flow regime of the river, such as the initiation of power station operation with two turbines; a unique, extended high flow event; and extended periods of power station shut down;
- The loss of vegetation on the bank between high and low water levels has lead to an increase in erosion rates, with loss of plant-root induced bank face and toe stability;
- Pre-regulation suspended sediment loads were very low in the Gordon, and regulation has not altered this considerably;
- Bank toe scour is evident throughout the study area, with Zones 1 – 3 showing the highest rate; extended periods of maximum discharge from the power station may have increased rates during the study year;
- Bed scour is largely limited to the transport of sand and gravels, with B-axis lengths of <5 cm;
- Regulation has increased potential rates of transport of sand at the bank toe in Zone 1;
- Seepage erosion following extended periods of maximum power station operation is considered to be a major sediment transport mechanism in the Middle Gordon River.

7.5 Stages of Bank Instability – Working Hypothesis

This section synthesises the results of the sandy-alluvial bank investigations into a working hypothesis linking erosion in the Middle Gordon River to flow regulation. This working hypothesis is presented as a series of idealised stages that are also shown graphically in Figure 33 - Figure 36, and is most applicable to study area Zones 1, 2 and 3 where river level fluctuations are greatest and scour and seepage erosion appear to be the most active. In these zones, there appears to be a progression of bank stages, which are summarised in this working hypothesis. In the downstream zones, as river level fluctuations decrease in size and rate, and the denuded portion of the bank is more limited, erosional processes appear similar to those observed in tributaries, and a clear progression of erosional stages is not as evident. It is likely that the greater presence and viability of vegetation on the banks in these zones coupled with the higher vegetation recruitment rates cause these areas to be dynamic, but not necessarily progressing through a series of recognisable stages.

7.5.1 Pre-regulation Bank Erosion

Prior to flow regulation, the banks of the middle Gordon River would have been vegetated to low water level with a range of riparian species. Evidence of undercutting would have been present at a range of bank heights, associated with variable flood levels, and many of the older features would have been revegetated. Episodic seepage erosion was likely to have occurred, spread across the banks face, and sediment flows where present would have been small. The live vegetation was probably the primary stabilising influence on the banks.

7.5.2 Stage 1

The increased duration of high water level resulting from operation of the power station, inundated and destroyed the lower riparian vegetation (mosses, ferns, etc.). The inundation also waterlogged the organic rich vegetative layer, and resulted in organosol retreat to the high water mark. Higher median water levels also affect the root structures of riparian trees that would not have naturally penetrated into the saturated zone of the bank for extended periods prior to regulation. The inherent cohesiveness of the fibrous remnant root-mat, even after loss of overlying vegetation, results in a drape of the degraded mat over the remaining bank.

Where tea tree is present, the rate of vegetation loss is considerably slower, due to the species adaptations to inundation. The small roots associated with the tea-tree greatly increase the cohesion of the sand banks and increases the resistance of this zone to erosion. Some of these areas still remain intact, although display prominent signs of surface scour. This root-induced cohesiveness maintains a stable bank area, through which water movement can occur, but sediment transfer cannot. Down slope of the root zone, scour of the bank toe occurs, leading to steeper bank toe slopes. The eventual loss of the tea tree through scour, results in the exposure of the banks underlying the riparian forest to direct inundation and scour. This has lead to the notching and undercutting of banks at the high watermark.

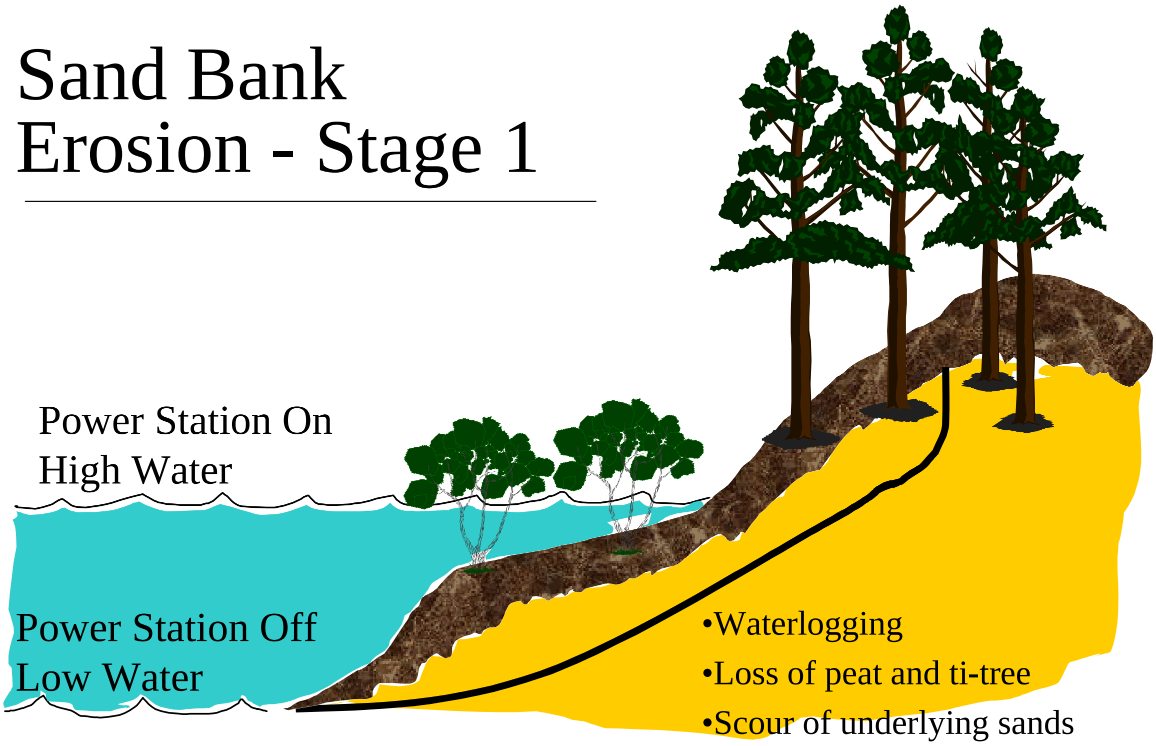


Figure 33. Schematic of erosional processes on sandy alluvial banks – Stage 1.

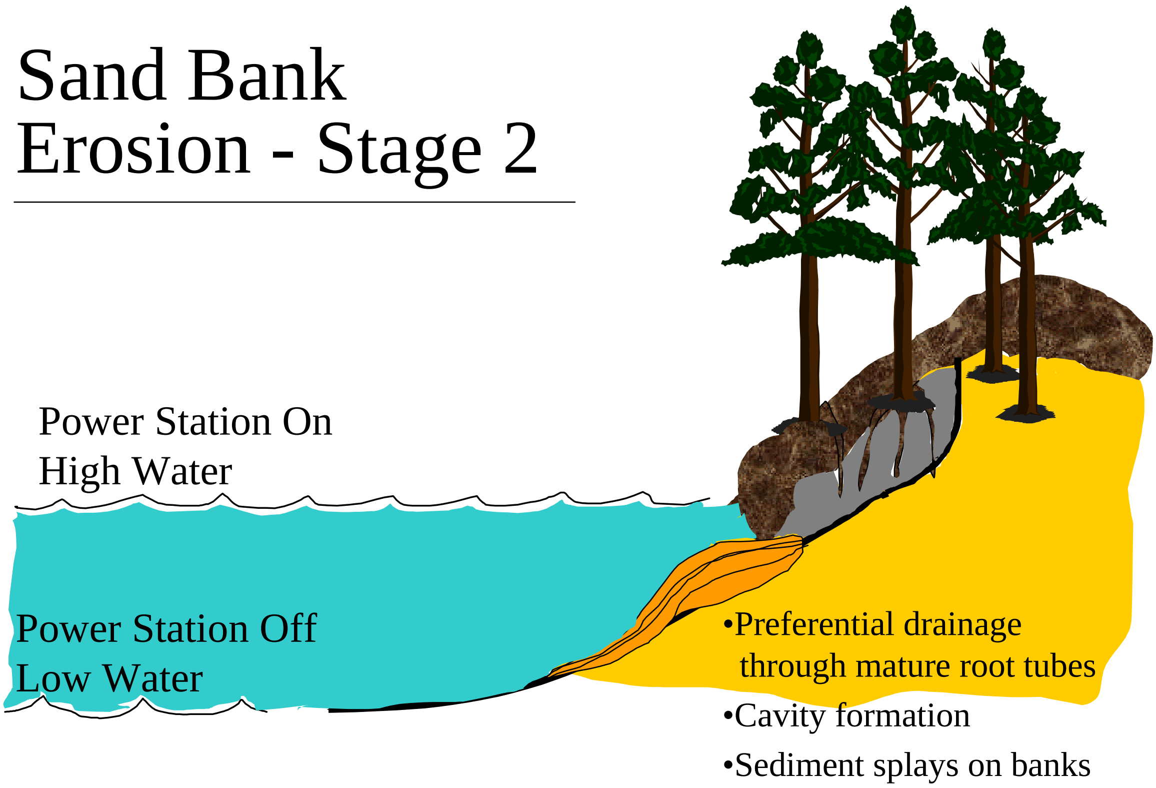


Figure 34. Schematic of erosional processes on sandy alluvial banks – Stage 2.

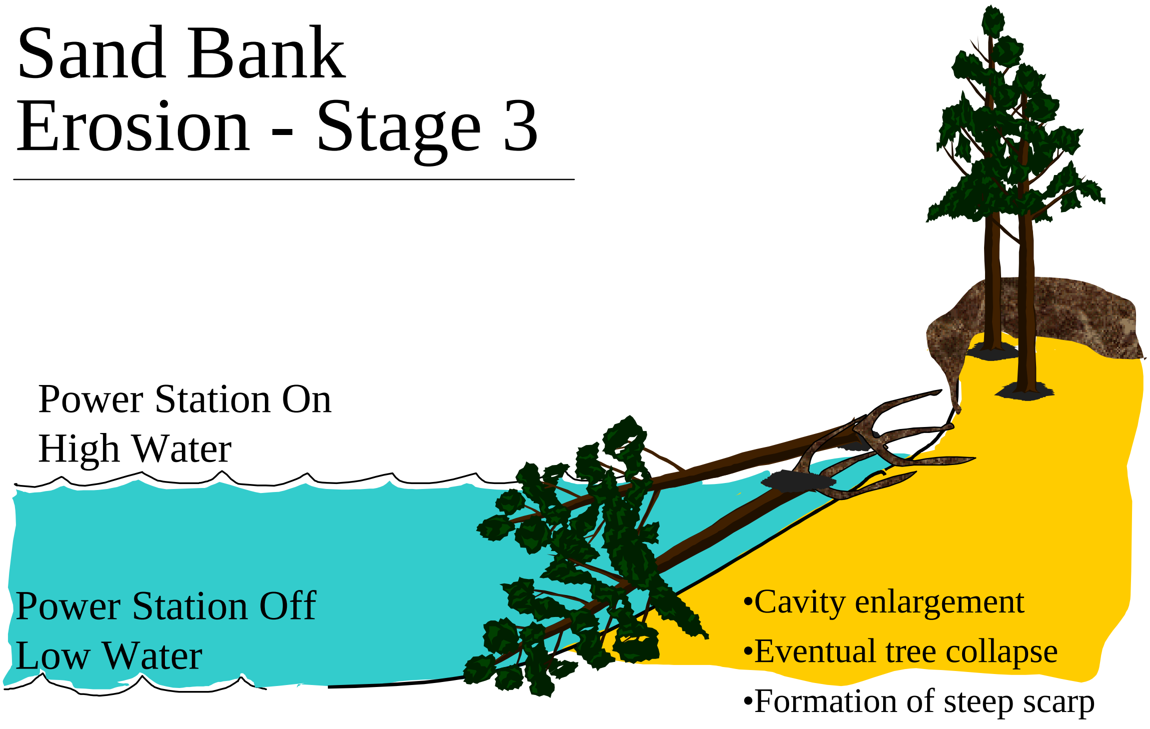


Figure 35. Schematic of erosional processes on sandy alluvial banks - Stage 3

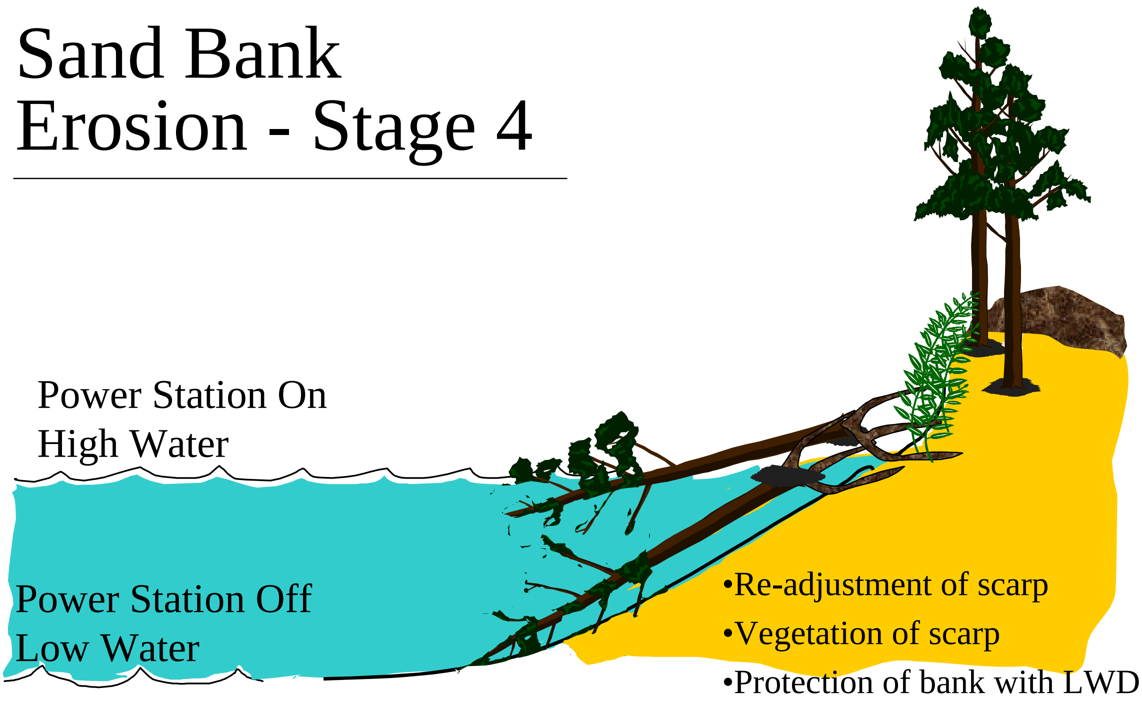


Figure 36. Schematic of erosion processes on sandy alluvial banks - Stage 4

7.5.3 Stages 2 & 3

The bank material exposed through the inundation and scour of Stage 1 is relatively lower in the river bank profile than the root-bound sands associated with the toe. Being more removed from the overlying vegetation, root induced cohesion from fine roots is lower although larger roots are common (Photo 68). Because these exposed sand banks have cohesion, they are prone to liquifaction and movement when pore-pressures are high and river level is low (drawdown following power station operation). The void spaces that were initiated through scour from river flow are enlarged horizontally through scour and saturation of the bank, leading to seepage induced sediment transport following power station shut down. This is accompanied by the development of preferential flow-paths (pipes) by the delivery of rainwater to the river at high flow, and drainage from the bank (Figure 34). Groundwater contributes to the filling of the banks during high river level.

These processes can proceed until the bank is destabilised and tree-fall occurs. The undercutting of the trees from the river side results in tree fall to be directed down slope towards the river, creating near vertical scarps on the riverbank. The scarps are exposed to direct inundation below the high water level (Figure 35, eg. Photo 19). This leads to the accumulation of large woody debris on the bank slope, and the re-colonisation of the bank above high water level.

7.5.4 Stage 4 – What Is the End Point?

Predicting geomorphic changes and end points is difficult, especially attempting to predict and assess the importance of individual bank changes compared to large-scale channel changes through channel widening. Questions such as ‘Will the channel widening that is occurring in limited areas result in sufficient changes in channel geometry such that the present erosional attack of alluvial banks will be lessened’, can not be easily answered. Because the alluvial reaches of the river typically occur as limited pockets between bedrock controlled reaches, channel widening is unlikely to have a major effect on channel geometry. An exception may be in Zone 2 where the greatest proportion and longest reaches of alluvial banks occur. The following discussion of potential stable endpoints of the alluvial banks focuses on bank stability being achieved independently of changes to channel geometry.

In the zones closest to the power station where water fluctuations are greatest, the balance between the vegetation-enhanced cohesion of the bank and scour and seepage induced failure, will determine the bank stability. With distance from the power station, as the proportion of regulated flow decreases, and river fluctuations decrease, seepage processes are greatly reduced, and scour is likely to be the dominant process.

Scour and seepage erosion have opposite impacts on bank slope, with scour steepening banks whereas seepage erosion leads to low angle stable-seepage slopes. In the absence of vegetation, these two processes would promote channel widening, as a stable seepage slope would not be achieved due to the on going steepening of the bank face. However, there are a number of stabilising factors operating on the banks as well.

The coherent fibrous root mat that remains in-tact after the underlying bank has been partially eroded, drapes over the slope and enhances bank stability through protecting the bank face from scour. The fibrous root mat will also affect water transport into the sand, acting like a surface ‘sponge’ during periods of rainfall and regulating the delivery of water to the sands. The overlying vegetation will also assist in bank dewatering through transpiration.

The deposition of large woody debris on the bank face and toe promotes bank stability by directly protecting the toe from scour, reducing near bank water velocities and trapping seepage induced sediment flows and/or river transported sands (Photo 69, Photo 70). Areas that have progressed to Stage 2, are often found to be depositional, rather than erosional, due to the local backwaters created by the downed vegetation which promotes deposition. (Photo 71) The comparative air photo interpretation indicates that most of the fallen trees present in 1974 are still present, demonstrating the stabilising role played by these trees operates on at least decadal time scales. Evidence from the Stanley indicates this process is operational on scales of centuries to millennium.

Based on field observations, the balance or 'end point' of these processes is the stabilisation of the bank toe through the deposition of large woody debris and readjustment and colonisation of the subaerial bank face (Figure 36). The large woody debris reduces scour and promotes a depositional rather than erosional environment (Photo 70, Photo 71). The vegetation observed to colonise the zone above the high water mark is similar to the river bank assemblage identified by (Jarman and Crowden.,1978) and may represent the establishment of a new riparian community.

This projected stable endpoint has been most commonly observed in areas characterised by low bank slopes, and abundant large woody debris indicative of historic treefall. The distribution of Stages one through three in the alluvial reaches of the study area Zones 1, 2 and 3 can be roughly estimated using the tea tree and recent erosional activity maps in Attachment 6. Stage one coincides with the presence of tea tree in high concentrations (>75%). Stage two shows up as high present erosional activity, whereas Stage three is characterised by a high LWD rating.

Uncertainties about the long-term stability of the banks remain, owing to the shallow stabilising influence of ferns and to a lesser extent the decay of woody debris on the toe. If the bank is stable, then a continuous supply of woody material will not be delivered to the bank toe from the bank. The flow in the river is not sufficient to move large fallen trees long distances, and ultimately the material will decompose, on time scales of decades to centuries or longer. If a stable bank becomes destabilised, scour and seepage erosion would be expected to promote channel widening. The final stability of the banks will ultimately depend on the quantity and nature of vegetation on the bank, both alive and dead.

7.6 Present Susceptibility to Erosion of Alluvial Banks

The susceptibility of sandy alluvial banks to erosion has been linked to a number of bank and flow variables. High erosional activity is linked to high bank slopes, the absence of tea tree, absence of large woody debris, lack of buttressing, and large fluctuations in river level. Using the bank mapping dataset, the following criteria were used to evaluate erosion potential on a reach-by-reach basis:

- Sandy alluvial bank material
- Moderate to High bank slope (>~20°)
- Low Buttressing (<25%)
- Low occurrence of Tea Tree (<25%)
- Low occurrence of Large Woody Debris on bank (<25%)
- Height to Continuous Vegetation >2 m, indicative of large water level fluctuations

The number of the criteria met in each river reach was determined, and 'Susceptibility to Erosion' maps were produced based on a rating of 0 to 5, with 0 indicating a very low susceptibility (none of the criteria met) and 5 (all criteria met) indicative of a High susceptibility. The maps are contained in Attachment 9. It must be recognised that the maps are based on the characteristics mapped, and other factors affecting erosion, such as 'inside' or 'outside' bends are not considered.

The susceptibility maps show strong similarity with the 'Present Level of Activity' maps in Attachment 6, as would be expected. Medium to high susceptibility to erosion is most common in Zone 2. Zones 1 and 3 contain limited areas with elevated erosion susceptibility. Overall, susceptibility to erosion decreases with distance from the power station, as does the present level of erosion activity.

7.7 Summary of Alluvial Sand Bank Processes

The field observations and investigations of the fine alluvial river banks in the Middle Gordon River show that the present erosion processes are directly related to the regulated flow of the Gordon River. Erosional features are more common closer to the power station, and diminish in occurrence and extent downstream. This decreased occurrence coincides with an increase from tributary inputs and a general decrease in the height of the Plimsoll line.

The loss of vegetation below high water level through inundation and water logging has been a primary factor in the destabilisation and erosion of the fine alluvial banks. Scour and 'notching' of the banks has lead to undercutting of the cohesive organosol. Scour of bank toes occurs throughout the study area, and although the data is limited, appears to increase with higher power station discharge.

Prolonged saturation of the banks at high water level through long duration power station operation, coupled with rapid drawdown rates promote seepage erosion leading to additional undercutting of the banks. In general, seepage erosion is most prominent following the use of all three turbines in the power station, with fewer seepage features present following power station operations involving 1 or 2 turbines. This leads to the conclusion that the area of banks subjected to water level changes involving 1 or 2 turbines are in at least quasi equilibrium with respect to seepage erosion, and is probably related to the dominant usage of 2 turbines over the past 30 years. Simultaneous use of all three turbines has only been possible since 1988 when the third machine was installed, and historically has been limited to <10% of the time. Given this, it is not surprising that the higher bank areas inundated by three-machine use are still showing a marked response to inundation.

Stabilising bank processes include increased cohesion due to plant roots, protection of the bank face by the organosol 'drape' and buttressing by large woody debris, boulders and cobbles. Stabilisation of the bank toe and face through the deposition of large woody debris and revegetation of the subaerial portion of the bank is postulated to be the stable endpoint in Zones 1-3 where impacts from the power station are most pronounced.

The alluvial banks presently showing the highest levels of erosional activity are those which have a steep slope, are subjected to large fluctuations in river level, do not support tea tree in the riparian zone, and are devoid of large woody debris or cobbles or bedrock at the toe of the bank. An assessment of the alluvial bank's susceptibility to erosion based on these criteria found that the potential for erosion in general decreases with distance from the power station. The greatest concentration of 'high' susceptibility to erosion areas is in Zone 2, with more limited areas identified in Zones 1 and 3.

8 CURRENT PROCESSES AND RATES – COBBLE BANKS

8.1 Introduction

Cobble units are present in the river banks of the Middle Gordon River in two general positions; as low units underlying sandy alluvial beds, or as relatively high vertical faces measuring up to several metres. The cobble units are found throughout the study area, with major exposures in Zones 2, 3 and 5. The high vertical banks are less common than the low basal cobbles, and it is estimated that only about 6% of the Middle Gordon River study area consists of these vertical banks.

The basal cobbles are frequently contiguous with mid-river cobble bars, and may be an extension of the present cobble bar system which have experienced sedimentation and colonisation as part of channel migration or constriction. In this position, the cobbles protect the toe of the bank (Photo 65). Slopes on the cobble toes of the banks range between 25° and 32°.

The vertical to sub-vertical cobble banks range up to 4+ m in height, and are overlain by soil and vegetation. These units are typically composed of matrix-supported well-rounded cobbles, showing imbrication in some places. The deposits range from loosely consolidated to well indurated. Similar to bedrock, the banks have moss growing on the near vertical faces above high water mark. At low Gordon River flow, cobble lag deposits are visible at the toe of some of the banks.

8.2 Erosional Processes Affecting Cobble Banks

8.2.1 Basal cobbles

The erosional processes affecting the basal cobble units are similar to the previously described processes affecting sand banks. The protection and buttressing of the bank by unconsolidated cobbles limits scour and stabilises the bank toe. The basal cobbles are typically devoid of vegetation, as they are located in the denuded portion of the bank, between low and high water levels.

Basal cobbles are common in the Franklin and Denison Rivers, although they are typically covered with mosses and ferns making them less noticeable than in the middle Gordon River (Photo 30).

The basal cobbles may enhance the draining of water from the banks, and thus perhaps reduce seepage related erosion. This was not directly investigated, as attempts to install piezometers into the cobble unit were unsuccessful.

8.2.2 Vertical cobble banks

The erosion processes acting on these cobble river banks vary considerably depending on the height and induration of the banks, and have similarities with both the previously described white sands overlain by organosols, and bedrock units.

Where the height of the cobble terrace is less than the high water level, erosion of the overlying organosol is evident (Photo 72). Free draining of water out of these units has been observed following power station shutdowns and tension cracks are present in some areas. Algal deposits on the face of the banks suggest relative stability.

In cobble banks extending above the height of high water, the presence of algae, and scouring of the matrix (Photo 12) are common near the Plimsoll line. Recent erosion is indicated by the exposure of non-algae coated material in the deposit, and at the base. The presence of mosses above the high water mark suggests that these deposits are stable over fairly long time scales.

The vertical expression of these banks is indicative of bank slope being controlled by shear failure. Destabilisation of the bank toe leads to the creation of an over-hanging block that falls vertically down. In the middle Gordon, even in situations where the river terraces are subjected to strong currents, and recent bank erosion is evident, the terraces retain this vertical morphology. Photo 73 is of a high energy, outside river bend, in the middle of a riffle (above Abel Gorge). The exposed tree roots, and freshly exposed material below the Plimsoll line indicate recent erosion. Although there is evidence of undercutting at the Plimsoll line, in general the bank retains its vertical shape.

During initial reconnaissance in October 1999, several examples of historical cobble bank failure were observed in Zone 2 in these units, but they were judged by investigators to be relatively stable because of the presence of algal coatings on the banks. During and following the 2000 summer of extensive maximum discharge power station usage, several new large slips occurred in these units, and raised speculation that the extensive prolonged high water may have resulted in atypical saturation of the banks, which precipitated new slip failures following drawdown.

The comparison of aerial photos demonstrates that large scale erosion of these banks has not occurred during the past 25 years. In the Albert River, channel widening is far less pronounced in the vertical cobble section of the river as compared to the nearby alluvial banks, even though the cobbles occupy an outside bend. This indicates that under the operating regime of the power station over the past 25 years, the cobbles have been more resilient to erosional processes than the alluvial banks.

The ‘working hypothesis’ for this type of bank is that during high flow, the river supports the banks, and though some scouring occurs below the water level, it is not sufficient to destabilise the bank over short time scales. During low flow, the bank is sufficiently coherent to withstand the transition from submerged to saturated conditions, and bank failure due to drawdown effects is minimal. This last summer may have been an exception to this, and more extensive saturation of the bank lead to failure. At very low flow, the toe of the bank is protected from scouring due to the presence of cobble lag deposits. When undercutting does occur, the bank fails by shear slip, retaining the vertical profile.

8.3 Summary of Cobble Bank Processes

Cobble banks in the study area are more stable than the sandy-alluvial banks. The weathered coatings and colonisation of the banks above high water level by mosses and lichens support this argument as do the similarities in aerial photos between 1974 and 1999 for reaches dominated by cobbles. Scour of the bank toe is limited by buttressing by cobbles derived from previous failures.

Cobble bank failures observed during the summer of 2000 are believed to be related to the unique high river flow experienced by the river during this period. It is theorised that prolonged inundation lead to atypical saturation of the banks, which upon drawdown resulted in slip failures.

9 COMPARISON OF PREDICTIONS WITH OBSERVATIONS

In Section 3.7, predictions regarding the channel response of the middle Gordon River were made based on the flow regime of the river and case studies from the literature. Each of these predictions is revisited below.

Minimal change to the bedrock channel reaches

The investigations have shown little change to the bedrock channel reaches of the river. The only documented change has been an increase in vegetation between historic flood levels and the present Plimsoll line. This is attributed to the reduction in flood events that has allowed vegetation to be established in previously unsuitable environments.

Minimal change to the gravel bed of the river

Because the bed of the river would have been armoured by the former annual floods of 500 m^3/s or more, and reinforced by the long duration medium flows, it was predicted that there would be minimal change to the gravel bed. Observations and measurements support this prediction, with the armoured bed comprising materials larger than those moved by power station controlled flows.

Deposition of tributary bars

This prediction assumed that the continued sediment supply from unregulated tributaries could deposit tributary bars in the Gordon River, especially because the supply of sediment to the Gordon from tributaries could be increased through tributary rejuvenation. The investigations suggest that suspended sediment supply from the tributary streams is low, and the widespread deposition of tributary bars has not occurred. In Zone 1, closest to the power station, one new bar has formed since flow regulation. The estimated average clast size in the bar exceeds the size of material mobilised by power station flow in Zone 2. The bar is situated at the end of a long steep bedrock control section with a small tributary entering immediately upstream. However, given its placement in the first river pool at the base of a steep, narrow bedrock reach, the bar reflect inputs from several tributaries below the power station as well as the catchment downstream of the power station.

In Zone 2, the greatest increase in the size of cobble bars is found downstream of the Albert River. These larger bars are probably related to the ready supply of sediment from the Albert, which is under going significant channel widening.

Channel narrowing is unlikely

Channel narrowing was predicted as unlikely due to the diversion of water from other catchments to the Gordon River system. This channel response has not been observed in alluvial reaches of the river. A narrowing of the drip line, though not channel, has occurred in some bedrock sections, associated with an increase in vegetation.

Channel widening is considered likely where bank materials permit

It was predicted that the dense riparian vegetation would oppose channel widening through stabilisation of the banks. This is occurring in the study area where tea-tree is stabilising banks. In areas where vegetation has been lost, channel widening was predicted as a likely response of the river because of the following changes associated with flow regulation:

- Reduction in the sediment supply to below the sediment transport capacity of the river resulting in scour of the bank toe.

- Increase in the duration of shear stress on the bank face due to an increase in the frequency of moderate flows (ie. flows are not dissipated on the floodplain).
- Increase in drawdown rates combined with long durations of high flows will produce seepage induced erosion.

Channel widening has occurred in up to 1% of the study area, generally limited to the alluvial reaches of Zone 2.

A reduction in sediment supply to the Gordon is unlikely to have occurred, due to the present extremely low suspended sediment concentrations being similar to hypothesised pre-dam concentrations. Therefore, it is suggested that this process is not responsible for the scour of the banks documented in the study area.

A substantial increase in the duration of shear stress on the banks in Zone 1 following flow regulation has been demonstrated through shear stress modelling. In the other Zones, although modelling suggests a reduction in sediment transport capacity as compared to the natural flow regime, the loss of riparian vegetation has increased the susceptibility of the banks to scour. It is likely that it is this increased exposure rather than increased shear stress which has lead to an increase in scour in the Middle Gordon River.

Seepage erosion has been widely observed in the upstream Zones 1 and 2, where river levels fluctuations are high and dominated by power station releases. Sediment flows are most common following extended periods of three-turbine power station operation, when bank saturation is at a maximum. The lack of sediment flows following one or two turbine power station operation suggests the slope of the banks are in quasi-equilibrium with a two-turbine flow regime with respect to seepage. Sediment flows are a response to higher water levels associated with the operation of the third turbine.

Increase of no change in meander migration rates

Meander migration rates were predicted to increase or not change due to the very low natural rates believed to operate in the catchment. Observations indicate that channel widening in alluvial banks has not been concentrated along the outside bends of the river, but is more commonly observed along straight reaches. This is consistent with the prediction, but does not provide proof.

Overall, the predictions of channel response to flow regulation and the results of the observations and investigations are consistent. The bedrock sections of the river have not been altered by flow regulation, and the gravel bed has not changed. The planform of the river has not been modified, and there is no evidence of increased meander rates. Channel widening has occurred in limited alluvial reaches.

The primary erosion processes identified, scour and seepage erosion, vary in importance depending on the flow regime. During one or two turbine flow, seepage erosion is uncommon, and scour is the predominant process. Seepage erosion, where operative, becomes an important process on banks above the 2-turbine operating level.

10 PREDICTED BASSLINK CHANGES

10.1 Introduction

The main aim of this report is to identify the potential geomorphological changes to the Gordon River arising from Basslink, and to identify mitigation options that could minimise any potentially negative impacts identified. The first nine chapters of this report have focused on the present flow and geomorphological processes operating in the Middle Gordon River. Based on this foundation, this chapter identifies likely changes to the flow regime under Basslink and modelled by Hydro Tasmania and potential changes to the geomorphological processes as a result of the changes.

10.2 Description of Hydrologic Changes under Basslink

As proposed, Basslink is an undersea cable that will connect Tasmania to the National Electricity market. Connection to the national electricity market will allow the sale of hydro-electric and wind power to the mainland. As envisaged, Tasmania would export power during peak power demand on the mainland, and import power during off peak energy periods. Modelling of Basslink has indicated that the Gordon Power Station would be used more as a 'peaking' station, utilised to produce high energy output for relatively short durations (typically <8 hours, or 16 - 32 hours). Table 19 contains summary statistics for Basslink changes to operation of the Gordon Power Station.

Table 19. Comparison of Actual and Simulated Hourly Flow Records at the Gordon Power Station (1997 - 1998) (from Palmer *et al*, 2001)

STATISTICS	CURRENT OPERATION OF POWER STATION [1]	BASSLINK OPERATION OF POWER STATION
Mean flow (m^3/s)	116	115
Ave. Annual % Discharge at Full Capacity [2]	22%	25%
Annual Mean Minimum Flow 1 Hour Minimum (m^3/s) 7 Day Minimum (m^3/s)	 0 6	 0 0.3
Annual Mean Maximum Flow 1 Hour Maximum (m^3/s) 7 Day Maximum (m^3/s)	 245 206	 249 229
The Number of Annual Events -Greater than mean flow -from and to 0 m^3/s	Flow / No. Events 116 m^3/s / 219 0 m^3/s / 73	Flow / No. Events 115 m^3/s / 297 0 m^3/s / 254
Flow Duration Analysis		
Flow	% of Time Exceeded	% of Time Exceeded
210	8.6	29.3
220	5.6	27.5
230	0.2	25.8
240	<0.1	24.0

[1] Record contains missing values, and is generally of poor quality.

Under Basslink there will be a marked increase in the amount of time discharge from the power station exceeds 210 m^3/s, accompanied by a decrease in the amount of time flow is less than this value. The summary statistics in Table 19 predict an increase in the 7-day maximum flow (from 206 to 229 m^3/s)

and an increase in the number of high flow events, as compared to both mean flow and power station off conditions. Compared to present, the number of annual events that result in total shutdowns of the power station will increase by about 3-fold (75 to 254). These events will commonly have a duration of 2 to 7 hours, and 12 to 28 hours (Palmer *et al*, 2001). The changes in flow duration and event numbers reflect the short duration, high energy production use of the power station to meet peak demand. The other statistics in Table 19 show minor changes between the 'present' and Basslink scenarios.

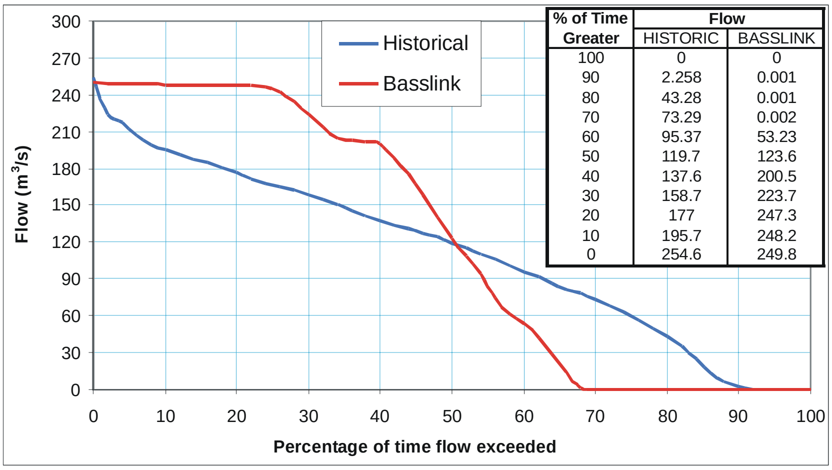
This increased frequency of on and off events leads to a greater proportion of time that water level is either increasing or decreasing. Table 20 contains hourly flow change statistics, for small (<5 m^3/s per hour) and large (>20 m^3/s per hour) flow changes. The 'Natural' and 'Present' values were discussed in Section 2.5.3 and Section 2.5.4. These flow changes equate to changes in river level in Zone 2 of <5 cm/hr (<5m^3/s per hour) and >22 cm/hr (>20 m^3/s per hour). The rapid turning on and off of the power station results in a reduction in the hourly flow changes of <5 m^3/s and large increase in the hourly flow change of >20 m^3/s. It should be stressed that the rate of water level rise and fall under Basslink will be the same as under present power station operations. It is only the higher frequency of on/off events that leads to the high proportion of flow change.

As modelled, Basslink will double the frequency of 4 to 8 hour shut downs and 20 to 28 hour shutdowns compared to present operations (Palmer *et al*, 2001). Presently there are about 45 of the shorter shut downs and 15 of the longer events, which will increase to approximately 90 and 35, respectively.

Table 20. Proportion of flow change <5 m^3/s or >20m^3/s per hour at the power station and above the Franklin River

	Flow change< 5m^3/s per hour		**Flow change >20 m^3/s per hour**	
	Gordon at Power Station	Gordon above Franklin	Gordon at Power Station	Gordon above Franklin
Natural	93.8%	85.0%	0.2%	2.0%
Present (97 – 98)	58.4%	57.1%	14.3%	4.8%
Basslink	65.0%	47.2%	22.1%	20.7%

Figure 37 shows the present and potential Basslink flow duration plots. The Figure shows that under Basslink, the power station is at or near maximum discharge for about 1/3 of the time (0-35%), off for 1/3 of the time (65-100%), with the remaining third corresponding to rising and falling. This is in contrast to the present flow duration plot that indicates more gradual changes.



% of Time Greater	Flow HISTORIC	Flow BASSLINK
100	0	0
90	2.258	0.001
80	43.28	0.001
70	73.29	0.002
60	95.37	53.23
50	119.7	123.6
40	137.6	200.5
30	158.7	223.7
20	177	247.3
10	195.7	248.2
0	254.6	249.8

Figure 37. Flow duration curves at Gordon Power Station under Historic and Basslink Operations (hourly data, 1997 – 1998).

10.3 Geomorphic Implication of Basslink Changes

The ‘Basslink’ changes at the Gordon Power station will result in an increase in the percentage of time the highest power station induced flow levels are experienced in the river, and result in more frequent rise and fall of water level over the full operating range of the station. These changes in hydrology are likely to produce the following changes in geomorphology.

- Increase in probability of scour due to longer duration of high flows
- Increase in probability of scour due to more frequent on / off resulting in steep water surface slopes
- More frequent on / off may increase the occurrence of seepage erosion, although bank saturation and hence severity may be reduced due to shorter duration on events.

These changes are discussed with respect to each of the bank types in the following sections.

10.3.1 Basslink Impacts on Bedrock Banks

Basslink will have little change on the bedrock banks in the Middle Gordon River. There may be a slight increase in the Plimsoll line if vegetation that is presently viable being inundated only 10% of the time is not viable when inundated 30% of the time. This viability of vegetation under Basslink is discussed in Appendix 6 of this report series (Davidson and Gibbons, 2001).

A discussion of potential changes to the dissolution rate of bedrock under varying flow regimes is beyond the scope of this report, but would be expected to be negligible over the timescale of power station influence.

10.3.2 Basslink Impacts on Alluvial Banks

The predominant processes identified as affecting alluvial banks in the middle Gordon River are scour of the bank toe, most particularly associated with power station turning on or running at maximum discharge and seepage erosion at high river level following 3-turbine usage. The severity of both scour and seepage erosion increases with longer duration high flow events. It is anticipated that under Basslink, erosion will continue to be most pronounced closer to the power station, especially in Zone 2 where alluvial banks are most common, with impacts decreasing with distance downstream as a greater proportion of flow is derived from unregulated sources.

Based on the TEMSIM model results, the changes in flow due to Basslink will:

- Increase the opportunity for notching and scour at high water level due to an increase in the proportion of time the power station operates at maximum capacity;
- Increase the opportunity for bank scour during rising river level and high river level, due to the greater percentage of time these events will occur;
- Decrease the extent of bank filling for an individual power station 'on' event due to the shorter duration of 'on' events;
- Increase the potential opportunity for seepage erosion to occur due to the greater number of maximum discharge to off events power station events; and
- Increase the opportunity for bank draining due to the increased frequency of shut downs

These changes are discussed in the following sections, followed by a discussion of potential changes to the projected 'endpoint' for alluvial banks.

10.3.2.1 Increased opportunity for scour and notching of bank at high water level

Near bank shear stress is proportional to the square of the river velocity, so increasing the amount of time the power station operates at maximum capacity (higher velocity) will increase the amount of time maximum shear stress is exerted on the high water level of the bank.

The predominance of 3-turbine operation under Basslink will reduce the range of high flow levels experienced by the banks, and concentrate the shear stress over a narrower zone on the bank than is presently the case. This will increase the opportunity for scour and notching to occur at this level, which could lead to additional undercutting of the bank, loss of remnant root-mats that presently protect banks, and loss of vegetation, all of which could increase the rate of bank retreat.

10.3.2.2 Increased Scour of the Bank Toe

The erosion pin results suggest that scour of the bank toe is common in the Middle Gordon, while little net change observed higher on the bank, leading to a steepening of the bank face. The results also suggest, although the data is very limited, that prolonged durations of high river flow increase the rate of scour.

The shear stress analysis in Attachment 9 determined potential sediment transport capacity for three sites in the study area (Zone 1 km 75, Zone 2 km 69, Zone 4 km 61) by using daily discharge records to establish daily discharge stage duration curves. These curves were then used to establish a shear stress duration curve and using this information sediment transport capacity was determined using the Ackers-White equation (Ackers, 1993). The results are shown in Figure 38 along with the previously presented results for the 'Natural' to 'Present' flow change. In the graph, the Zero value is different for the two groups of bars. In the 'Natural' to 'Present' grouping, zero indicates the 'Natural' condition. For the 'Present' to 'Basslink' bars, zero indicates the Present condition. The model results indicate the change in sediment transport capacity at the bank toe assuming an infinite supply of sediment is available.

The results show an increase in potential sediment transport capacity at the bank toe in all zones under Basslink. In Zone 1, the predicted increase in Zone 1 is similar in magnitude to the increase the model predicts has already occurred under the 'Natural' to 'Present' flow change, resulting in a net increase of about 70% when both changes are considered. In Zone 2, sediment transport capacity is predicted to increase by 80 percent under Basslink. In Zone 4, the predicted increase is about 30% compared to the 'Present' flow regime, however, the model indicates the 'Present' sediment transport capacity is reduced by about 20% compared to 'Natural' conditions. These results suggest that in Zone 4, the predicted increase between 'Natural' and Basslink sediment transport capacities is of the order of 10%. The errors associated with the model results range from about 20% to 40%.

These analyses are sensitive to the effect of local hydraulic variations that alter the flow slope. Another point to stress, is that these figures are crude estimates of sediment transport potential, and do not consider the large effect of vegetation.

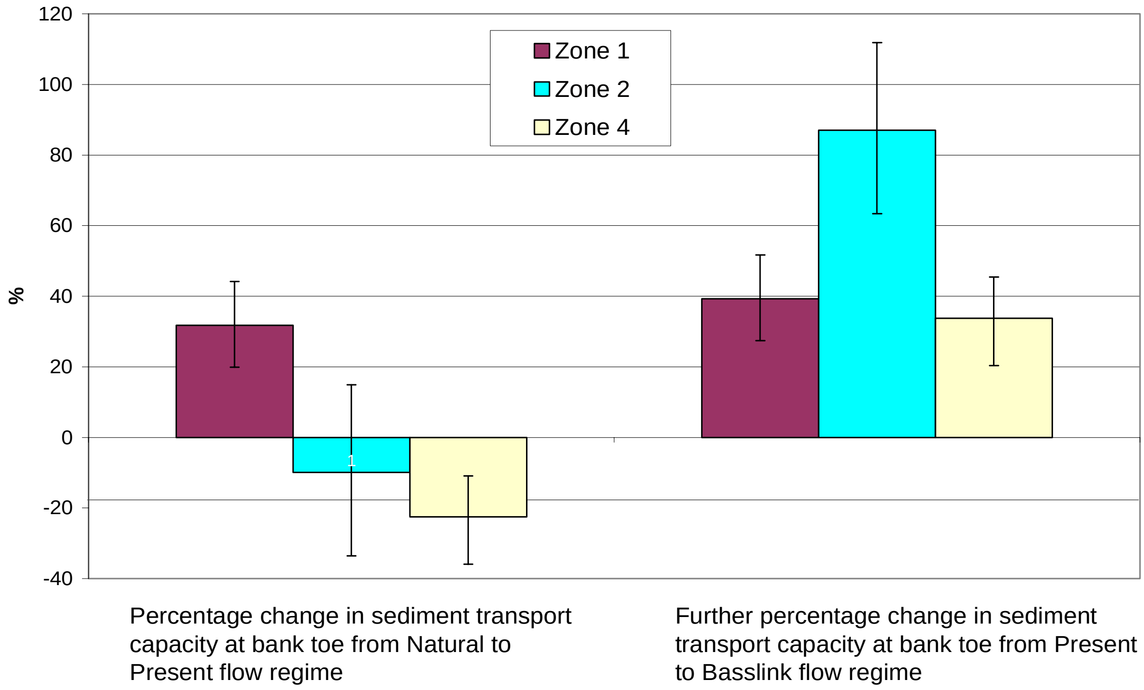


Figure 38. Percent increases in sediment transport capacity. Natural compared to Present, and Present compared to proposed Basslink

Based on the model results, scour of the bank toe is likely to increase in all zones, with the greatest increase in Zone 2. Increased scour could lead to an increased rate of loss of tea tree from the upstream Zones of the study area, which has been found to be a major stabilising factor on the alluvial banks. The loss of tea tree would 'trigger' the progression of erosion from 'Stage 1' to 'Stage 2' in the upstream zones of the study area, and increase seepage erosion on banks presently affected by scour only.

The impact of increased scour in Zone 4 is difficult to predict, because vegetation is present on the lower banks which limits scour and stabilises the banks. If the increase in scour is sufficient to remove this vegetation, than scour of the bank toes would be expected to increase. However, because undercutting and sediment flows due to seepage erosion are less common in the downstream zones, increased scour may not result in progression to 'Stage 2' erosion.

10.3.2.3 Changes to Bank Saturation and Draining

Changes to bank saturation and draining will depend on the duration and size of discharge events from the power station, and the number and duration of power station shut-downs.

The investigations have shown a clear relationship between the duration of power station operation, and the extent of bank saturation (Figure 27, Figure 28). Piezometer results show that short duration (6 hr) power station ‘on’ and ‘off’ events reduced the rate of bank filling relative to continuous maximum discharge for an equivalent time period, but that extended variable power station operation of 5 to 10 days lead to equivalent bank saturation as compared to maximum discharge operation over the same time period. Shut-downs of 24-hours or greater were required to substantially lower in-bank water levels. Table 21 contains a summary of flow statistics for Present and modelled Basslink operations, dividing flow and shut-down events into durations of greater than and less than 24 hours.

Table 21 shows that overall there are greater opportunities for banks to drain under Basslink as compared to present, and a greater proportion of flow occurs as events of <24 hours, which would slow bank filling. However, there is also a sizeable increase in the total percentage of time that flows in excess of 200 m^3/s occur under Basslink, and an increase in the percentage of time these high flows persist for longer than 24 hours. Under Basslink approximately one-half of all power station ‘On’ events that exceed 24 hours in duration is predicted to have flows in excess of 200 m^3/s.

Table 21. Percentage of time power station operates under various conditions for the 'Present' flow regime and as modelled for Basslink.

Power Station Flow	Present (% of time)	Basslink (% of time)
Power Station Off (draining banks)	10	33
Off events <24 hours	9	21
Off events >24 hours	1	12
Power Station On (any flow)	90	66
Events <24 hours	8	32
Events >24 hours	82	33
Power Station on Flow >200 m^3/s (all durations)	10	40
Events>200 m^3/s & >24 hours	5	16

The percentage of time discharge from the power station is zero on a monthly basis is presented in Table 22 for the present flow regime and modelled Basslink results. Compared to present operations, Basslink increases the percentage of power station shutdown in every month. The values in the table suggest that under the present operating regime, the groundwater surface in the banks would rarely drain to a power station off low water level.

The seasonal patterns between the two operating regimes are similar. Shut-downs constitute a minor portion of the summer months when flows in the other hydro catchments are low. During the wet winter months, the Gordon Power station is utilised less, and shut-downs are common. Under Basslink, it is projected that for 3 months (August – October) the power station will be off more than it is on. Banks would be expected to drain significantly during this period, even though the ingress of groundwater would be high due to precipitation. In the summer months (January – March) the banks would be expected to be saturated under Basslink. In the other months, the extent of bank saturation would be controlled by the operating patterns. Because of the high variability of power station operation during these months, it is not possible to reliably predict the extent of bank filling under Basslink or present operating conditions.

Table 22. Percentage of time discharge from power station is zero on a monthly basis under the present operating regime and under Basslink. Data from Hydro Tasmania.

Month	% of Time P/S Off	
	Present Flow Regime (1997 – 1998)	Basslink Flow Regime (1997 – 1998)
Jan	0.0	2.0
Feb	0.5	6.5
Mar	0.3	6.3
Apr	1.7	32.9
May	8.8	24.1
Jun	8.6	25.2
Jul	8.2	39.8
Aug	29.5	56.9
Sep	31.0	84.3
Oct	24.5	69.5
Nov	1.6	38.4
Dec	4.8	41.4
YEAR	9.9	35.7

10.3.2.4 Increased Risk of Seepage Failure

The greatest risk of seepage induced bank failure occurs following drawdown when the banks are saturated to river level height, resulting in the in-bank groundwater surface sloping towards the river. Because Basslink as proposed would increase the incidence of high flow to 'off' drawdown by 3 to 4 fold, the opportunity for seepage erosion to occur will increase similarly. Because the severity of seepage erosion is related to the extent of bank saturation, it is likely to change on a seasonal basis as bank saturation fluctuates (see previous section). During summer, when the power station is operating almost continuously, seepage erosion risk is likely to be high. During the autumn, winter and spring, when power station operation is more variable, the risk of seepage erosion will increase as the duration of power station operation increases. As an example, if the Gordon Power Station operates for short events during the week and then shuts down on weekends, the risk of seepage erosion will increase through the week, as the extent of saturation increases within the banks.

10.3.2.5 Stabilising Mechanisms under Basslink

The predominant erosion processes presently affecting alluvial banks, scour and seepage erosion, are not predicted to change under Basslink. Scour is predicted to increase, whilst it is less clear what impacts Basslink will have on seepage erosion. Under present conditions, the most important stabilising process for the alluvial banks is the deposition of large woody debris on the bank face and toe. Large woody debris is required because the re-establishment of vegetation on the bank face between low and high water levels is unlikely (see Davidson and Gibbons, 2001). The deposited large woody debris reduces scour and traps seepage derived and fluvially transported sediments.

Under Basslink, the same stabilising mechanism will be operative. The deposition of large woody debris on the bank faces is part of a feedback mechanism operating in the study area (destabilisation of the banks leads to deposition of large woody debris through tree fall), which is not predicted to change under Basslink. What is likely to change is the rate at which this process occurs. If the rate of both scour and seepage erosion is increased under Basslink, the rate of large woody debris deposition will increase. This implies a higher rate of tree fall associated with 'Stage 2' erosion as compared to present. Conversely, in river reaches where seepage erosion is presently the dominant process controlling bank stability, the rate may decrease if seepage rates decrease. Accurate and quantitative prediction of this is not possible, and can only be confirmed with monitoring (see Section 11).

10.3.2.6 Impacts of Basslink with Distance from the Power Station

Power station related impacts on alluvial banks decrease with distance from the power station as the proportion of unregulated flow increases and river level fluctuations decrease. In Zone 4, river level fluctuations, the rate of river level decrease and the maximum water surface slopes developed following drawdown are all considerably less than in Zone 2. The bank stability modelling (Section 7.3.3) indicated that the present range of power station operations affects bank stability at the site below the confluence of the Gordon and Denison Rivers (Zone 4) by about 6 percent, where as in Zone 2, river level fluctuations can alter Factor of Safety values by almost 15% (see Section 7.3.3).

Bank toe scour rates also appear to be lower with distance from the power station. Degradation of bank toes was on the order of ≤1 cm in Zones 4 and 5 over the duration of the investigation; where as degradation of 15 to 30 cm was documented using erosion pins in Zones 2 and 3. This downstream reduction is despite the higher flows experienced in the downstream sections, due to tributary inputs. The lack of scour of the downstream banks is undoubtedly related to the greater presence of vegetation on the banks, which in turn is related to greater fluctuations in water levels. It also supports the hypothesis that the steep water surface slope created when the power station is turned on is a major contributor to scour in the upstream sections.

This downstream decrease in power station related impacts should not change under Basslink, as the proportion of flow derived from unregulated rivers will continue to increase with distance downstream. In contrast with present conditions, there will also be a greater proportion of time that the banks are subjected to natural rates of water level fluctuations, coinciding with the increased periods of power station shut down. The potential sediment transport capacity is predicted to increase in all zones. In Zone 4, the magnitude of the predicted increase is similar to the predicted decrease the site experienced due to initial regulation, and is similar to the error estimates associated with the analysis.

Similar to present conditions, the most pronounced erosion under Basslink is likely to occur predominantly in Zone 2, and in some alluvial areas of Zones 1 and 3. In Zone 2 both scour and possibly seepage erosion will be exacerbated because of the dominance of power station derived flow combined with a relatively narrow but steep river channel. These produce high river-level fluctuations and high water velocities. Areas currently most prone to erosive attack are steep alluvial banks, where tea tree is absent, and coverage by large woody debris is low. These areas will remain highly susceptible to erosion until bank stability is increased through the accumulation of debris on the bank toe and face, under the present or Basslink flow regimes.

Scour and the eventual removal of tea tree communities in the riparian zone of the banks will eventually occur in Zones 1 –3 under the present flow regime or under Basslink as the river respond to 3-turbine power station operation. This removal is likely to occur more rapidly under Basslink, assuming the rate of scour increases. Once the tea tree and root mat is removed, the higher banks supporting rainforest species inland of the tea tree will be exposed to scour and seepage erosion, thus progressing from ‘Stage 1’ to ‘Stage 2’ of the idealised erosion scenarios. Therefore, the present areas of Zones 1- 3 occupied by tea tree must also be considered to be ‘hot spots’, although on much longer time frames.

10.3.3 Basslink Impacts on Vertical Cobble Banks

Due to the buttressing of cobble banks by unconsolidated cobbles at the toe and lower bank, it is assumed that seepage induced slip failures following drawdown is the primary erosion process affecting the vertical cobble banks under the present flow regime. It is also assumed that the slip failures witnessed during the summer of 2000 on vertical banks was the result of the extended period of power station operation. Linking recent erosion to extended power station full-gate operation is warranted because initial investigations in October 1999, prior to extended high flow suggested the vertical cobble banks were stable, and the comparative aerial photo analysis shows no significant changes in these banks over 25 years.

Under Basslink, the occurrence of draw-downs will increase due to the more frequent maximum discharge to 'off' flow changes, however, saturation of the banks will vary on a seasonal basis. It is possible that in the summer months under Basslink, when the power station is operated at or near maximum capacity for extended periods, saturation of the cobble banks will be equivalent to that produced during the summer of 2000, and the banks will become unstable following draw-down. It is unlikely the risk of failure would be increased for other seasons.

10.3.4 Basslink Impacts on In-Stream Cobble Bars and Bed

The present morphology and positioning of bars within the Middle Gordon River would not be expected to change under Basslink as compared to present operations, as the bars will be subjected to the same range of flow conditions. The aerial photo comparison (1974 and 1999) indicates that the bars have remained stationary during the first 20+ years of power station operation, and changes to release patterns anticipated under Basslink should not change this.

The extension of cobble bars at the downstream end, most apparent in Zone 2, may continue assuming the delivery of sediment from the Albert River and upstream is unchanged.

Under Basslink, there should be no changes to the surfaces and crests of cobble bars presently above high water level, with colonisation of the surfaces by vegetation continuing.

Bar surfaces subjected to inundation at high flow may experience more scour, as slightly higher current velocities associated with maximum discharge operation will occur a greater proportion of the time. The limited presence of 'rip up clasts' on bar surfaces suggests that this process occurs occasionally under the present flow regime. If this process is related to maximum discharge power station operation, then it may increase under Basslink. However, it is important to emphasise that there is still a huge difference between the peak shear-stresses associated with 3-gate operation under Basslink, and the flood peaks that preceded regulation. These flood peaks were responsible for armouring the bars.

Because the highest flows will not increase in size, only duration, the size of bed load presently transported by the river is not expected to change.

The mobile flanks of cobble bars may experience greater movement due to the longer duration high flow events resulting in undermining of the stable bar surfaces.

Overall, given the size of the material contained in the cobble bars compared to the size of the material presently transported by high river flow, no major modification to the morphology of the bars is expected. Breaching of cemented surfaces through undermining and 'ripping' may increase under a Basslink flow regime, but because the flow is insufficient to transport the large cobbles, most of the material will not be exported from the bar.

10.4 Visual Changes under Basslink

Because of the inaccessibility of the Middle Gordon River, seeing the area requires either travel by helicopter, aircraft, or below the 'Splits', by boat. Therefore, views of the study area tend to be from the air, or from the river channel.

An assessment of potential visual changes to the banks of the Middle Gordon River was completed by selecting four images of Zone 2 and applying the postulated changes under Basslink to the photos using photo enhancement techniques. Three images reflecting a range of 'typical' bank conditions were chosen along with one image showing an 'extreme' series of landslips part of which occurred during the study period. All chosen shots depict low water level, because during high water, the bank features are not visible (Photo 74). Changes applied to the photos included:

- Increasing the height of the Plimsoll line through loss of vegetation;
- Decreasing bank slope reflecting potential seepage and sub-aerial erosion;
- Reducing the amount of tea tree on banks; and
- Increasing the deposition of LWD on banks due to tree fall.

Paired photos showing the 'present' photo and the potential theorised 'Basslink' changes are shown in Photo 75 to Photo 82. The Basslink impressions for the first three 'typical' images are intended to show banks in equivalent stages of bank adjustment to the flow regime as the present images. Intermediate stages that are likely to be characterised by high erosion activity, including seepage erosion and tree fall are not shown, but would be expected to occur. The Basslink image in the final set of photos shows a possible 'stable' endpoint for slips and tree fall occurring in steep alluvial banks. The actual bank shown in the photo contains a several metre thick section of cobbles, and it is possible that the 'endpoint' of these slips may actual have steeper vertical faces than depicted.

The first image (Photo 75 and Photo 76) is an aerial shot of a reach of the Gordon River in Zone 2. The Plimsoll line is higher under Basslink, and there is increased tree fall, but overall, aerial views of the river are not expected to alter markedly under Basslink. The next two sets of images (Photo 77 and Photo 78; Photo 79 and Photo 80) show shallowly sloping and steeply sloping banks, respectively. The steeply sloping banks are upstream of the Splits, where water level fluctuations are greatest in the study area. In both sets of images, the Basslink visualisations show an increase in the Plimsoll line, and devegetated bank toes. The shallowly sloping banks show a loss of tea tree. The steeply sloping bank would be expected to undergo significant additional tree fall under Basslink as the Plimsoll line increases in height (due to longer duration high flow events).

The final set of images (Photo 81 and Photo 82) shows a series of landslips, several of which occurred during the study period. The Basslink visualisation shows a decrease in bank slope, the accumulation of woody debris on the lower bank face and toe, and revegetation of the slips above high water level by ferns. As mentioned before, the presence of cobbles in these banks may result in steeper vertical faces with less vegetation than shown here. However, the depicted 'endpoint' is applicable to scarps created in steep riverbanks due to tree fall.

These photos are idealised, and should not be considered to be exact projections, but rather indications of changes anticipated to occur under Basslink based on the present understanding of bank erosion in the river. The photos show the types and magnitude of changes anticipated to occur over a long period (decades), recognising that a period of active adjustment is likely to occur following the implementation of a new flow regime.

10.5 Summary of Basslink Impacts

The potential impacts to riverbanks in the Middle Gordon River due to the implementation of Basslink as compared to present power station operation can be summarised as follows:

- There will be no significant broad scale changes to the planform of the river, as the river channel is largely controlled by bedrock.
- There will be little change to bedrock or vertical cobble riverbanks, except perhaps a minor upward adjustment of the Plimsoll line.
- Generally, the placement and morphology of instream cobble bars, which are largely stable under the present flow regime of the river, are unlikely to be affected by Basslink. In Zones 1 and 2, the incision and head cutting of bars is likely to increase due to increased high flow.

Vegetation on bars below high water level will continue to be lost in Zones 1-3 due to scour, as is occurring under the present flow regime.

- The size of bed load material transported by the river will not change, especially in the reaches above the Splits where bed load input by tributaries is limited.
- Alluvial riverbanks will continue to show the greatest response to flow regulation.
- Scour of alluvial banks may increase, as high flows, and steep water surface slopes associated with the power station turning on, occur a greater proportion of the time.
- A change in patterns of riverbank saturation due to shorter periods of power station operation will alter conditions leading to seepage-induced erosion. The probability of 'worst case conditions' which lead to full bank saturation are lessened with Basslink, because power station discharge durations are short and there are more opportunities for drainage of the banks with frequent power station shutdowns. However, the average annual number of drawdown events increases significantly with Basslink, which may lead to an increase in the occurrence of seepage induced erosion, but probably not an increase in severity because banks are less saturated. .
- Stability of the banks under Basslink will be controlled by the same processes presently operating in the system: stabilisation of the bank above high water by vegetation, and of the bank face and toe by deposition of large woody debris. Revegetation of the bank faces between low and high water levels is unlikely to occur under Basslink (or the present operating regime).
- Overall, Basslink will alter the rates rather than the processes leading to bank erosion, and the processes contributing to bank stability will be the same under either operating regime.

11 MITIGATION OPTIONS

Ideally, the stabilisation of the bank face and toe through the re-establishment of vegetation would be the preferred mitigation objective in a natural river system. The size and importance of the Gordon Power scheme to the State's electricity grid negates the possibility of establishing a 'natural' flow regime in the river which would promote the establishment of vegetation in the riparian zone. Therefore, mitigation options that seek to stabilise the banks and control the egress of water from the banks in the absence of vegetation need to be identified.

Potential mitigation options fall into three general categories: altered flow regime from power station, altered flow regime due to large scale engineering works downstream of the power station; and physical bank protection works.

11.1 Altered Flow Regimes from Power Station

The aim of altering the flow regime from the power station would be to alter the rate of present erosional processes, and minimise scenarios that produce a high risk of alluvial bank erosion. This could be accomplished through:

- Limiting the duration of maximum power station 'on' events involving three turbines;
- Establishing drawdown rates or steps when flow is decreased from the power station; and
- Maintaining a minimum environmental flow requirement in the river.

The merits of each of these potential management strategies are discussed below.

11.1.1 Limiting Duration of Maximum Discharge Events

A management strategy that included controlling the duration of power station 'on' events would aim to minimise the large-scale saturation of banks, and thus reduce the hydraulic head between the bank and river following river level decrease. This would reduce the risk of seepage erosion, and limit the duration of maximum bank scour. This approach is warranted for three-turbine operation only because field measurements and observations suggest that seepage erosion is far less active when only two turbines have been in use, and scour rates are lower.

Piezometer results indicate that power station 'on' events of 24 hours or less do not increase water levels in the banks at distances of greater than 5 to 10 metres from the river (depending on bank morphology), and could be used as an upper limit for three-turbine operation. The duration of the subsequent shutdown would need to be long enough to allow drainage of water from the banks prior to the next power station 'on' event. Limiting the duration of maximum power station operation would also allow vegetation on the top of the bank the opportunity to drain and obtain a fresh supply of oxygen in the root system (see Davidson and Gibbons, 2001). This is an important consideration for the geomorphology, as vegetation is a primary stabilising factor on the tops of the banks.

11.1.2 Power Station Ramp downs / Step Downs

Seepage erosion may be reduced if the rate of drawdown following 3-turbine operation to off events, is reduced. There are two options for this approach. One would be to 'step' down to an intermediate operating level for a fixed time period promoting the establishment of a relatively shallowly dipping hydraulic gradient between the bank and the river while the top portion of the bank drains. This would reduce the amount of sediment that could be entrained by the water draining from the upper portion of the riverbank. If the power station has been operating at three-turbines for only a very short time, delaying a decrease in river level could lead to an increase in bank saturation. However, if the intermediate level was equivalent to two-turbines operation, there should not be a negative impact on the banks, as they are believed to be in at least quasi-equilibrium with this operating level.

Alternatively, a maximum rate at which the power station could reduce discharge following three-turbine operation (rampdown) could also decrease hydraulic gradients in the bank and may reduce seepage erosion. Under present operating practices, water level at the tailrace can decrease up to 5 m in approximately 30 minutes following a maximum discharge (260 m^3/s) to off event. This translates into river level decreases on the order of 3 m over about 2 hours in Zone 2.

Two experimental power station ramp-downs were conducted by Hydro Tasmania to investigate the impact these measures might have on in-bank water levels. Power station usage prior to each trial resulted in partially saturated banks, and ramp-downs of 30 m^3/s per hour and 60 m^3/hour were tested. For each trial, the flow from the power station was reduced by the prescribed amount and then held for 1-hour prior to the next reduction. The 60 m^3/s per hour ramp-down is equivalent to reducing power station output from 3 turbines to 2 turbines.

Figure 39, Figure 40 and Figure 41 show hourly water levels at the Zone 2 piezometer site for maximum discharge to off drawdown events without a rampdown and with a 30 m^3/s per hour and 60 m^3/s ramp-down, respectively. A summary of river water level change and water surface slopes for these events and the 60 m^3/s per hour rampdown are presented in Table 23 and Figure 42 and Figure 43.

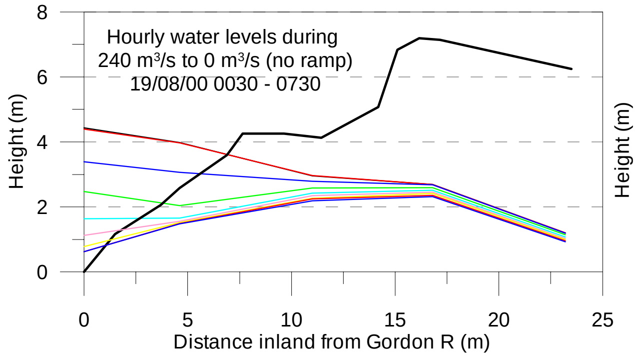


Figure 39. Hourly water levels during a maximum discharge to off drawdown event in a partially saturated bank.

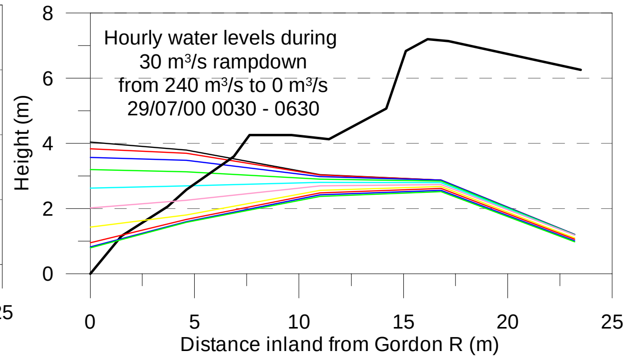


Figure 40. Hourly water levels during a 30 m^3/s per hour ramp-down from maximum discharge to off

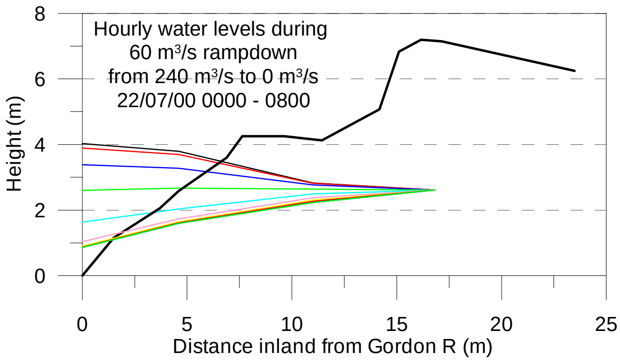


Figure 41. Hourly water levels during a 60 m^3/s per hour ramp-down from maximum discharge to off

Comparing the results from the 3 cases indicates that a 30 m^3/s per hour rampdown reduces the rate of water level decrease considerably compared to the no rampdown scenario, with the 60 m^3/s per hour rampdown producing intermediate results. The 30 m^3/s per hour case delays the development of maximum water slopes out of the bank by several hours, but all three cases have similar slopes six hours after shutdown.

The water surface slopes associated with all three of the partially saturated bank cases presented here are lower than the slopes created when the banks are fully saturated (see Table 16), which ranged from 0.16 to 0.19 for 3 to 8 hours following power station shutdown. No experimental ramp-downs were conducted when the banks were fully saturated. However, extrapolating the findings of from the partially saturated bank rampdowns suggests that water surface slopes could be reduced by up to 50% for up to 5 hours following shutdown, after which time similar maximum slopes (0.19) would be expected to form.

Table 23. Summary of river level and in-bank water slopes following at Zone 2 piezometer site following no rampdown, and rampdowns of 30 m^3/s per hour and 60 m^3/s per hour. The water slope is shown as the height difference between Probe 3 and Probe 2. Negative values indicate water surface slopes into the bank.

Time (hours)	No Ramp Down			30 m^3/s per hour Rampdown			60 m^3s per /hr Rampdown		
	River Level (m)	Change in River Level (m)	Water Slope	River Level (m)	Change in River Level (m)	Water Slope	River Level (m)	Change in River Level (m)	Water Slope
0	4.43		-0.16	4.04		-0.12	4.03		-0.15
1	4.39	-0.04	-0.16	3.84	-0.2	-0.1	3.7	-0.33	-0.11
2	3.39	-1	-0.04	3.57	-0.27	-0.08	3.03	-0.68	-0.04
3	2.47	-0.92	0.08	3.19	-0.38	-0.04	2.11	-0.92	0.04
4	1.63	-0.84	0.12	2.63	-0.56	0.02	1.26	-0.85	0.09
5	1.12	-0.51	0.12	2.02	-0.61	0.07	0.94	-0.31	0.10
6	0.78	-0.34	0.12	1.43	-0.59	0.12	0.88	-0.06	0.10
7	0.62	-0.17	0.12	0.96	-0.47	0.13	0.87	-0.01	0.10
8	0.62	0	0.11	0.82	-0.13	0.13	0.85	-0.02	0.09

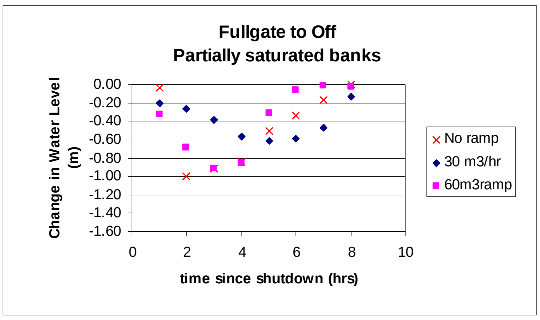


Figure 42. Hourly changes in river level following power station shutdown for a 60 m^3/s per hour rampdown; a 30 m^3/s rampdown and no rampdown.

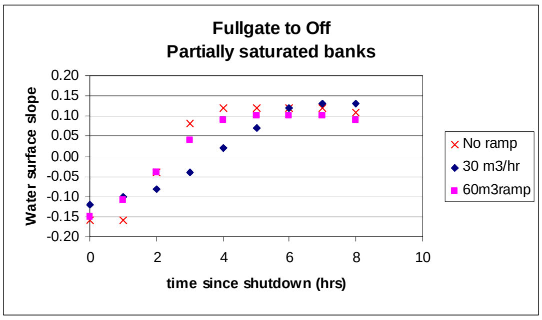


Figure 43. Hourly water surface slopes at Zone 2 piezometer site following a 60 m^3/s per hour rampdown, a 30 m^3/s per hour rampdown and no rampdown

A hindrance to establishing appropriate ramp-down or step down rates at the present time is a lack of information pertaining to the threshold conditions required for sediment flows to occur. Maximum water surface slopes may not be required for the initiation of sediment movement, and the extent of near bank, rather than total bank, saturation may exert a stronger control on the process. This issue is discussed in Section 12.

A step-down rule has been considered by Hydro Tasmania that reduces power station discharge from 210 m^3/s or greater to 150 m^3/s in a step, and then maintains the 150 m^3/s flow for a minimum of one-hour. Initial analysis suggests that the rule has limited value when the banks are fully saturated. This is because by the time the banks have become fully saturated, a large volume of water has been stored in the pools, backwaters and banks upstream of Zone 2. Although the power station reduces flow by 60 m^3/s in the first hour, there is almost no lowering of river water level during this time, presumably due to the draining of water stored upstream. At the end of 1-hour, when power station discharge can be reduced to zero, water levels decrease from virtually maximum-discharge levels to off, resulting in little or no net benefit for the banks. Increasing the time the 150 m^3/s step is occupied may increase the efficacy of the mitigation option, and is discussed in Section 12.

11.1.3 Minimum Environmental Flow

The maintenance of a minimum “environmental” flow in the Middle Gordon River would increase river levels during periods of power station shut down, leading to a reduction in the height of river level fluctuations, and a reduction in the hydraulic gradient between the banks and the river during power station shutdown events. Importantly, higher power station ‘off’ river levels would also produce a lower water surface slope at the beginning of the next power station ‘on’ event, which would reduce scour caused by the steep water surface slope when the power station turns on. The minimum environmental flow reduces the water surface slope because it reduces the bed friction which must be overcome for the water surface to rise.

This option in combination with a ramp-down or step-down may be the optimal approach for reducing erosion rates in the Middle Gordon River.

11.2 Altered flow regime from an engineered structure downstream of the power station

A second approach to the regulation of flow downstream of the power station would be the construction of large-scale physical works, such as a re-regulation weir, that could smooth peaks and troughs in the discharge pattern and deliver a more constant flow to the river. The implementation of this type of infrastructure could reduce the heights and rates of water level fluctuations, prevent the repeated saturation and draining of banks, promote the re-establishment of vegetation below the present high water level, and reduce maximum scour rates.

In spite of the potential benefits of such an approach, its investigation has not been pursued as part of the geomorphic investigations, as it is not in keeping with the ‘Wilderness’ designation of the WHA. Its implementation would have significant negative environmental impacts that are believed to outweigh any benefits, and such a plan is unlikely to be socially or politically acceptable.

11.3 Physical bank protection works

The third type of potential mitigation option involves the physical stabilisation of riverbanks. Stabilisation of the bank toe would reduce scour rates and promote the development of a stable bank slope. Stabilisation of the banks further upslope, particularly adjacent to void openings, would trap seepage derived sediments and promote the development of a stable seepage slope. This mitigation option is proposed because of repeated observations and documentation in this study of natural materials (fallen trees, cobble and bedrock seams, etc) physically stabilising the banks.

During field investigations, trials were undertaken in which vertical netting was placed over void openings, resulting in the trapping of sediment flows whilst allowing the water to drain. The trapped sediment formed a near horizontal surface, extending from the net to the back wall of the void. The placement of logs, sandbags, or geotechnical fabrics that retain sediments while allowing water drainage are all potential mitigation strategies that are likely to be effective in local stabilisation of banks.

To be effective over a large area of the river (e.g. Zone 2 or mouth of the Albert River), a large number of installations would be required, which might conflict with the Wilderness zoning of the Gordon River in the WHA Management Plan. Depending on the techniques used and the scale of the works, it could give the banks an unnatural appearance, and be visually intrusive under low flow conditions. There may also be prohibitive logistical difficulties and extended power station shutdown requirements which could be costly. It may, however, be an option that could be pursued on a trial basis over limited areas.

12 FUTURE MONITORING AND INVESTIGATIONS

12.1 Outstanding Questions

The Basslink geomorphology investigations have resulted in a huge increase in the understanding of the current geomorphological condition of the Middle Gordon River and the predominant processes controlling erosion of the riverbanks. Like any scientific investigation, a number of questions have been raised during the course of the investigations that have not been able to be thoroughly addressed. Areas that may be of interest to pursue with further investigations include:

- the establishment of a sediment budget for the area;
- water movement in the vertical cobble banks;
- identifying the precise hydraulic conditions leading to seepage induced sediment flows; and
- the influence of rain on bank saturation.

The importance and feasibility of investigating each of these issues is discussed below.

The establishment of a sediment budget would provide a quantitative estimate of the sand and gravel contributed by the tributaries or mobilised from the banks, assuming the sediment released from Lake Gordon is minimal. If the tributary and bank contributions could be separated, then estimates of alluvial bank retreat could be made. The very low concentrations of suspended sediments measured in the study area suggest that either bed load transport is the dominant transport mechanism, and/or sediment transport is episodic. Given the logistical difficulties associated with sampling the river under high flow conditions (inaccessible upstream of the Splits due to safety considerations; limited and very difficult and costly access downstream of the Splits), and the amount of sampling that would be required under a variety of flow regimes in order to establish a useful budget, pursuing this investigation is not feasible.

Turbidity meters would not be useful as suspended sediment rates are too low, the material is predominantly sand which is not well-detected by turbidity meters, and the dark water colour could confuse the results. One also has to question whether the information gained from trying to develop a sediment budget would merit the considerable cost and effort, as it has already been established that sand and gravels are the predominant sediment size classes transported by the river, and that the alluvial banks are being eroded through scour and seepage erosion. Using more passive indicators, such as erosion pins, scour chains and repeat surveying, over a long monitoring period and relating results to power station operating histories, would adequately yield the required information.

The water movement into and out of cobble banks became a question during the study year because the first field observations suggested long-term stability, whereas following the unique summer high flow event in the river, several landslips were observed. This change in apparent stability of the vertical banks lead to the hypothesis that there is a saturation trigger beyond which the banks are not stable, which is not routinely achieved under ‘typical’ power station operating conditions, but was exceeded during the summer extended high flow event.

It was not feasible to install piezometer in the vertical cobble banks as attempts at drilling a bank containing a basal cobble unit were unsuccessful due to the hard quartzite cobbles. It is also questionable how applicable the information would have been to the cobble banks overall, as a large variation in draining characteristics was observed in the field, with some units freely draining, while others did not. In lieu of documenting water movement in the banks, it is suggested that photo monitoring, especially following unique or changing flow regimes, be used to relate changes in the vertical cobble banks to flow conditions in the river.

Throughout the study period, the active deposition of sediment flows following maximum discharge operation was never observed. Typically, between the time the power station shutdown and access to the river was feasible, eight hours or more had passed. Due to safety considerations, it was not possible to be situated on the banks of Zones 1 – 3 during a drawdown episode. By the time observations were possible, water was observed to exit the banks, but what were interpreted to be fresh sediment flows were already deposited. This time-frame, of up to eight hours following power station shut-down is consistent with pipe-meter data showing maximum hydraulic gradients within the first 6 hours following drawdown.

Knowing the precise conditions leading to seepage flows is necessary for developing power station operating constraints that minimise these conditions. This can be determined through the collection of piezometer data and direct observation of the banks following a range of power station operating patterns. Similar observations would be required to assess the effectiveness of any experimental ramp-down or other mitigation option.

Another outstanding question from the investigations is, what is the role of precipitation in bank saturation and seepage erosion? For much of the study period, rainfall was very low. Unfortunately, access to the river was not possible during May and June when rainfall was highest, which prevented direct observations of the banks under high rainfall conditions. The piezometer, which were installed in March, experienced some failures during May through July, resulting in unreliable information. Although frequently repaired, the amount of useable data generated continued to be limited, and a good record of bank water levels through a major rain event was not obtained, although smaller events were captured.

Given the high permeability of the sand banks and the high transmissivity of the overlying organosol, water levels in the banks are likely to respond quickly to rainfall events, resulting in an increase in the groundwater surface in the banks. The observation of pipes above present high water level on the banks indicates that water levels increase above high river level, and water exits the banks, which is consistent with piezometer data that show an increase in water level during / following rainfall events. Knowing how different rainfall rates affect bank saturation would be useful for refining potential power station operating rules conditions, such as on a seasonal basis, but is not a major impediment to the initial development of experimental operating rules.

12.2 Monitoring Considerations

Any further monitoring of Gordon River fluvial geomorphology should consider the following.

Future monitoring of the study area is strongly recommended whether Basslink is implemented or not. On going monitoring is warranted to confirm and extend the present understanding of the system drawn from a one-year study period. This is especially true because the study year included a four-month unique high flow event in the river's history, and many of the processes observed undoubtedly reflect these conditions. It is possible that the relative significance of processes such as scour and seepage vary depending on the flow regime, and a fuller understanding of the system can only be gained through additional monitoring.

Short term monitoring should focus on identifying groundwater surface slope conditions associated with occurrences of sediment flows, so that ramp-down or step-down rules can be developed, if appropriate. These investigations require the establishment of at least one long-term, more reliable piezometer array in Zone 2, and the development of infrastructure that would provide access to the river for researchers (probably a helicopter landing site). Observations of sediment flows could then be linked to the elapsed time since power station shut-down and the groundwater surface within the bank. Observations would need to incorporate both fully and partially saturated bank conditions due to variable power station operation, as well as inflows due to rainfall.

Apart from these specific investigations, general, long-term monitoring of the Middle Gordon River is also warranted. Because of the logistical difficulties in accessing the study area, and the high costs involved, the final monitoring strategy should be developed in consultation with researchers from other disciplines, such that common sites can be identified that would streamline logistics and provide a multi-disciplinary understanding of bank processes. It is especially important to integrate geomorphological monitoring with vegetation monitoring, due to the strong relationship between vegetation and bank stability.

The continued measurement of established erosion pins in stable or semi-stable areas is essential to extend the available data set relating to scour of the bank toe, and to establish/confirm the relationship between power station operations and scour response. Now that there is a better understanding of the role tea tree, and LWD play in the study area, new erosion pin and scour chain sites should be established in stable and active areas.

During the study, erosion pins and scour chains located in areas prone to seepage erosion were unsuccessful, due to the down-slope mass movement of sediment banks. Different techniques, such as repeat photo monitoring and/or the surveying of banks should be used to track changes. Ideally, non-intrusive methods should be chosen because disturbance of the bank through investigator access lead to increased down-slope movement of material.

Regular photo monitoring of selected sites will provide information about rates of processes, 'end points' and the relative stability of different banks. Selected sites need to reflect the spectrum of conditions present in the system, ranging from active to stable banks. Of particular use is the continued visitation and photo monitoring of major tree falls that have occurred during the study year. The continued erosion of the banks through undercutting of the newly exposed material has been well documented, and the same sites warrant continued observation to provide an indication of the time scales associated with the establishment of more stable conditions. Similarly, photo monitoring of cobble bars will provide information about the stability of the bar surfaces and rates of undermining through cobble movement on the flanks.

On a longer time-scale (5-10 years?), aerial photography of the study area should be repeated, especially before and after major alterations to the flow regime of the river. The lower Albert River and the mouths of other tributaries should be included in the photographs and subsequent comparative analysis.

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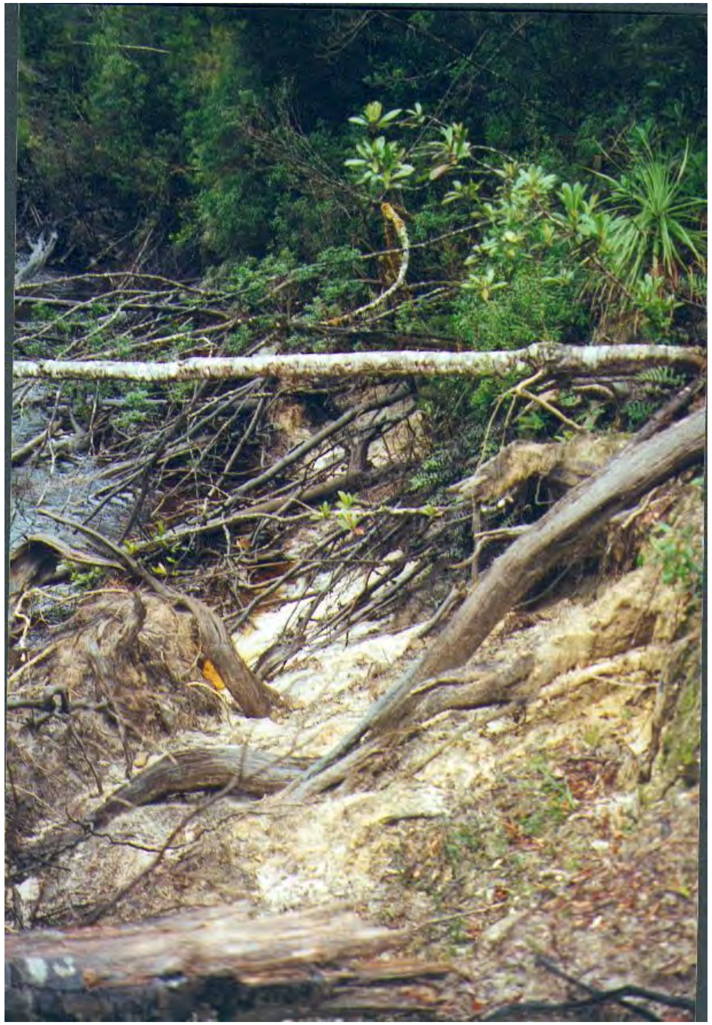

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ATTACHMENT 1

LIST OF CONTRIBUTORS

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Contributor	Affiliation	Contribution
Dr. Bruce Abernethy	SKM	General geomorphic advice & pore water pressure discussion
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Matt Brook	Univ Tasmania	Sediment analysis
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Dr. Fiona McConachy	Hydro Tasmania	Hydrologic modelling &analysis
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Lennie Palmer	Hydro Tasmania	Hydrologic modelling & analysis
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Hayden Foley	Hydro Tasmania	Photo visualisations
John Styles	Univ Melbourne	Bank stability modelling advice
Scott Wilkinson	University of Melbourne	Potential sediment transport modelling

ATTACHMENT 2

DESCRIPTION OF GEOMORPHOLOGICAL UNITS

(ROBERTS AND NAQVI, 1978)

LAND SYSTEMS

From Christian and Sharp-Paul. 1979.

Refer to Figure 2. Geomorphic Map of Middle Gordon River for distribution of land systems

<u>Area A (Dissected Broad Ridge):</u> this broad north-south trending ridge with moderately dissected sides and very uneven crest comprises Lower Ordovician sandstone folded into a broad north-south trending anticline with gently to steeply dipping strata and a sub-rectangular pattern of structural discontinuities. The drainage pattern is sub-parallel to rectangular, and controlled by structural discontinuities, particularly on the crest. The principal feature is the superimposed main drainage valley of the Gordon River as it enters its tidal reach. Relief 0 - 500 m.

<u>Area B (Dissected Hills and Ridges):</u> this is the eastern and northern slopes of a dissected and partly eroded north-south trending range of Pre-cambrian quartzite and schist (Charles Range). Extensive areas of quartzite outcrop along some ridges, while schist occupies the slopes. Drainage patterns are dendritic. Relief 100 – 750 m.

<u>Area C (Dissected Ridge):</u> this land form has a characteristic scalloped appearance, caused by dissected steep dip slopes in mainly steeply dipping Lower Ordovician dolomitic sandstone with limestone/dolomite beds. Slopes are moderate to steep and drainage is incised, parallel and down dip. Relief 80 – 280 m.

<u>Area D (Low Lying, Broad, Alluvial Plain):</u> the elongate, north-south trending plain is covered by late Tertiary or Quaternary alluvium of gravel, sand and silt overlying steeply dipping or intensely folded Lower Ordovician limestone and siltstone (Gordon Limestone). Narrow semi-continuous ultra low narrow ridges and swells run parallel to the long axis of valley: these are common to the south, but rare and les continuous north and east of the Gordon/Franklin Rivers, representing bedrock highs and containing rare outcrops. Main drainage is sinuous and incised with sub-parallel second order streams at intervals of 1 – 3 km. More deeply incised stream beds (Lower Olga and Gordon-Franklin Rivers) consist of pools, short rapids and gravel bars and contain common narrow-backed ridges or steep cliff banks of limestone. Relief 0 – 80 m.

<u>Area E (Repeated Ridges and Valleys):</u> Silurian and Devonian sandstone, siltstone and minor dolomite have been folded into a series of plunging anticlines and synclines elongated north-south with steeply dipping limbs and broken across strike by several major dislocations. Differential erosion patterns along the bedding have produced a parallel ridge and valley topography with clearly defined extremities. An elongated trellis drainage pattern predominates; at intervals, first and second order streams breadk across the ridges in an east-west direction. Relief 80 – 400 m.

<u>Area F (Dissected, Elongated Dome):</u> this north-south trending, faulted structural dome, with steeply dipping flanks of Silurian and Devonian sandstone, siltstone and minor dolomite, has been dissected by the east-west trending, superimposed drainage valley of the Gordon River. Relief 80 - 400 m.

<u>Area G (Complex Valley Floor):</u> solution activity in limestone has resulted in a low lying area subsequently covered in part by a thick blanket of gravel, sand and silt, now partly cemented. Recent river erosion by the Gordon and Denison Rivers has cut through the gravel and the river bed is in limestone. Present minor stream activity north of the Gordon is partly underground, resulting in at least one discontinuous open cave system. Relief 30 – 80 m.

<u>Area H (Repeated Ridges and Valleys):</u> differential resistance to erosion has produced repeated ridges of more resistant Silurian-Devonian sandstone between softer siltstone and minor calcareous beds in the valleys. The ridges are normally steep and narrow, and elongated approximately north-south parallel to the axes of the folds. Drainage is dominantly of the trellis type, elongated north-south. Relief 120 – 400 m.

<u>Area J (Alluvial Plain):</u> an elongated north-south, trending alluvial plain is covered by a late Tertiary or Quaternary alluvium of gravel, sand and silt overlying steeply dipping and/or complexly folded Silurian and Lower Devonian sandstones and siltstones with minor calcareous beds. The eastern margin is a faulted contact against the deformed Precambrian metamorphics. Relief 40 – 120 m.

<u>Area K (Repeated, High, Dissected Ridges and Valleys):</u> this unit comprises dissected, partly eroded north-south trending mountain ranges (Nicholls Range,Doherty Range) where differential resistance to erosion has produced repeated strike ridges of more resistant Precambrian metaquartzite and intervening valleys in softer schist. The western boundary of this unit is marked by the Orange River Fault, a major structural discontinuity between Precambrian and Palaeozoic rocks. Drainage is dominantly trellis type. Relief 80 – 600 m.

<u>Area L (Elongated, Dissected Flat Valley):</u> this elongated, north-south trending, narrow valley is covered by late Tertiary or Quaternary alluvial material overlying easterly dipping, Precambrian schist. Outwash fans are common, particularly on the eastern slopes. Relief 24 – 320 m.

<u>Area M (Mixed Dissected Ridges and Valleys):</u> this land unit has been deeply dissected by the erosion of soft Precambrian schist and is characterised by irregular narrow short gullies. Relief 80 – 300 m.

<u>Area N (Dissected High Mountain Range):</u> this comprises the western slopes of the dissected and partly (selectively) eroded north-south trending Prince of Wales-Wilmot Ranges. Extensive area of quartzite and schist outcrop along the ridges. The effects of glacial action are visible on the eastern slopes of Wilmot Range in the form of cirques and moraine deposits. Relief 80 – 1060 m.

<u>Area O (Complex, Intermontane Valley Floor):</u> solutional activity in dolomite has eroded a low lying area subsequently covered by a thick blanket of sand and gravel; recent erosion by the Denison and Maxwell Rivers has cut down through the gravels to bedrock in eastern and southern areas. Broad, undulating, dissected ridges give scalloped landforms in relatively unmetamorphosed argillaceous sediments. Trellis, dendritic and swampy drainage patterns occur. Relief 100 – 320 m.

<u>Area P (Broad, Low, Dissected Ridge):</u> this broad, north-south trending ridge, in weathered, steeply dipping phyllite and quartzite of Precambrian age, shows dissected sides and a very uneven rounded crest. Relief 120 – 320 m.

<u>Area Q (Elongate Alluvial Fan Complex):</u> quartzite and schist eroded from the step western slopes of the Wilmot Range have produced a series of outwash fans up to 1 km long and 0.5 km wide in the valley of the Albert River. Relief 200-340 m.

ATTACHMENT 3

DESCRIPTION OF AERIAL PHOTO INTERPRETATION

Gordon River Pilot Mapping Project

PHOTOGRAPHY:
Two sets of aerial photography were used. Black and white photography, at a scale of 1:20 000, flown in 1974 was compared to colour photography, at a scale of 1:5000, flown in December 1999.

PHOTOGRAMMETRIC EQUIPMENT:
The mapping was undertaken using a Zeiss Planicomp P2 stereoplotter.

METHOD:
Photography flown in 1974 was used to download control onto the Dec1999 photography, this was done by identifying “common points” on both sets of photos and then determining their spatial coordinate values from the 1974 images. Aerotriangulation was performed on the new photos using the P2 Planicomp and the coordinates derived from the photos used as our spatial reference. The results of the triangulation were determined by processing the data with BINGO bundle adjustment software.
The stereo models were then absolutely oriented to the ground and the mapping process begun. Data was mapped from the photos and recorded in Microstation design files.

SCALE:
Approximate mapping scales are 1:5000 from 1:20000, 1974 photography and 1:1000 from the 1:5000, 1999 photography

ACCURACY:
With the dense vegetation surrounding the Gordon River, the absolute accuracy of the mapping would be +/- 5m in X,Y & Z, however, in a relative sense the accuracy of the mapping would be +/- 1m in X,Y & Z although this does not take into account different water levels and vegetation at the time of photography.

INTERPRETATION:
- The *drip line* was mapped by capturing data along the edge of the trees, as best as possible.
- The *sandy/rocky shoreline* was mapped by capturing data wherever the edge of the river was visible and where it was not coincident with the drip line.
- The *logs* were mapped firstly from the 1999 photography with a line placed along the visible edge. The trunks of trees were mapped only. The 1974 photography was more difficult to interpret. The data captured from the 1999 photography was laid underneath and the 1974 photography was checked closely to see whether the same logs were present then or not.
- The *clearings* were mapped where there was obvious vegetation disturbance close to the river, but behind the drip line.
- The *pools within sand banks* were mapped where possible. At times it was difficult to distinguish staining from the actual presence of water.
- The *buildings* were a little difficult to interpret due to glare on the 1974 photography.
- The *approx channel* was mapped in the Gordon Splits areas and are an approximation of the colour change from rocks regularly covered with water.
- The *underwater sand bank* was mapped in one area to indicate the extend of the accumulation of sand that has occurred between 1974 and 1999.

- The Gordon Splits areas were difficult to map due to the steepness of the terrain.

ANNOTATION:
The 1999 photography was mapped first. While the 1974 photography was being mapped, it was compared with the data captured from the 1999 photography. As these comparisons were made, annotation was added to assist explaining areas of difference between the two datasets.

- *sig* was used when it was clear that there was a significant difference between the two datasets because of a change in the terrain between 1974 and 1999. The word *sig* often flags areas of landslip and treefall.
- *not sig* was used when it was possible that the disturbance visible on the 1999 photography was already present in 1974.
- *shadow* was used to explain that due to shadows on the 1974 photography it was not possible to accurately map that section of river. However, it was still often possible to state that the differences were *probably sig* or *probably not sig.*
- *veg grown up* was used to explain differences in the drip line where it had advanced from 1974 to 1999 and it was clear that the reason was that vegetation had grown up during that time.

ATTACHMENT 4

PARTICLE SIZE DISTRIBUTION

MATT BROOK

					Grainsizes		Mass of each Seive Division (g)													
					Aus. Standard		Fine Gravel		Coarse Sand			Med sand			Fine sand				Clay silt	
					Phi		<-1.5	-1.00	-0.50	0.00	0.50	1.00	1.50	2.00	2.50	3.00	3.50	4.00	>4	Total
					Metric (mm)		4.00	2.00	1.40	1.00	0.71	0.50	0.355	0.250	0.177	0.125	0.088	0.063	<0.63	
Zone	Site	Sample	Depth (cm)	Description	Labelled	Initial Mass (g)														
1	1	1		Coarse grey Sand	Zone 1 site 1 #1	250.0	3.73	13.09	14.12	21.09	34.07	48.69	51.11	32.75	19.65	4.70	3.12	0.66	0.46	247.24
1	1	2		Orange Unit	Zone 2 Site 1 #2	200.0	2.55	10.55	12.10	12.41	17.14	23.49	30.74	25.26	21.80	16.11	12.61	6.13	16.32	207.21
1	2	1		R.B.	Zone 1 site RB.	300.0	0.00	0.46	1.14	3.30	7.74	12.94	29.37	36.01	48.78	52.18	47.74	25.31	33.67	298.64
1	3	1		L.B.	Zone 1 site 3 (1)	300.0	0.32	0.66	1.67	3.26	23.94	93.29	85.53	52.38	12.29	10.23	5.46	1.77	1.37	292.17
1	3	2		L.B.	Zone 1 Site 3 Sample 2	200.0	0.32	0.41	0.41	2.98	11.85	12.98	19.56	19.91	25.48	27.14	32.55	17.22	26.72	197.53
1	Below G3	G3 #2 (2)	surface		Below G3 #2 surface	300.0	0.06	0.53	0.51	0.49	0.71	1.10	4.78	15.96	46.98	85.47	79.64	37.32	26.05	299.60
1	Below G3	G3 #2 (1)	20 - 30		Below G3 #2 20 - 30 cr	300.0	0.06	0.85	3.39	2.75	3.80	4.13	7.28	17.35	39.93	70.87	71.29	37.15	39.01	297.86
1	Below G3	G3 (1)	30		Below G3 Depth 300 m	300.0	0.49	0.32	0.39	0.43	1.03	3.24	15.72	31.19	56.14	59.35	52.08	29.77	49.63	299.78
1	Below G3	G3 (2)	50		Below G3 depth 500 m	345.0	31.35	114.09	48.56	39.21	30.80	22.62	23.70	13.13	8.31	4.82	3.69	1.45	2.05	343.78
1	Below G3	G3 #3 (1)	top 3 - 4	"depositional"	G3 (1) top 3-4cm	300.0	0.00	0.00	0.23	1.61	9.09	50.60	152.92	59.08	18.86	3.81	0.61	0.06	0.06	296.93
1	Below G3	G3 #3 (2)	0 - 10	near surface	Below G3 #3 top 10 cm	300.0	0.67	7.72	6.25	4.16	3.29	3.25	8.10	32.08	51.52	44.87	45.52	32.11	65.15	304.69
1	Below G3	G3 (1)	30 - 40	near surface	Below G3 #3 30-40 cm	300.0	0.15	0.36	0.20	0.23	0.31	0.56	2.37	10.06	31.18	54.83	71.28	44.88	82.95	299.36
1	G4, Geo1	51	0-20		#51	230.0	10.60	7.60	6.43	8.91	13.23	19.90	32.30	32.04	33.76	27.64	21.66	8.07	7.44	229.58
1	G4, Geo1	52	30 - 60		#52	300.0	18.58	30.95	26.30	27.22	31.79	34.47	38.43	27.97	23.23	16.04	12.34	5.28	7.02	299.62
1	G4, Geo1	53	0 - 40		#53	250.0	4.17	15.84	14.15	14.49	18.05	19.46	23.15	22.97	30.06	30.18	28.84	12.41	16.32	250.09
1	G4, Geo1	54	40 - 65		#54	300	13.22	36.98	34.83	39.21	45.99	37.18	29.82	17.15	14.23	10.41	8.79	4.25	7.82	299.88
1	G4, Geo1	55	65 - 100		#55	300.0	9.76	34.20	32.09	30.70	34.90	35.28	35.73	23.86	20.06	15.17	11.98	5.69	10.33	299.75
1	G4, Geo1	56	0 - 40		#56	250.0	2.38	6.05	7.38	9.71	15.67	12.53	30.51	24.38	28.00	30.44	29.70	14.17	30.48	241.40
1	G4, Geo1	57	15 - 40		#57	240	1.79	5.01	11.82	21.88	35.85	40.89	40.39	26.11	20.53	14.38	10.43	4.56	6.36	240.00
1	G4, Geo1	58	40 - 80		#58	300.0	5.38	9.48	14.88	31.53	51.10	47.25	48.12	31.14	23.46	14.98	10.38	3.90	8.90	300.50
1	G4, Geo1	59	80 - 120		#59	300.0	6.30	7.69	10.69	17.65	29.37	40.24	52.74	38.00	32.48	24.18	17.85	6.95	15.74	299.88
1	G4, Geo1	60	120 - 160		#60	200.0	3.05	11.73	12.03	14.10	21.30	26.83	33.80	22.81	18.51	12.96	9.63	4.31	8.58	199.64
2	H.P.	3		sand	H.P 1 (C)	150.0	0.43	0.20	0.24	0.42	1.66	6.80	36.36	34.64	22.42	13.29	11.73	6.50	15.09	149.78
2	G5,Geo 2A	1		bar	G5 (1)	150	0.62	0.33	0.41	0.94	1.67	1.83	5.11	16.87	35.4	33.8	26.68	12.51	13.61	149.78
2	G5,Geo 2A	3		sand below	G5 (3) Sand Below	250.0	1.73	1.51	3.48	15.10	32.75	41.48	62.66	38.28	26.52	11.11	8.75	2.05	1.86	247.28
2	G5,Geo 2A	101	0 - 27	L.B. grey sand	#101	300	0.22	0.39	0.36	0.4	0.78	2.28	18.84	67.11	93.27	61.77	31.08	10.78	11.82	299.10
2	G5,Geo 2A	102	27 - 45	fine sand with organic layer	#102	300	0.16	0.19	0.58	1.07	1.62	2.09	4.13	8.23	32.43	75.29	80.7	40.03	53.3	299.82
2	G5,Geo 2A	103	45 - 78	coarse sand	#103	300	1.18	1.1	0.89	1.28	4.86	28.09	100.87	70.5	33.81	19.79	17.12	8.56	11.87	299.92
2	G5,Geo 2A	105	5 - 28	L.B. clean grey med sand	#105	300	0	0.02	0.07	0.13	0.24	1.69	5.72	28.75	69.86	77.99	56.59	24.45	34.26	299.77
2	G5,Geo 2A	106	28 - 50	clean white sand	#106	250	0	0.17	0.22	0.29	0.44	1.18	9.08	29.94	56.21	60	48.8	20.46	23.12	249.91
2	G5,Geo 2A	107	50 - 55	cohesive layers in sand	#107	200.00	0.00	0.05	0.58	0.95	1.44	1.45	1.88	4.34	18.63	42.21	54.87	31.74	41.71	199.85
2	G5,Geo 2A	108	55 - 80	clean white sand	#108	250	0	0	0	0.01	0.02	0.32	1.01	2.43	17.83	53.74	71.18	35.73	63.55	245.82
2	G5,Geo 2A	109	80 - 115	yellow sand	#109	300	0.13	0.52	3.81	4.31	10.41	20.93	48.32	59.45	59.63	39.81	25.6	10.38	15.95	299.25
2	G5,Geo 2A	110	0 - 5	R.B. white sand + dark fragmer	#110	150	0.16	0.65	1.44	2.09	2.26	1.63	1.58	2.22	7.22	17.35	31.22	22.74	59.48	150.04
2	G5,Geo 2A	111	5 - 45	grey sandy clay	#111	300	0	0.01	0	0.01	0.02	0.04	0.18	1.04	17.27	48.58	66.84	21.5	143.78	299.27
2	G5,Geo 2A	112	45 - 54	mixed white sand	#112	250	0.02	0.1	0.1	0.31	0.22	0.4	0.76	4.76	12.45	36.74	72.37	33.08	88.25	249.56
2	G5,Geo 2A	113	54 -	brown sand clay	#113	200	0.02	0.05	0.19	0.36	0.66	0.64	0.86	6.68	8	46.67	50.52	4.27	80.55	199.47
2	G5,Geo 2A	114	90 - 99	yellower brown sandy clay	#114	200.0	0.00	0.02	0.06	0.18	0.32	8.50	11.01	9.44	13.33	21.00	37.24	12.68	84.92	198.70
2	G5,Geo 2A	115	138 - 152	yellower	#115	150.0	0.00	0.03	0.02	0.10	0.18	0.17	0.37	0.69	19.20	17.12	26.79	9.66	75.01	149.34
2	G5,Geo 2A	116	0 - 20	R.B slushy fawn muddy sand	#116	300.0	0.40	0.12	0.18	0.24	8.33	9.52	9.42	9.82	18.15	34.69	57.87	2.12	148.76	299.62
2	G5,Geo 2A	118	30 - 48	yellow brown muddy sand	#118	300.0	0.16	0.13	0.08	0.11	0.27	0.18	0.40	0.83	11.01	61.38	94.05	32.31	98.29	299.20
2	G5,Geo 2A	119	48 - 53	mottled yellow clayey sand	#119	220.0	0.00	0.06	0.03	0.12	0.26	0.21	0.29	0.33	2.22	41.37	61.47	29.89	83.54	219.79
2	G5,Geo 2A	120	53 - 90+	brown sandy clay	#120	295.00	0.0	0.07	0.05	0.08	0.10	0.36	15.15	0.55	3.93	46.64	69.96	6.06	155.11	298.06
2	G5,Geo 2A	121			#121	300.00	0.0	0.00	0.00	0.00	0.01	0.03	0.11	0.65	20.14	50.86	62.31	48.09	116.57	298.77
2	G6,Geo 2B	1	0 - 10	R.B.	#1	300.0	0.00	0.00	0.06	0.12	1.16	1.96	2.95	4.93	12.50	32.89	75.52	52.28	115.15	299.52
2	G6,Geo 2B	2	10 - 60		#2	300.0	0.00	0.67	0.50	0.45	0.83	1.30	5.84	18.79	47.63	66.88	64.54	32.52	59.59	299.54
2	G6,Geo 2B	3	60 - 70		#3	300.0	0.46	2.45	5.43	16.35	32.00	35.35	47.40	35.01	31.02	26.80	25.71	15.10	26.95	300.03
2	G6,Geo 2B	4	100 - 120	grading to fine sand	#4	300.00	16.27	22.12	26.32	43.22	48.73	37.84	40.26	21.03	12.94	9.7	8.54	4.44	8.58	299.99
2	G6,Geo 2B	6	15 - 30	v. fine sand	#6	300.00	0.09	0.06	0.19	0.44	1.00	1.28	1.96	3.33	13.13	45.89	90.59	63.72	79.14	300.82
2	G6,Geo 2B	7	60 - 65	v. white	#7	125.0	0.00	0.03	0.09	0.10	0.21	0.30	0.55	0.77	3.37	14.07	36.73	30.73	37.55	124.50
2	G6,Geo 2B	8	65 - 75	clayey	#8	200.0	0.10	0.19	0.11	0.30	4.70	5.36	8.75	13.03	22.04	29.64	38.42	24.60	52.01	199.25
2	G6,Geo 2B	9	85 - 90	increasingly clayey	#9	170.0	0.55	0.14	0.10	0.17	0.29	0.58	2.19	17.24	15.92	23.18	33.02	16.95	58.51	168.84
2	G6,Geo 2B	10	0 - 15	R.B. soil	#10	200.0	3.77	1.38	2.52	3.51	6.72	13.25	32.48	14.64	17.53	17.81	31.15	19.28	34.93	198.97
2	G6,Geo 2B	11	25 - 33	lighter coloured, slightly sandy	#11	240.0	0.44	0.23	0.37	0.79	1.47	1.48	17.89	28.33	28.47	30.88	37.77	23.36	67.22	238.70
2	G6,Geo 2B	12	33 - 48	sandier, light brown	#12	300.0	0.00	0.07	0.11	0.76	0.52	24.45	26.45	21.92	23.86	26.65	36.21	27.22	107.99	296.21
2	G6,Geo 2B	13	85 - 95	clayier, grey brown	#13	300.0	0.00	0.04	1.19	0.37	0.47	2.47	26.72	23.33	25.33	33.44	38.91	32.48	113.47	298.22
2	G6,Geo 2B	14	140 - 155	grey brown coarse sand	#14	300.0	0.00	0.07	0.00	0.23	16.12	17.29	20.16	19.11	20.98	27.06	36.18	30.89	111.49	299.58
2	G6,Geo 2B	15	0 - 18	L.B. 1 m from pipe meter	#15	300.0	0.17	0.62	1.24	3.07	7.00	13.80	35.38	39.22	39.19	37.57	36.02	26.85	57.74	297.87
2	G6,Geo 2B	16	55 - 63		#16	300.0	0.00	0.54	0.99	2.48	11.02	19.66	35.08	34.24	36.28	31.83	33.25	15.89	77.98	299.24
2	G6,Geo 2B	17	73 - 85		#17	300.0	0.00	0.11	0.92	2.92	5.20	9.59	25.93	38.36	50.65	46.21	40.89	20.06	58.35	299.19
2	G6,Geo 2B	18	95 - 104		#18	300.0	0.29	0.15	1.44	2.56	7.95	13.23	34.39	56.06	64.61	46.40	35.01	11.70	25.51	299.30
2	G6,Geo 2B	19	140 - 150		#19	300.0	0.00	0.06	1.10	3.21	4.78	8.84	29.98	51.21	66.39	50.22	35.69	15.49	33.00	299.97
2	G6,Geo 2B	20	0 - 27	L.B. 1.5m from p. m. coarse sa	#20	300.0	1.44	0.68	3.91	6.86	8.54	13.31	27.31	33.57	40.17	39.99	42.14	25.38	55.37	298.67
2	G6,Geo 2B	21	27 - 49	grey coarse sand	#21	300.0	0.00	0.00	0.10	1.29	1.71	10.78	27.52	43.10	51.94	45.89	42.17	24.04	51.34	299.88
2	G6,Geo 2B	22	85 - 91		#22	300.0	0.00	0.00	0.23	5.44	14.98	21.30	34.80	37.50	43.01	38.78	36.05	16.61	51.07	299.77
2	G6,Geo 2B	23	100 - 110	same with clay layer	#23	300.0	0.33	6.01	11.94	17.07	17.36	21.10	30.99	31.30	35.48	33.17	33.00	18.14	43.56	299.45
2	G6,Geo 2B	24	113 - 143	fine grey sand clay	#24	300.0	0.26	0.36	1.76	1.69	12.23	16.35	30.76	36.09	42.81	40.04	38.89	20.85	57.28	299.37
2	G6,Geo 2B	25	143 - 155	with strong smell	#25	300.0	1.35	2.49	3.11	3.76	5.07	11.99	54.51	65.06	51.41	46.31	36.44	9.40	2.81	293.71
2	3	3 (1)		yellow sand	Site 3 (1)	250.0	0.06	0.20	2.32	3.45	5.99	7.50	14.66	25.80	48.30	50.62	43.48	20.45	25.45	248.28
2	4	4 (1)		sand upper bank brown	Site4 (1)	329.5	0.05	0.39	0.51	2.38	8.11	35.35	82.36	72.76	58.55	33.27	19.70	7.93	14.30	335.66
2	5	5 (1)		underlying sand	Site 5 (1) underlying sa	250.0	0.00	0.00	88.37	91.10	26.52	5.13	10.03	1.80	5.14	6.41	4.03	1.53	1.85	241.91
2	5	5 (2)		surface layer	Si te 5 (2)	300	0.33	0.6	1.15	1.49	1.43	1.02	1.02	10.51	26.35	36.02	65.95	5.55	146.81	298.23
2	6	6 (1)		top of bank	Site 6 (1) top of Bank	300	0.03	0.15	0.69	1.55	4.11	7.9	14.34	24.24	41.36	55.51	57.54	29.13	62.82	299.37
2	6	6 (2)		lower slope	Site 6 (2) Lower Slope	300.0	0.13	2.67	2.05	1.96	2.92	6.54	32.80	58.58	61.72	47.93	39.33	18.81	24.28	299.72
2	7	7 (1)		sand	Site 7 (1)	300.0	3.67	1.98	3.64	10.14	29.40	55.86	62.01	38.34	29.47	21.09	18.45	9.08	16.82	299.95
3	8	8 (1)		upper bank	Site 8 (1) Upper Bank	300.0	0.27	0.76	2.55	8.73	27.51	47.82	62.62	39.35	30.10	23.11	21.55	12.23	22.94	299.54
3	8	8 (2)		root mass	Site 8 (2)	300	1.82	2.25	3.6	8.36	16.98	24.53	37.14	35.27	35.03	33.46	36.85	4.1	59.86	299.25
3	8	8 (3)		iron stained below 30 cm	Site 8 (3)	280.0	0.16	0.65	1.09	4.96	24.66	66.15	103.05	51.17	18.34	5.36	2.38	0.66	0.46	279.09
3	9	9 (1)		upper level	Site 9 (1)	300.0	1.06	0.54	0.39	0.44	0.55	1.83	9.12	34.31	38.85	49.58	54.86	24.81	82.72	299.06
3	10	10 (1)		lower layer	Site 10 (1)	300	0.33	0.13	0.22	0.41	6.27	7.1	3.46	29.41	39.53	41.12	55.01	9.41	112.03	304.43
3	10	10 (2)		surface layer	Site 10 (2)	300	0.62	0.76	0.84	1.42	0.99	13.89	23.44	19.83	20.88	26.68	46.61	35	108.37	299.33
3	11	11 (1)		300 m above denison R	Site 11 (1)	300	0.42	0.27	0.27	0.42	0.55	0.72	2.88	29.26	52.41	66.42	66.95	20.35	58.25	299.17
3	13	13 (1)		above denison	Site 13 (1)	300.0	0.34	0.72	0.73	1.35	1.44	4.45	13.45	34.26	73.85	70.35	53.12	23.01	23.18	300.25
4	12	12 (1)		surface layer	Site 12 (1)	200	0.53	0.54	0.6	0.95	1.43	1.38	7.56	14.71	21.67	27.9	38.3	26.2	57.35	199.12
4	12	12 (2)		lower layer	Site 12 (2) lower Layer	250.0	2.32	1.58	1.32	1.39	1.61	1.74	2.90	6.06	23.51	50.65	70.86	34.61	51.56	250.11
4	14	14 (1)		above G9	Site 14 (1) Surface Sar	300.0	0.00	0.16	0.07	0.17	0.94	5.85	40.05	70.05	67.28	44.99	34.02	12.67	23.08	299.33
5	above olga	1		Right bank yellow overlying whi	Above Olga R.B.	300.0	0.84	5.56	6.76	5.63	6.80	12.39	33.19	41.97	45.14	35.26	36.01	20.62	50.28	300.45
					Zone 5	300.0	2.65	1.98	1.80	2.50	3.62	4.41	12.82	25.15	44.55	55.95	60.36	34.59	50.26	300.64
					Zone 5 or 2 (2) Left ban	300.0	0.01	5.00	9.36	6.98	9.05	19.08	75.31	76.41	43.51	20.08	13.72	6.22	13.90	298.63
					Count	89														
2	H.P.	1		root mass																
2	H.P.	2		soil behind roots																
2	G5,Geo 2A	2		Root mass																
2	G5,Geo 2A	117	20 - 30	muddy yellow sand																
2	G6,Geo 2B	5	0 - 5	R.B																
2	7	7 (2)		matted sand																
3	9	9 (2)		Sand Bar grey																
3	G7	1		black																
3	G7	2		orange																

				Percent of each Seive Division													
				Fine Gravel		Coarse Sand			Med sand			Fine sand				Clay silt	Pecrent
				<-1.5	-1.00	-0.50	0.00	0.50	1.00	1.50	2.00	2.50	3.00	3.50	4.00	>4	Difference
				>4.0	2.00	1.40	1.00	0.71	0.50	0.355	0.250	0.177	0.125	0.088	0.063	<0.63	
Zone	Site	Sample	Labelled														
1	1	1	Zone 1 site 1 #1	1.51	5.29	5.71	8.53	13.78	19.69	20.67	13.25	7.95	1.90	1.26	0.27	0.19	-1.10
1	1	2	Zone 2 Site 1 #2	1.23	5.09	5.84	5.99	8.27	11.34	14.84	12.19	10.52	7.77	6.09	2.96	7.88	3.60
1	2	1	Zone 1 site RB.	0.00	0.15	0.38	1.11	2.59	4.33	9.83	12.06	16.33	17.47	15.99	8.48	11.27	-0.45
1	3	1	Zone 1 site 3 (1)	0.11	0.23	0.57	1.12	8.19	31.93	29.27	17.93	4.21	3.50	1.87	0.61	0.47	-2.61
1	3	2	Zone 1 Site 3 Sample 2	0.16	0.21	0.21	1.51	6.00	6.57	9.90	10.08	12.90	13.74	16.48	8.72	13.53	-1.24
1	Below G3	G3 #2 (2)	Below G3 #2 surface	0.02	0.18	0.17	0.16	0.24	0.37	1.60	5.33	15.68	28.53	26.58	12.46	8.69	-0.13
1	Below G3	G3 #2 (1)	Below G3 #2 20 - 30 cr	0.02	0.29	1.14	0.92	1.28	1.39	2.44	5.82	13.41	23.79	23.93	12.47	13.10	-0.71
1	Below G3	G3 (1)	Below G3 Depth 300 m	0.16	0.11	0.13	0.14	0.34	1.08	5.24	10.40	18.73	19.80	17.37	9.93	16.56	-0.07
1	Below G3	G3 (2)	Below G3 depth 500 m	9.12	33.19	14.13	11.41	8.96	6.58	6.89	3.82	2.42	1.40	1.07	0.42	0.60	-0.35
1	Below G3	G3 #3 (1)	G3 (1) top 3-4cm	0.00	0.00	0.08	0.54	3.06	17.04	51.50	19.90	6.35	1.28	0.21	0.02	0.02	-1.02
1	Below G3	G3 #3 (2)	Below G3 #3 top 10 cm	0.22	2.53	2.05	1.37	1.08	1.07	2.66	10.53	16.91	14.73	14.94	10.54	21.38	1.56
1	Below G3	G3 (1)	Below G3 #3 30-40 cm	0.05	0.12	0.07	0.08	0.10	0.19	0.79	3.36	10.42	18.32	23.81	14.99	27.71	-0.21
1	G4, Geo1	51	#51	4.62	3.31	2.80	3.88	5.76	8.67	14.07	13.96	14.71	12.04	9.43	3.52	3.24	-0.18
1	G4, Geo1	52	#52	6.20	10.33	8.78	9.08	10.61	11.50	12.83	9.34	7.75	5.35	4.12	1.76	2.34	-0.13
1	G4, Geo1	53	#53	1.67	6.33	5.66	5.79	7.22	7.78	9.26	9.18	12.02	12.07	11.53	4.96	6.53	0.04
1	G4, Geo1	54	#54	4.41	12.33	11.61	13.08	15.34	12.40	9.94	5.72	4.75	3.47	2.93	1.42	2.61	-0.04
1	G4, Geo1	55	#55	3.26	11.41	10.71	10.24	11.64	11.77	11.92	7.96	6.69	5.06	4.00	1.90	3.45	-0.08
1	G4, Geo1	56	#56	0.99	2.51	3.06	4.02	6.49	5.19	12.64	10.10	11.60	12.61	12.30	5.87	12.63	-3.44
1	G4, Geo1	57	#57	0.75	2.09	4.93	9.12	14.94	17.04	16.83	10.88	8.55	5.99	4.35	1.90	2.65	0.00
1	G4, Geo1	58	#58	1.79	3.15	4.95	10.49	17.00	15.72	16.01	10.36	7.81	4.99	3.45	1.30	2.96	0.17
1	G4, Geo1	59	#59	2.10	2.56	3.56	5.89	9.79	13.42	17.59	12.67	10.83	8.06	5.95	2.32	5.25	-0.04
1	G4, Geo1	60	#60	1.53	5.88	6.03	7.06	10.67	13.44	16.93	11.43	9.27	6.49	4.82	2.16	4.30	-0.18
2	H.P.	3	H.P 1 (C)	0.29	0.13	0.16	0.28	1.11	4.54	24.28	23.13	14.97	8.87	7.83	4.34	10.07	-0.15
2	G5,Geo 2A	1	G5 (1)	0.41	0.22	0.27	0.63	1.11	1.22	3.41	11.26	23.63	22.57	17.81	8.35	9.09	-0.15
2	G5,Geo 2A	3	G5 (3) Sand Below	0.70	0.61	1.41	6.11	13.24	16.77	25.34	15.48	10.72	4.49	3.54	0.83	0.75	-1.09
2	G5,Geo 2A	101	#101	0.07	0.13	0.12	0.13	0.26	0.76	6.30	22.44	31.18	20.65	10.39	3.60	3.95	-0.30
2	G5,Geo 2A	102	#102	0.05	0.06	0.19	0.36	0.54	0.70	1.38	2.74	10.82	25.11	26.92	13.35	17.78	-0.06
2	G5,Geo 2A	103	#103	0.39	0.37	0.30	0.43	1.62	9.37	33.63	23.51	11.27	6.60	5.71	2.85	3.96	-0.03
2	G5,Geo 2A	105	#105	0.00	0.01	0.02	0.04	0.08	0.56	1.91	9.59	23.30	26.02	18.88	8.16	11.43	-0.08
2	G5,Geo 2A	106	#106	0.00	0.07	0.09	0.12	0.18	0.47	3.63	11.98	22.49	24.01	19.53	8.19	9.25	-0.04
2	G5,Geo 2A	107	#107	0.00	0.03	0.29	0.48	0.72	0.73	0.94	2.17	9.32	21.12	27.46	15.88	20.87	-0.07
2	G5,Geo 2A	108	#108	0.00	0.00	0.00	0.00	0.01	0.13	0.41	0.99	7.25	21.86	28.96	14.54	25.85	-1.67
2	G5,Geo 2A	109	#109	0.04	0.17	1.27	1.44	3.48	6.99	16.15	19.87	19.93	13.30	8.55	3.47	5.33	-0.25
2	G5,Geo 2A	110	#110	0.11	0.43	0.96	1.39	1.51	1.09	1.05	1.48	4.81	11.56	20.81	15.16	39.64	0.03
2	G5,Geo 2A	111	#111	0.00	0.00	0.00	0.00	0.01	0.01	0.06	0.35	5.77	16.23	22.33	7.18	48.04	-0.24
2	G5,Geo 2A	112	#112	0.01	0.04	0.04	0.12	0.09	0.16	0.30	1.91	4.99	14.72	29.00	13.26	35.36	-0.18
2	G5,Geo 2A	113	#113	0.01	0.03	0.10	0.18	0.33	0.32	0.43	3.35	4.01	23.40	25.33	2.14	40.38	-0.27
2	G5,Geo 2A	114	#114	0.00	0.01	0.03	0.09	0.16	4.28	5.54	4.75	6.71	10.57	18.74	6.38	42.74	-0.65
2	G5,Geo 2A	115	#115	0.00	0.02	0.01	0.07	0.12	0.11	0.25	0.46	12.86	11.46	17.94	6.47	50.23	-0.44
2	G5,Geo 2A	116	#116	0.13	0.04	0.06	0.08	2.78	3.18	3.14	3.28	6.06	11.58	19.31	0.71	49.65	-0.13
2	G5,Geo 2A	118	#118	0.05	0.04	0.03	0.04	0.09	0.06	0.13	0.28	3.68	20.51	31.43	10.80	32.85	-0.27
2	G5,Geo 2A	119	#119	0.00	0.03	0.01	0.05	0.12	0.10	0.13	0.15	1.01	18.82	27.97	13.60	38.01	-0.10
2	G5,Geo 2A	120	#120	0.00	0.02	0.02	0.03	0.03	0.12	5.08	0.18	1.32	15.65	23.47	2.03	52.04	1.04
2	G5,Geo 2A	121	#121	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.22	6.74	17.02	20.86	16.10	39.02	-0.41
2	G6,Geo 2B	1	#1	0.00	0.00	0.02	0.04	0.39	0.65	0.98	1.65	4.17	10.98	25.21	17.45	38.44	-0.16
2	G6,Geo 2B	2	#2	0.00	0.22	0.17	0.15	0.28	0.43	1.95	6.27	15.90	22.33	21.55	10.86	19.89	-0.15
2	G6,Geo 2B	3	#3	0.15	0.82	1.81	5.45	10.67	11.78	15.80	11.67	10.34	8.93	8.57	5.03	8.98	0.01
2	G6,Geo 2B	4	#4	5.42	7.37	8.77	14.41	16.24	12.61	13.42	7.01	4.31	3.23	2.85	1.48	2.86	0.00
2	G6,Geo 2B	6	#6	0.03	0.02	0.06	0.15	0.33	0.43	0.65	1.11	4.36	15.25	30.11	21.18	26.31	0.27
2	G6,Geo 2B	7	#7	0.00	0.02	0.07	0.08	0.17	0.24	0.44	0.62	2.71	11.30	29.50	24.68	30.16	-0.40
2	G6,Geo 2B	8	#8	0.05	0.10	0.06	0.15	2.36	2.69	4.39	6.54	11.06	14.88	19.28	12.35	26.10	-0.38
2	G6,Geo 2B	9	#9	0.33	0.08	0.06	0.10	0.17	0.34	1.30	10.21	9.43	13.73	19.56	10.04	34.65	-0.68
2	G6,Geo 2B	10	#10	1.89	0.69	1.27	1.76	3.38	6.66	16.32	7.36	8.81	8.95	15.66	9.69	17.56	-0.52
2	G6,Geo 2B	11	#11	0.18	0.10	0.16	0.33	0.62	0.62	7.49	11.87	11.93	12.94	15.82	9.79	28.16	-0.54
2	G6,Geo 2B	12	#12	0.00	0.02	0.04	0.26	0.18	8.25	8.93	7.40	8.06	9.00	12.22	9.19	36.46	-1.26
2	G6,Geo 2B	13	#13	0.00	0.01	0.40	0.12	0.16	0.83	8.96	7.82	8.49	11.21	13.05	10.89	38.05	-0.59
2	G6,Geo 2B	14	#14	0.00	0.02	0.00	0.08	5.38	5.77	6.73	6.38	7.00	9.03	12.08	10.31	37.22	-0.14
2	G6,Geo 2B	15	#15	0.06	0.21	0.42	1.03	2.35	4.63	11.88	13.17	13.16	12.61	12.09	9.01	19.38	-0.71
2	G6,Geo 2B	16	#16	0.00	0.18	0.33	0.83	3.68	6.57	11.72	11.44	12.12	10.64	11.11	5.31	26.06	-0.25
2	G6,Geo 2B	17	#17	0.00	0.04	0.31	0.98	1.74	3.21	8.67	12.82	16.93	15.45	13.67	6.70	19.50	-0.27
2	G6,Geo 2B	18	#18	0.10	0.05	0.48	0.86	2.66	4.42	11.49	18.73	21.59	15.50	11.70	3.91	8.52	-0.23
2	G6,Geo 2B	19	#19	0.00	0.02	0.37	1.07	1.59	2.95	9.99	17.07	22.13	16.74	11.90	5.16	11.00	-0.01
2	G6,Geo 2B	20	#20	0.48	0.23	1.31	2.30	2.86	4.46	9.14	11.24	13.45	13.39	14.11	8.50	18.54	-0.44
2	G6,Geo 2B	21	#21	0.00	0.00	0.03	0.43	0.57	3.59	9.18	14.37	17.32	15.30	14.06	8.02	17.12	-0.04
2	G6,Geo 2B	22	#22	0.00	0.00	0.08	1.81	5.00	7.11	11.61	12.51	14.35	12.94	12.03	5.54	17.04	-0.08
2	G6,Geo 2B	23	#23	0.11	2.01	3.99	5.70	5.80	7.05	10.35	10.45	11.85	11.08	11.02	6.06	14.55	-0.18
2	G6,Geo 2B	24	#24	0.09	0.12	0.59	0.56	4.09	5.46	10.27	12.06	14.30	13.37	12.99	6.96	19.13	-0.21
2	G6,Geo 2B	25	#25	0.46	0.85	1.06	1.28	1.73	4.08	18.56	22.15	17.50	15.77	12.41	3.20	0.96	-2.10
2	3	3 (1)	Site 3 (1)	0.02	0.08	0.93	1.39	2.41	3.02	5.90	10.39	19.45	20.39	17.51	8.24	10.25	-0.69
2	4	4 (1)	Site4 (1)	0.01	0.12	0.15	0.71	2.42	10.53	24.54	21.68	17.44	9.91	5.87	2.36	4.26	1.87
2	5	5 (1)	Site 5 (1) underlying sa	0.00	0.00	36.53	37.66	10.96	2.12	4.15	0.74	2.12	2.65	1.67	0.63	0.76	-3.24
2	5	5 (2)	Si te 5 (2)	0.11	0.20	0.39	0.50	0.48	0.34	0.34	3.52	8.84	12.08	22.11	1.86	49.23	-0.59
2	6	6 (1)	Site 6 (1) top of Bank	0.01	0.05	0.23	0.52	1.37	2.64	4.79	8.10	13.82	18.54	19.22	9.73	20.98	-0.21
2	6	6 (2)	Site 6 (2) Lower Slope	0.04	0.89	0.68	0.65	0.97	2.18	10.94	19.54	20.59	15.99	13.12	6.28	8.10	-0.09
2	7	7 (1)	Site 7 (1)	1.22	0.66	1.21	3.38	9.80	18.62	20.67	12.78	9.82	7.03	6.15	3.03	5.61	-0.02
3	8	8 (1)	Site 8 (1) Upper Bank	0.09	0.25	0.85	2.91	9.18	15.96	20.91	13.14	10.05	7.72	7.19	4.08	7.66	-0.15
3	8	8 (2)	Site 8 (2)	0.61	0.75	1.20	2.79	5.67	8.20	12.41	11.79	11.71	11.18	12.31	1.37	20.00	-0.25
3	8	8 (3)	Site 8 (3)	0.06	0.23	0.39	1.78	8.84	23.70	36.92	18.33	6.57	1.92	0.85	0.24	0.16	-0.33
3	9	9 (1)	Site 9 (1)	0.35	0.18	0.13	0.15	0.18	0.61	3.05	11.47	12.99	16.58	18.34	8.30	27.66	-0.31
3	10	10 (1)	Site 10 (1)	0.11	0.04	0.07	0.13	2.06	2.33	1.14	9.66	12.98	13.51	18.07	3.09	36.80	1.48
3	10	10 (2)	Site 10 (2)	0.21	0.25	0.28	0.47	0.33	4.64	7.83	6.62	6.98	8.91	15.57	11.69	36.20	-0.22
3	11	11 (1)	Site 11 (1)	0.14	0.09	0.09	0.14	0.18	0.24	0.96	9.78	17.52	22.20	22.38	6.80	19.47	-0.28
3	13	13 (1)	Site 13 (1)	0.11	0.24	0.24	0.45	0.48	1.48	4.48	11.41	24.60	23.43	17.69	7.66	7.72	0.08
4	12	12 (1)	Site 12 (1)	0.27	0.27	0.30	0.48	0.72	0.69	3.80	7.39	10.88	14.01	19.23	13.16	28.80	-0.44
4	12	12 (2)	Site 12 (2) lower Layer	0.93	0.63	0.53	0.56	0.64	0.70	1.16	2.42	9.40	20.25	28.33	13.84	20.61	0.04
4	14	14 (1)	Site 14 (1) Surface Sar	0.00	0.05	0.02	0.06	0.31	1.95	13.38	23.40	22.48	15.03	11.37	4.23	7.71	-0.22
5	above olga	1	Above Olga R.B.	0.28	1.85	2.25	1.87	2.26	4.12	11.05	13.97	15.02	11.74	11.99	6.86	16.73	0.15
			Zone 5	0.88	0.66	0.60	0.83	1.20	1.47	4.26	8.37	14.82	18.61	20.08	11.51	16.72	0.21
			Zone 5 or 2 (2) Left ban	0.00	1.67	3.13	2.34	3.03	6.39	25.22	25.59	14.57	6.72	4.59	2.08	4.65	-0.46

ATTACHMENT 5

GORDON RIVER BANK GEOTECHNICAL STABILITY STUDY

GORDON RIVER BANK GEOTECHNICAL STABILITY STUDY

Introduction

As part of the Hydro Basslink EIA investigations, a bank stability study of the Gordon River downstream of the power station is required to determine the present stability of the banks in order to project future changes under Basslink**.** The bank stability in the Middle Gordon River is of concern and in particular the area identified as the zone between Albert River and the Splits.

This study will predict the change in river bank stability produced by a change in river flow regime. It will also form the basis for developing mitigation options if the results indicate bank instability. This study is a continuation of the report by Jim Styles (Ref. 1) on bank stability, which included specific comments to questions, raised by the Environmental Dept., Hydro Tasmania.

This study does not include the effects of river geometry, velocity & geomorphology, or piping in the bank and only looks at the geotechnical slope stability of the river bank.

Gordon River Sites

The two selected sites on the Gordon River, where ground water pipes have been installed in augured holes (piezometers), are the Upstream site (G5a or Geo2A) and the Downstream site (G10 or Geo4). These piezometer sites are 70.6 & 61.62 kilometres respectively from the mouth of the river.
For each of the two sites on the Gordon River the power station operation scenarios for no rainfall are as follows:

- Full gate to off (high prior usage): Run Nos. U1 & D1,
- Full gate to off (moderate prior usage): Run No. U2,
- 6hr on full gate to off: Run Nos. U3 & D3,
- 24 hr on full gate to off (low prior usage): Run Nos. U4 & D2, &
- Full gate to efficient load: Run Nos. U5 & D4.

Each of these power station operations exist under present conditions (prior to Basslink) and will continue under Basslink operation regime, but the percentage of time that these occur will change.

Geotechnical Information

1. Geometry & Geology of Banks

The slope geometry of the Gordon River banks was based on the surveyed piezometers located in the banks at two piezometer sites. The banks generally appeared to have a composite structure of silt & sand above gravel overlain by organic root-permeated soil layer. For the geometry and assumed geology of the banks for both the upstream and downstream sites, refer to Figures A & B respectively.

2. Water Table Levels

The water table levels (phreatic surface) were noted by piezometers (probes) which are pressure transducers on the ends of steel rods inserted into PVC pipes with slotted holes. Note the tops of the piezometers are not sealed. The water table level profiles are shown below.

Upstream Site

P/Stn Operation	Run Nos.	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 5
Full gate to off	U1	0.318	1.773	2.965	3.279
Full gate to off (moderate prior usage)	U2	0.824	1.611	2.33	1.009
6hr on full gate to off	U3	0.78	--	1.991	0.818
24hr full gate to off (low prior usage)	U4	0.913	--	1.658	2.143
Full gate to efficient load	U5	3.809	3.841	3.832	3.834

Downstream Site

P/Stn Operation	Run Nos.	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4	Piezometer 5
Full gate to off	D1	1.143	1.904	2.407	2.537	--
24hr full gate to off (low prior usage)	D2	1.096	1.751	2.093	--	2.132
6hr on full gate to off	D3	0.98	1.48	1.837	1.938	1.976
Full gate to efficient load	D4	2.589	2.617	2.858	2.694	--

Legend: The alphanumeric used for the Run Nos. is as follows:-

U: Upstream site & D: Downstream site, & the numbers are based on the order of difference of the water table levels between piezometer 3 & the river level, for eg. 1 is the max. difference & 5 is the lowest difference.

3. In-situ Testing

Hand penetrometer readings in the sand banks near the upstream site, ranged from 0 to 0.9kPa (averaging 0.3kPa) and near the downstream site, ranged from 0.7kPa to 2.2kPa (averaging 1.4kPa).

No other type of in-situ testing was carried out.

4. Laboratory Testing

The dispersivity of the soil was tested by Pitt & Sherry to AS 1289.3.8.1 and the Emerson Class No. were as follows:

- Upstream Site – 3 & 5 (for deepest sample).
- Downstream Site – 3.

In this test soils are graded according to class, with Class 1 being highly dispersive and Class 8 non-dispersive. The submitted samples are therefore dispersive. According to Ref. 2 soils with Emerson Class 1 to 4 needs to be treated with caution in embankment dam construction.

The Atterberg Limits were determined by Pitt & Sherry to AS 1289.3.1.2, 3.2.1, 3.3.1 & 3.4.1 (127mm mould) and these are as follows:

Upstream Site

Sample (Monday 1)	**4B**	**4C**	**4D**
Liquid Limit (%)	Unobtainable	26	25
Plastic Limit (%)	26	24	24
Plasticity Index (%)	Non Plastic	2	1
Linear Shrinkage (%)	Unobtainable	2.5	2

Downstream Site

Sample (Monday 2)	**4B**	**4C**	**4D**
Liquid Limit (%)	Unobtainable	Unobtainable	Unobtainable
Plastic Limit (%)	22	26	25
Plasticity Index (%)	Non Plastic	Non Plastic	Non Plastic
Linear Shrinkage (%)	Unobtainable	Unobtainable	Unobtainable

The six samples consisted of various fine sands and were submitted by Hydro Tasmania on 26^{th} May 2000.

In this test the plasticity or Atterberg Limits of the soils are determined by calculating the plasticity index, which is the range of moisture content (liquid limit – plastic limit) over which the soil is plastic. The results indicate that the silt / fine sand samples are either non-plastic or very low plasticity. This is because plasticity is exhibited only by clays and silts, and not by sands and gravels.

The Particle Size Distribution or grading was done by Mathew Brook as part of his Honours project at the University of Tasmania. Refer to Appendix A of Ref. 3 for the data and distribution graphs. The results for samples #109 & site 14(1) were then plotted out as a particle size distribution curve with the cumulative percent of the material finer by mass versus the particle size. The soil was poorly graded and for the 0.075mm (75microns) size approximately 57% & 66% of the material is finer by mass for the upstream & downstream sites respectively. Note below the 75microns size it is difficult to see by the naked eye and also the 75microns is the finest sieve used in sieve analysis of soils (AS1289).

Based on the results of the plasticity test and the grading, the Unified Soil Classification was obtained and this is ML, ie. inorganic silts & very fine sands.

5. Material Properties

Based on the above classification and information below, the material properties adopted for this stability analysis were based on Table 6 (Ref. 6), and are as follows in Table below.

Material	**Unit Weight (kN/m^3)**	**Friction ϕ' (°)**	**Cohesion c' (kPa)**
Organic Soil (root-permeated)	15	0	11 & (c_r = 40)
ML: Silt / Fine Sand	19.3	30	5
GP: Poorly Graded Gravels	19.4	35	0

The above values for the ML material do not take into account the additional 'apparent' cohesion (c_r) provided by tree root reinforcement or the organic root-permeated upper horizon in the banks of the Gordon River. According to Ref. 4 for a root-permeated soil the Mohr-Coulomb failure criterion is modified to include c_r:

$$s = c' + c_r + (\sigma - u)\tan\phi'$$

where s is the shear strength of the soil-root composite.

A typical c_r value for the organic root reinforcement (upper horizon) is 40 kPa provided by Bruce Abernethy of Sinclair Knight Merz, Armadale, Victoria.

A sensitivity analysis was done on the above shear strength values, with a 20% reduction of the phi' (ϕ') & c' values, to check the FoS for bank stability. Note the unit weights of the material have not been measured to confirm the above values.

River Bank Stability Analyses

For the analyses of the Gordon River's two river bank cross-sections the SLOPE/W slope stability analysis computer program was used. A simplified Bishop's method of slices for circular failure surfaces was used to determine the minimum factor of safety for the critical slip surfaces that are structurally significant.

Only circular failure surfaces on the bank were considered for this stability analysis and for ease of analysis non-circular failure surfaces were not considered. The results give relative FoS's and not absolute FoS's as the actual failures on site are not deep seated rotational slips but bank slumps of localised shallow failures.

The acceptance criterion for stability analysis of the river bank under drawdown conditions is a relative factor of safety (FoS) not less than say 1.1.

To check the sensitivity of the factor of safety for stability to assumptions on shear strength, a 20% reduction was applied to both c' and phi' (ϕ') values, and the results shown in Table 1. Seismic loading has not been considered for the river banks.

Table 1 below shows that the river banks under drawdown conditions have a relative FoS of approximately 1.2 or greater. This is expected because the bank is comprised of semi-pervious zones of silt / sand which provide some drainage during rapid drawdown.

During Basslink operation it is expected that the ground water table during drawdown will generally be lower except near the bank it will be slightly higher than prior to Basslink.

Table 1 – Relative FoS for Gordon River Banks under Drawdown

Run Nos.	Power Station Operation	Relative FoS	Rel. FoS with 20% strength reduction	Figure Nos. with 20% str. red.
U1	Full gate to off (high prior usage)	1.61	1.24	1
U2	Full gate to off (moderate prior usage)	1.76	1.35	2
U3	6hr on full gate to off	1.79	1.38	3
U4	24hr on full gate to off (low prior usage)	1.86	1.43	4
U5	Full gate to efficient load	1.87	1.45	5
D1	Full gate to off (high prior usage)	1.53	1.18	6
D2	24hr on full gate to off (low prior usage)	1.54	1.19	7
D3	6hr on full gate to off	1.56	1.20	8
D4	Full gate to efficient load	1.64	1.26	9

Conclusions

The difference in the relative FoS's for the stability of the banks (comprising silt & fine sand) from the above table could indicate the following:

- Upstream Site Ch. 70.6 km: For power station operation (Run No. U1) the stability of the banks will be relatively less stable than the power station operations (Run Nos. U4 & U5). Therefore the effect of changed river conditions on bank stability is to reduce the relative factor of safety (FoS) from 1.45 (U5) to 1.24 (U1), ie. a reduction of 14.5%, as the maximum difference in water table level and the river level increase.

- Downstream site Ch. 61.62 km: For power station operation (Run No. D1) the stability of the banks will be relatively less stable than the power station operation (Run No. D4). Therefore the effect of changed river conditions on bank stability is to reduce the relative factor of safety (FoS) from 1.26 (D4) to 1.18 (D1), ie. a reduction of 6.35%, as the maximum difference in water table level and the river level increase.

Recommendations

- It will be essential to review and perhaps revise the findings of this report if further geotechnical investigations or monitoring of water tables reveal conditions that are significantly different from those that have been assumed in this report.
- That future monitoring of the two piezometer sites is carried out to confirm the trend of the above results and these are compared with monitoring during the Basslink operation.

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Hydro Tasmania

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4. Abernethy, B., & Rutherford, I. D. (Dept. of Civil Eng., Monash Uni., Melbourne), "The distribution and strength of riparian tree roots in relation to riverbank reinforcement", August 1999.

5. Thorne, C. R., & Tovey N.K. (Uni. of East Anglia, Norwich, U.K.), "Stability of Composite River Banks", August 1980.

6. USBR. "Design of Small Dams", 1977.

Figures

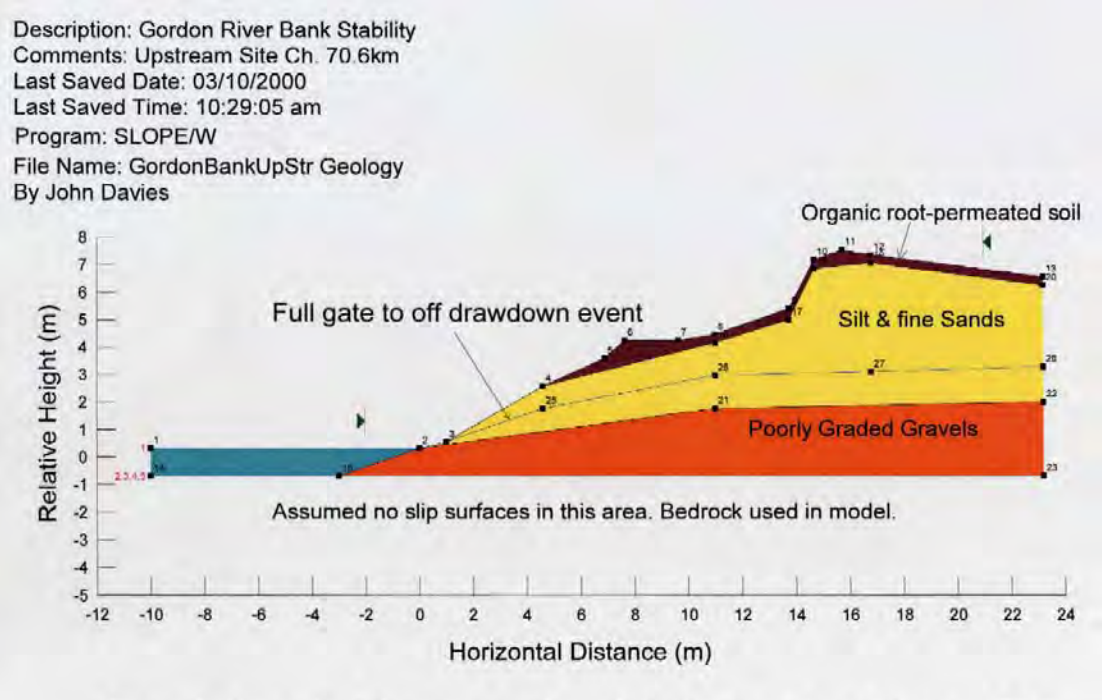


Figure A: Geometry & Assumed Geology of Gordon River Bank (Upstream Site)

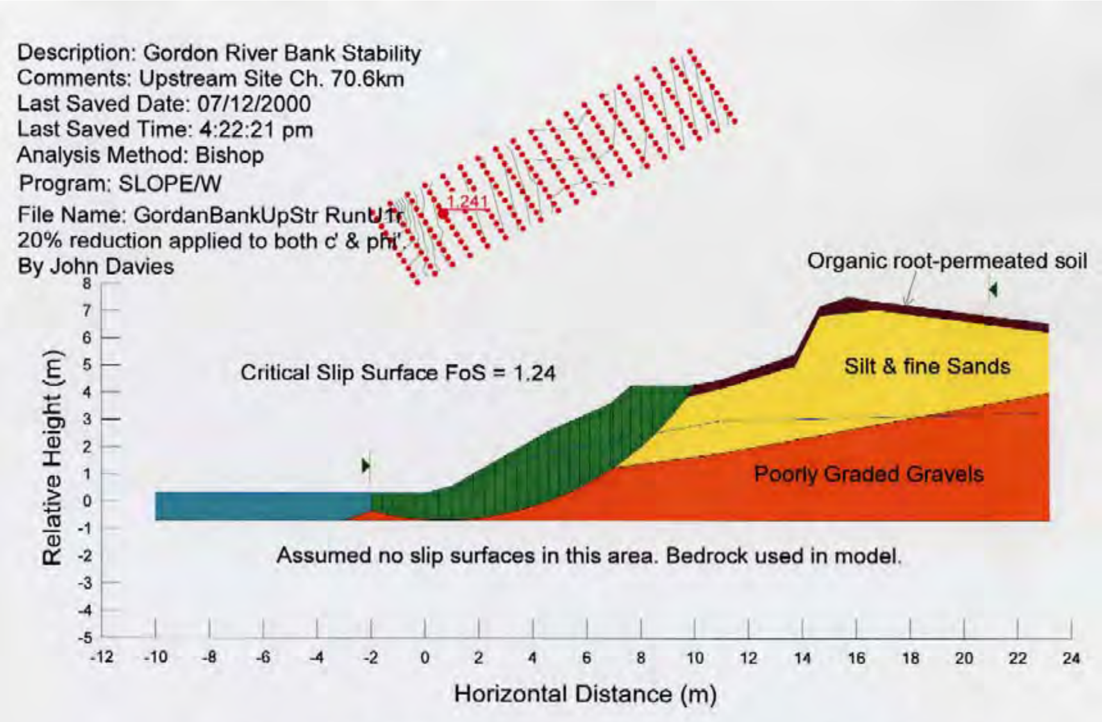


Figure 1: Full Gate to Off (high prior usage) Drawdown Event

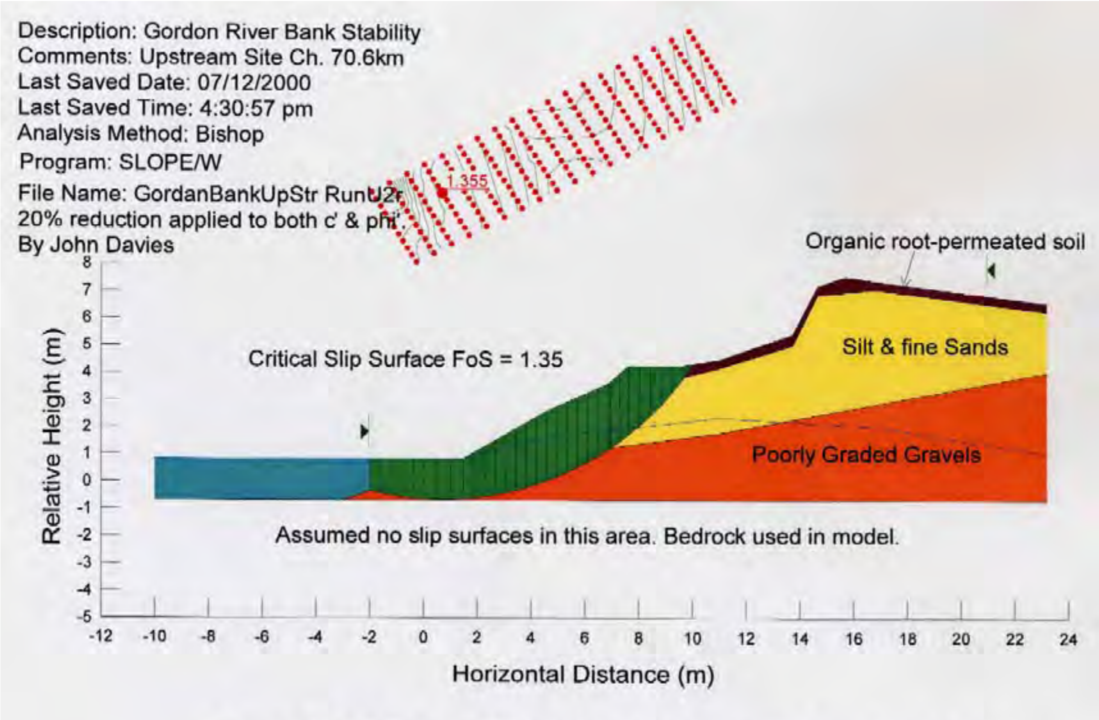


Figure 2: Full Gate to Off (moderate prior usage) Drawdown Event

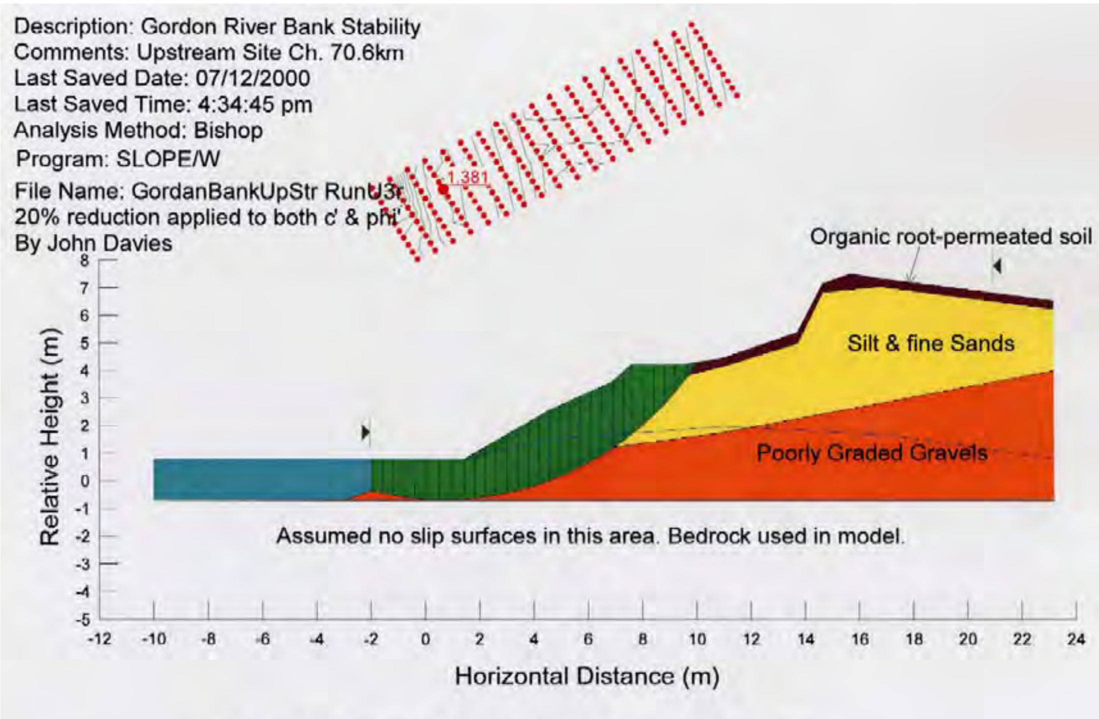


Figure 3: 6hr on Full Gate to Off Drawdown Event

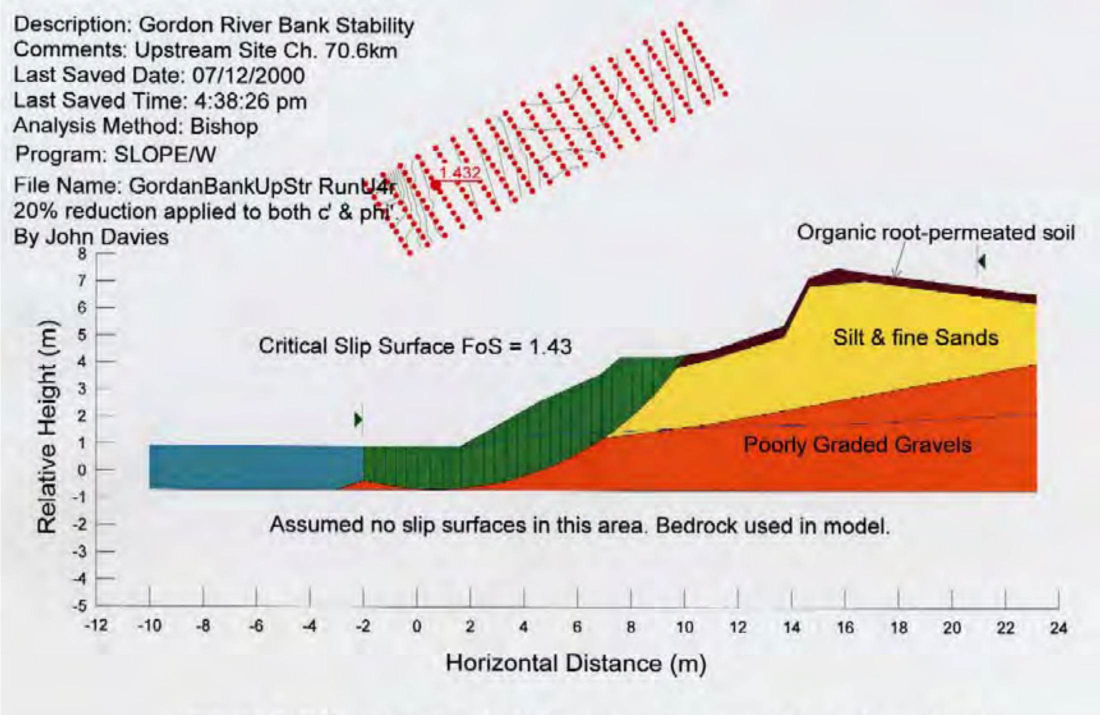


Figure 4: 24hr on Full Gate to Off (low prior usage) Drawdown Event

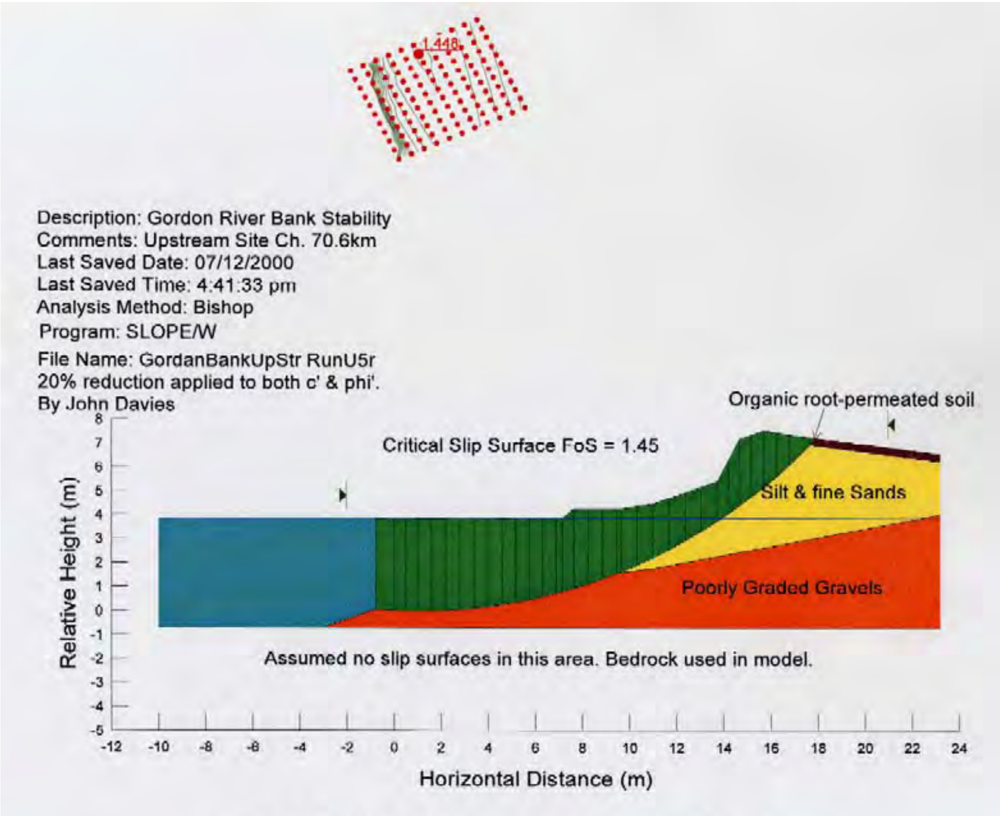


Figure 5: Full Gate to Efficient Load Drawdown Event

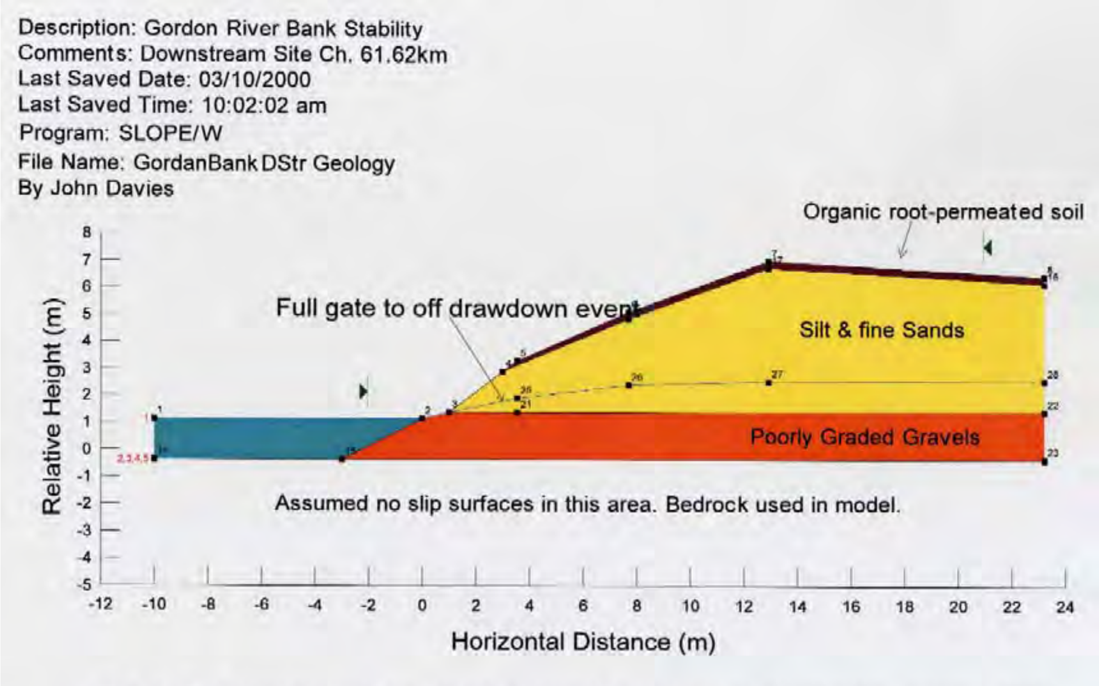


Figure B: Geometry & Assumed Geology of Gordon River Bank (Downstream Site)

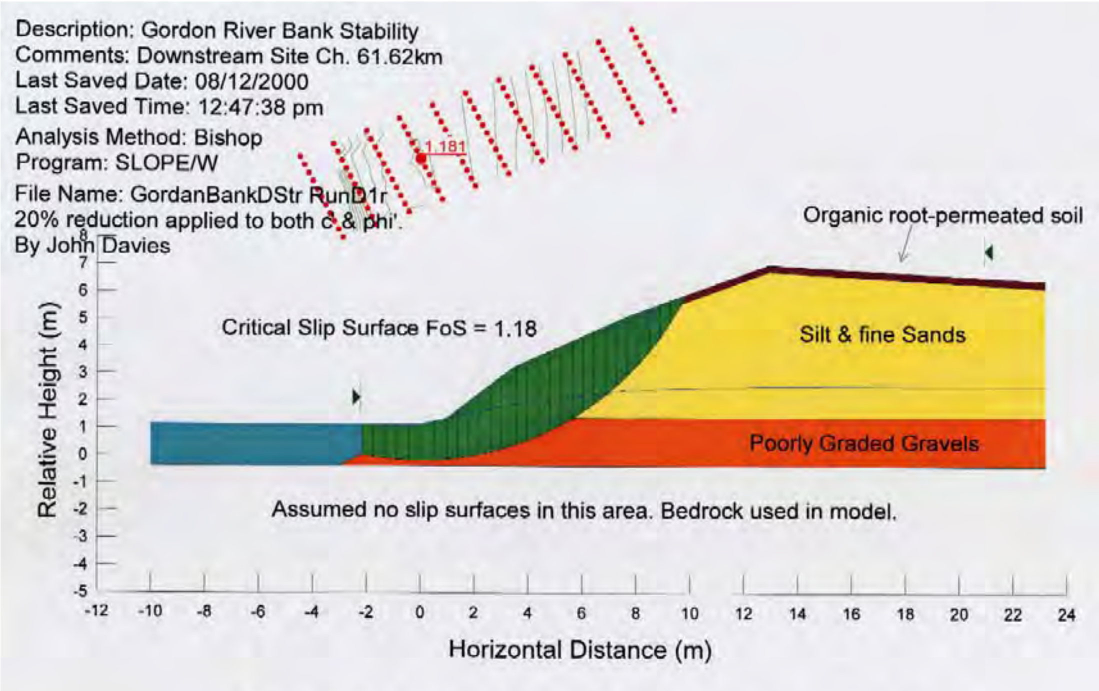


Figure 6: Full Gate to Off (high prior usage) Drawdown Event

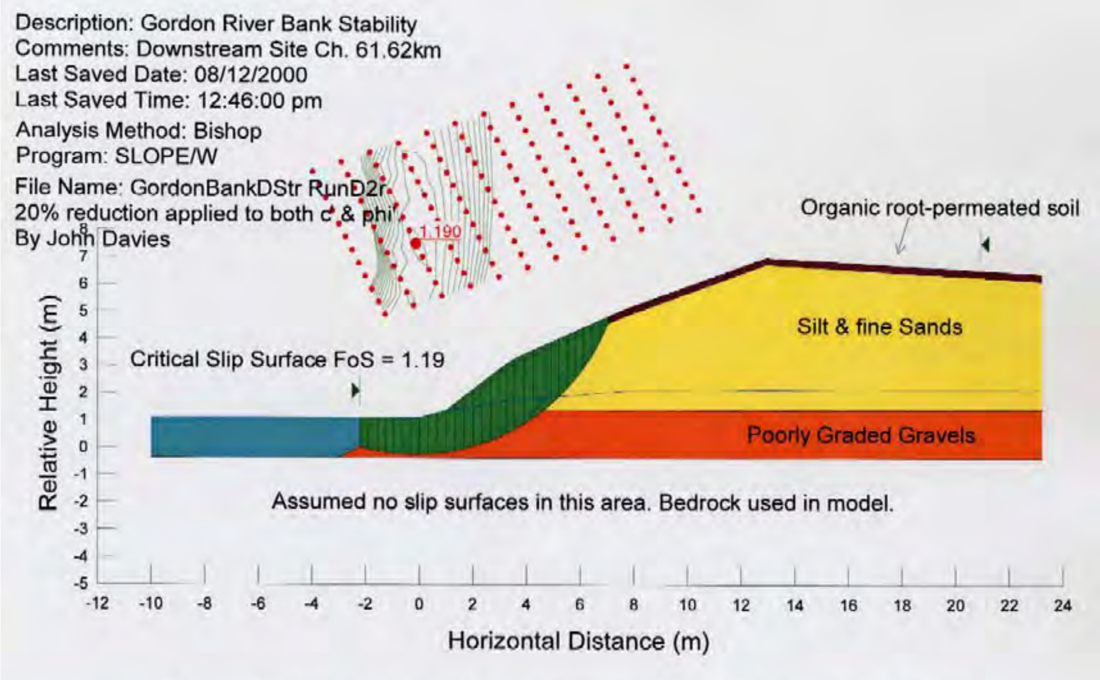


Figure 7: 24hr on Full Gate to Off (low prior usage) Drawdown Event

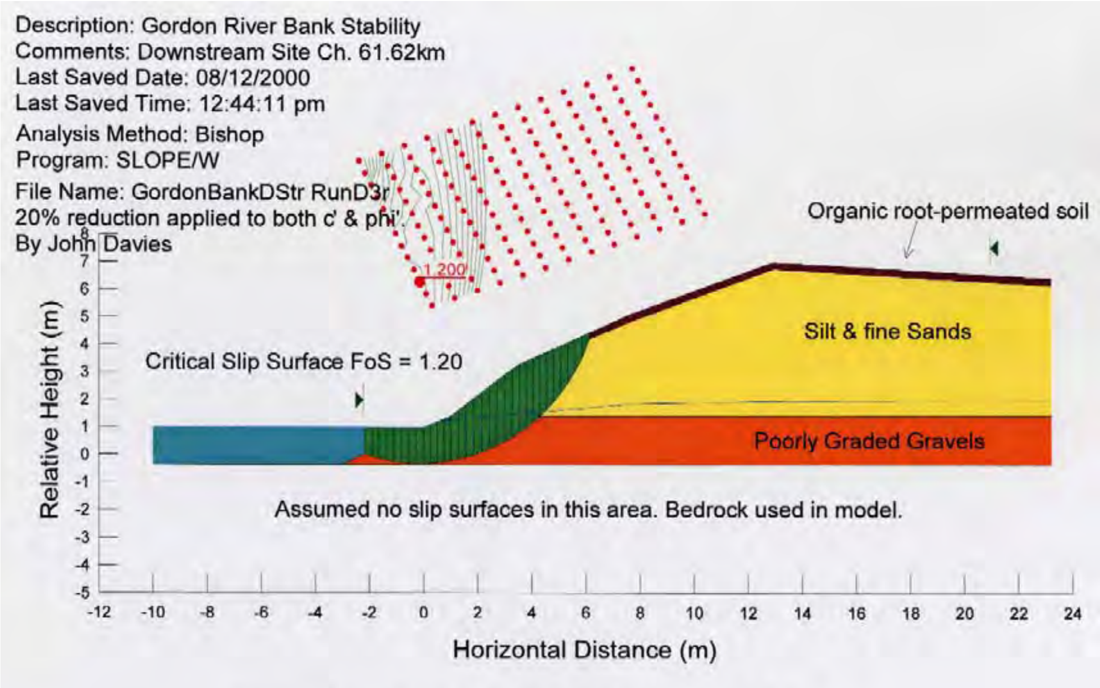


Figure 8: 6hr on Full Gate to Off Drawdown Event

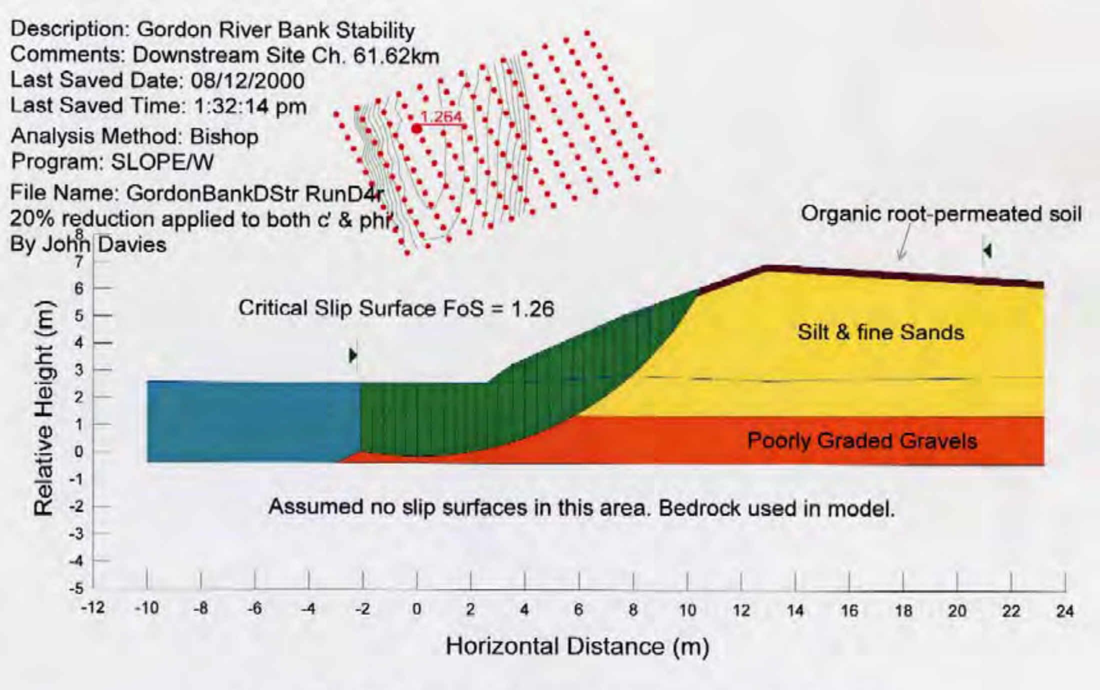
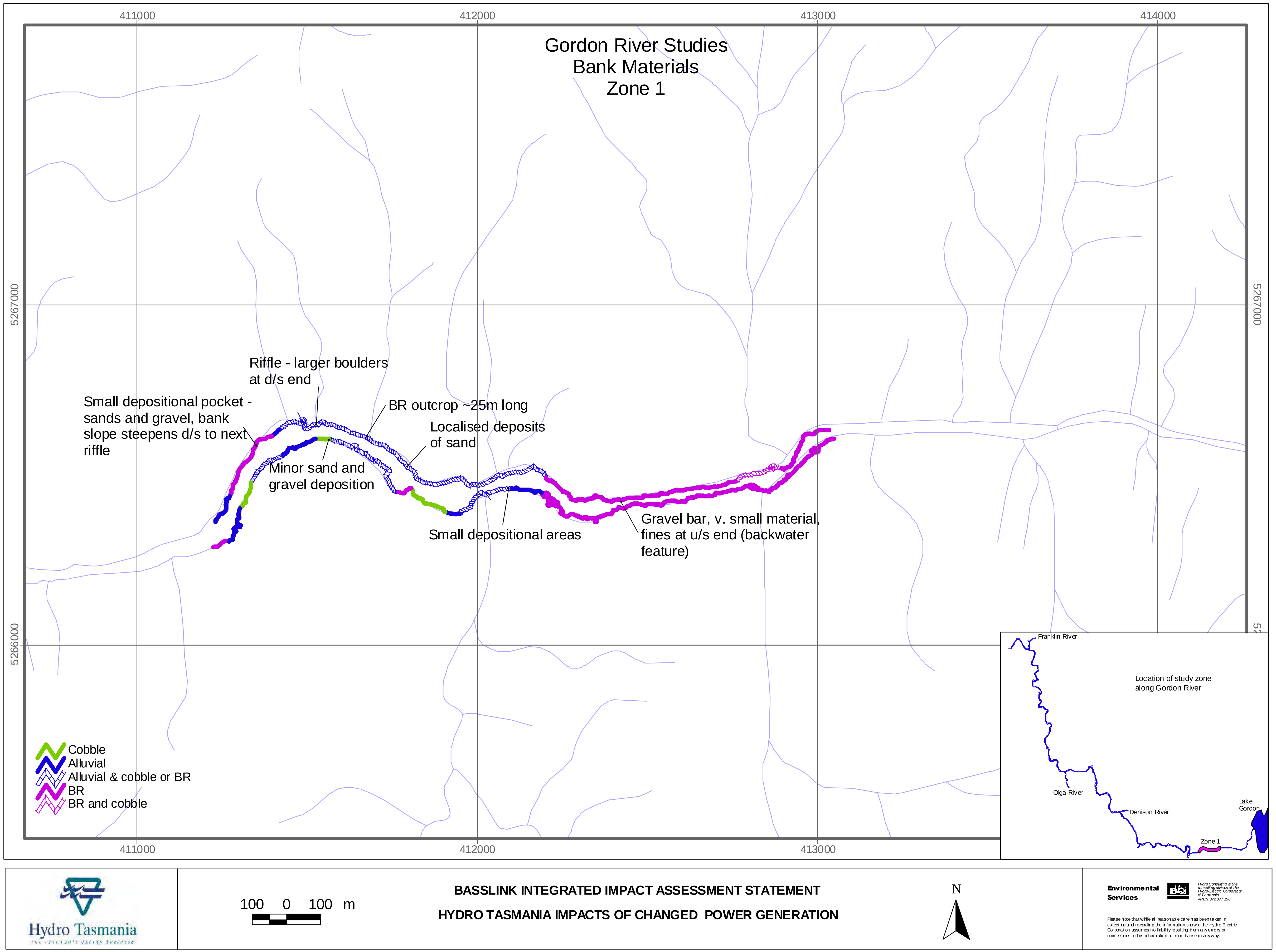
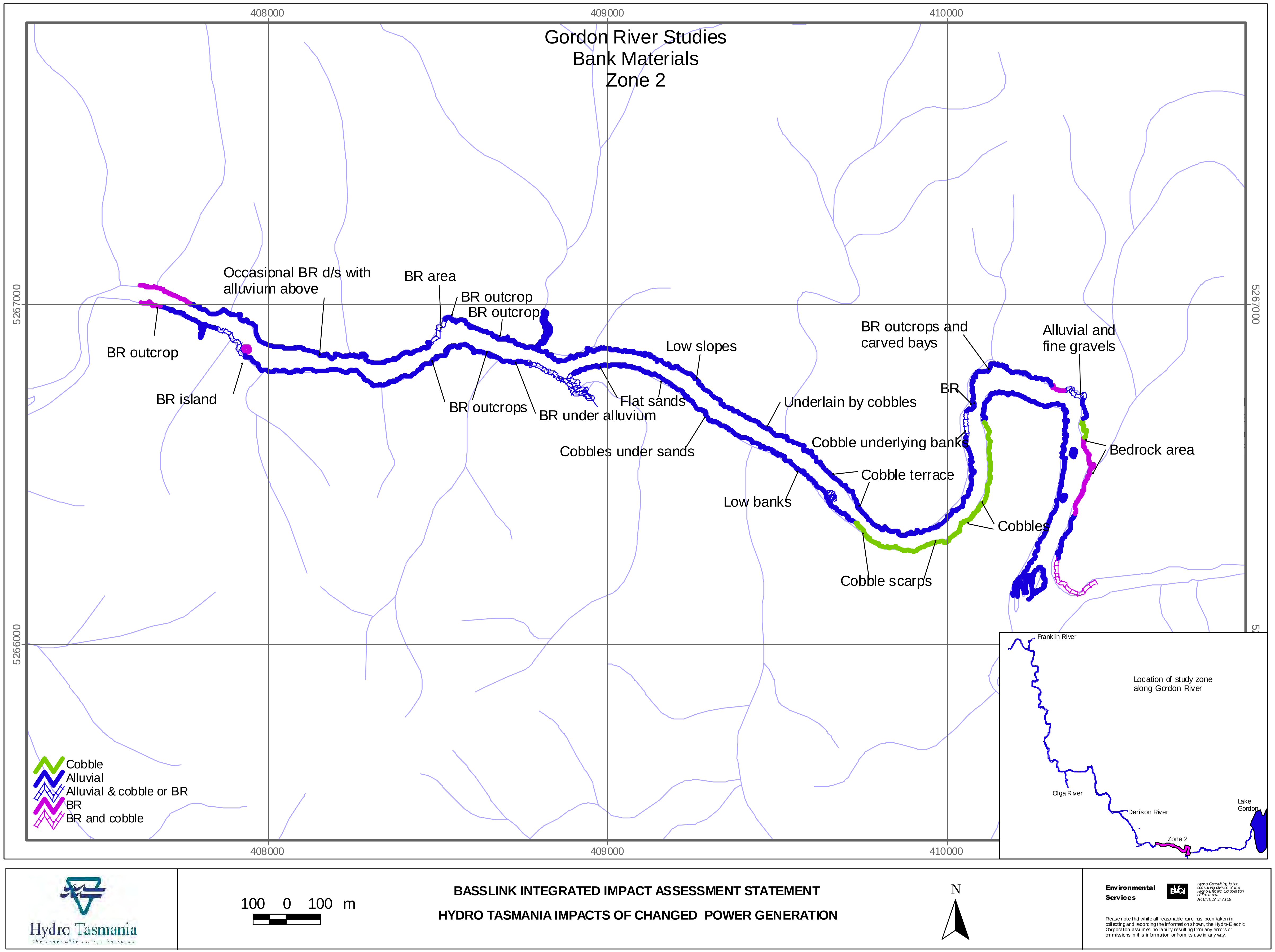


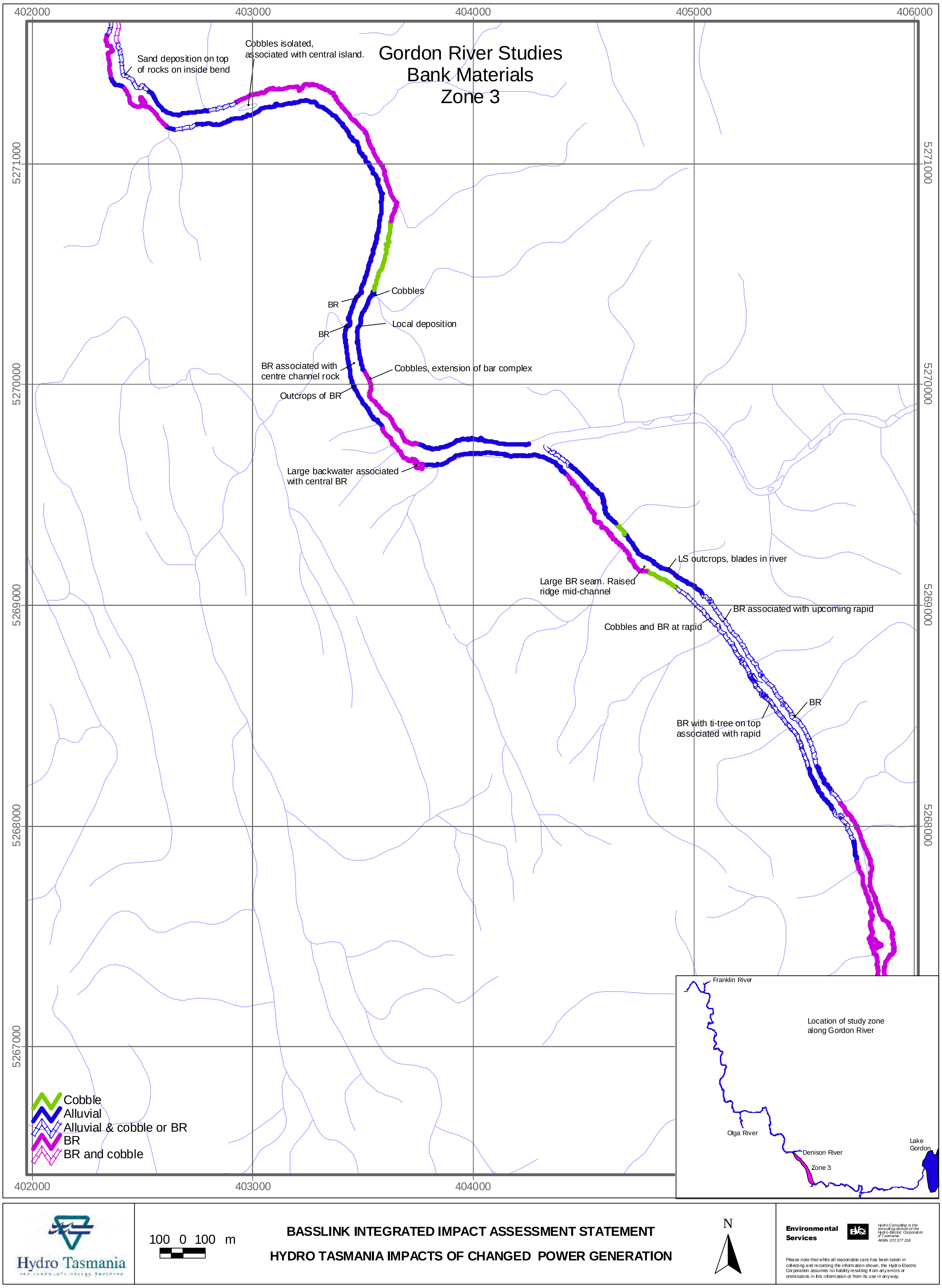
Figure 9: Full Gate to Efficient Load Drawdown Event

ATTACHMENT 6

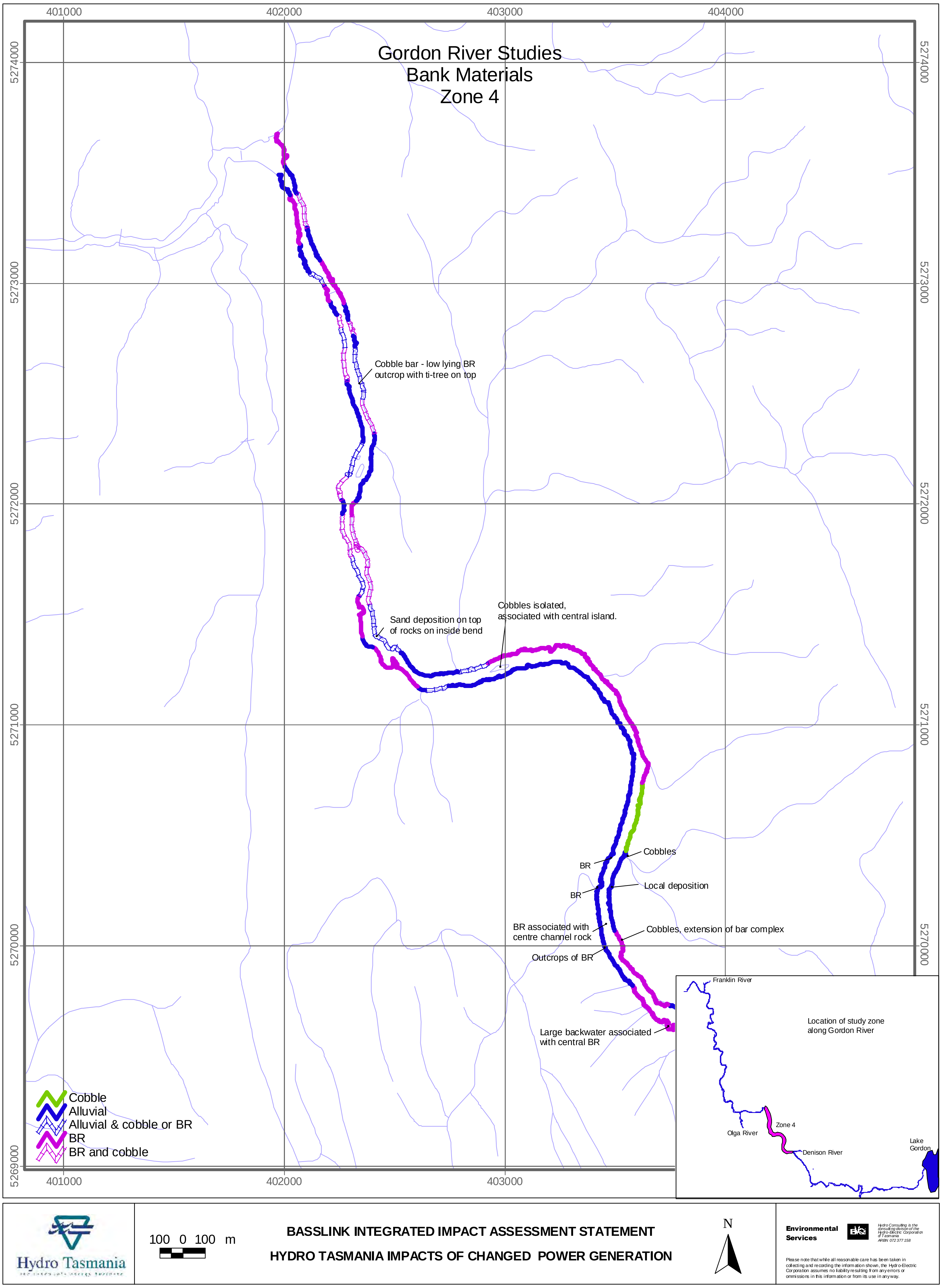
FIELD MAPPING RESULTS


Gordon River Studies
Bank Materials
Zone 1
411000
412000
413000
414000
5267000
5266000
Riffle - larger boulders at d/s end
Small depositional pocket - sands and gravel, bank slope steepens d/s to next riffle
BR outcrop ~25m long
Localised deposits of sand
Minor sand and gravel deposition
Small depositional areas
Gravel bar, v. small material, fines at u/s end (backwater feature)
Cobble
Alluvial
Alluvial & cobble or BR
BR
BR and cobble
Franklin River
Location of study zone along Gordon River
Olga River
Denison River
Lake Gordon
Zone 1
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
Environmental Services


Gordon River Studies
Bank Materials
Zone 2
408000
409000
410000
5267000
5266000
Occasional BR d/s with alluvium above
BR area
BR outcrop
BR outcrop
BR outcrop
BR island
BR outcrops
BR under alluvium
Flat sands
Low slopes
Cobbles under sands
Low banks
BR outcrops and carved bays
BR
Underlain by cobbles
Cobble underlying banks
Cobble terrace
Cobbles
Cobble scarps
Alluvial and fine gravels
Bedrock area
Cobble
Alluvial
Alluvial & cobble or BR
BR
BR and cobble
Franklin River
Location of study zone along Gordon River
Olga River
Denison River
Lake Gordon
Zone 2
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
Environmental Services



Gordon River Studies
Bank Materials
Zone 3
402000
403000
404000
405000
406000
5271000
5270000
5269000
5268000
5267000
Sand deposition on top of rocks on inside bend
Cobbles isolated, associated with central island.
Cobbles
BR
BR
Local deposition
BR associated with centre channel rock
Cobbles, extension of bar complex
Outcrops of BR
Large backwater associated with central BR
LS outcrops, blades in river
Large BR seam. Raised ridge mid-channel
BR associated with upcoming rapid
Cobbles and BR at rapid
BR
BR with ti-tree on top associated with rapid
Cobble
Alluvial
Alluvial & cobble or BR
BR
BR and cobble
Franklin River
Location of study zone along Gordon River
Olga River
Denison River
Zone 3
Lake Gordon
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
Environmental Services


Gordon River Studies
Bank Materials
Zone 4
401000
402000
403000
404000
5274000
5273000
5272000
5271000
5270000
5269000
Cobble bar - low lying BR outcrop with ti-tree on top
Sand deposition on top of rocks on inside bend
Cobbles isolated, associated with central island.
Cobbles
BR
Local deposition
BR
BR associated with centre channel rock
Cobbles, extension of bar complex
Outcrops of BR
Large backwater associated with central BR
Cobble
Alluvial
Alluvial & cobble or BR
BR
BR and cobble
Franklin River
Location of study zone along Gordon River
Zone 4
Olga River
Denison River
Lake Gordon
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
Hydro Tasmania
Environmental Services
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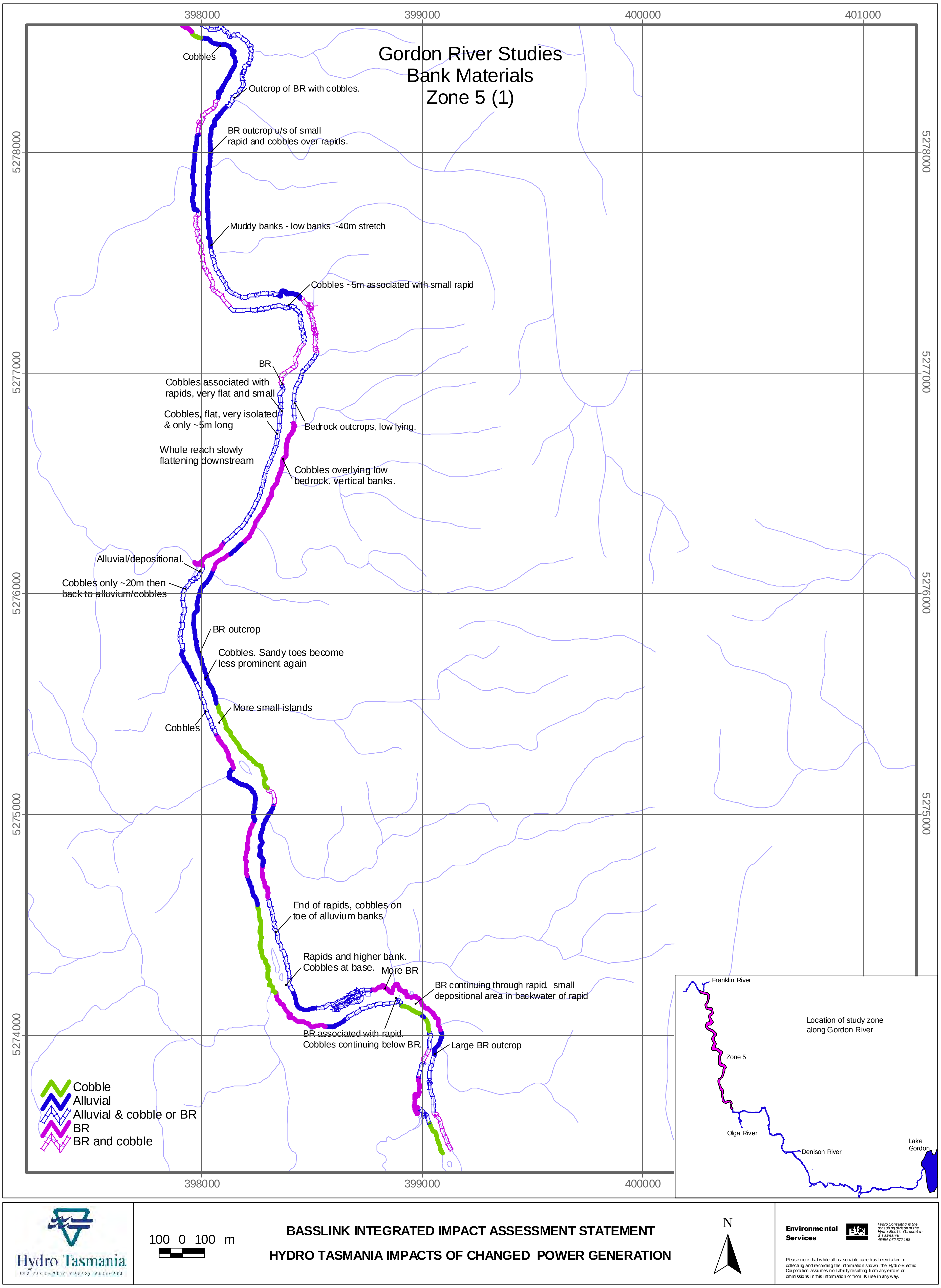
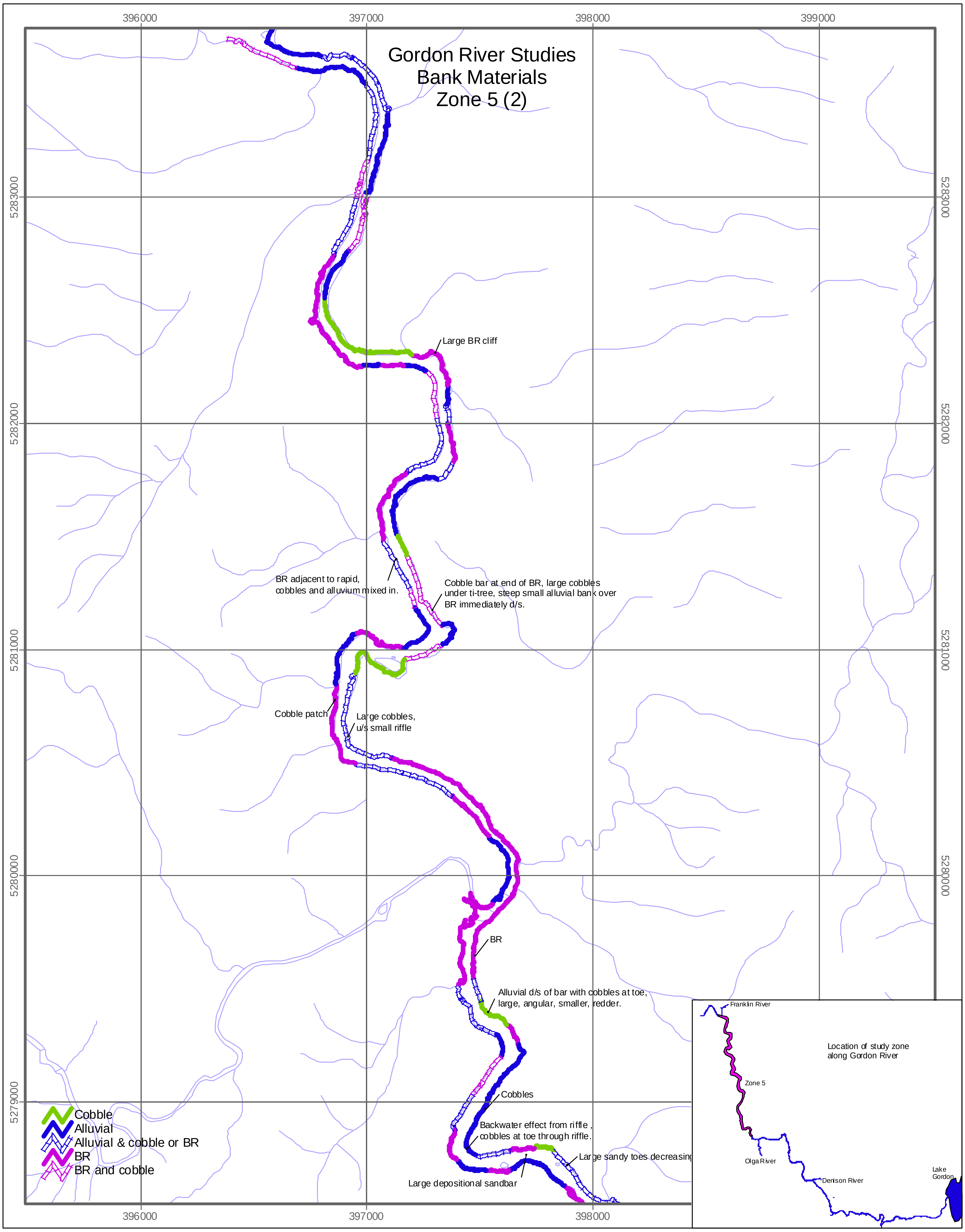

Gordon River Studies
Bank Materials
Zone 5 (1)
398000
399000
400000
401000
5278000
5277000
5276000
5275000
5274000
Cobbles
Outcrop of BR with cobbles.
BR outcrop u/s of small rapid and cobbles over rapids.
Muddy banks - low banks ~40m stretch
Cobbles ~5m associated with small rapid
BR
Cobbles associated with rapids, very flat and small
Cobbles, flat, very isolated & only ~5m long
Bedrock outcrops, low lying.
Whole reach slowly flattening downstream
Cobbles overlying low bedrock, vertical banks.
Alluvial/depositional.
Cobbles only ~20m then back to alluvium/cobbles
BR outcrop
Cobbles. Sandy toes become less prominent again
More small islands
Cobbles
End of rapids, cobbles on toe of alluvium banks
Rapids and higher bank. Cobbles at base.
More BR
BR continuing through rapid, small depositional area in backwater of rapid
BR associated with rapid. Cobbles continuing below BR.
Large BR outcrop
Cobble
Alluvial
Alluvial & cobble or BR
BR
BR and cobble
Franklin River
Location of study zone along Gordon River
Zone 5
Olga River
Denison River
Lake Gordon
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
Environmental Services



Hydro Tasmania

100 0 100 m

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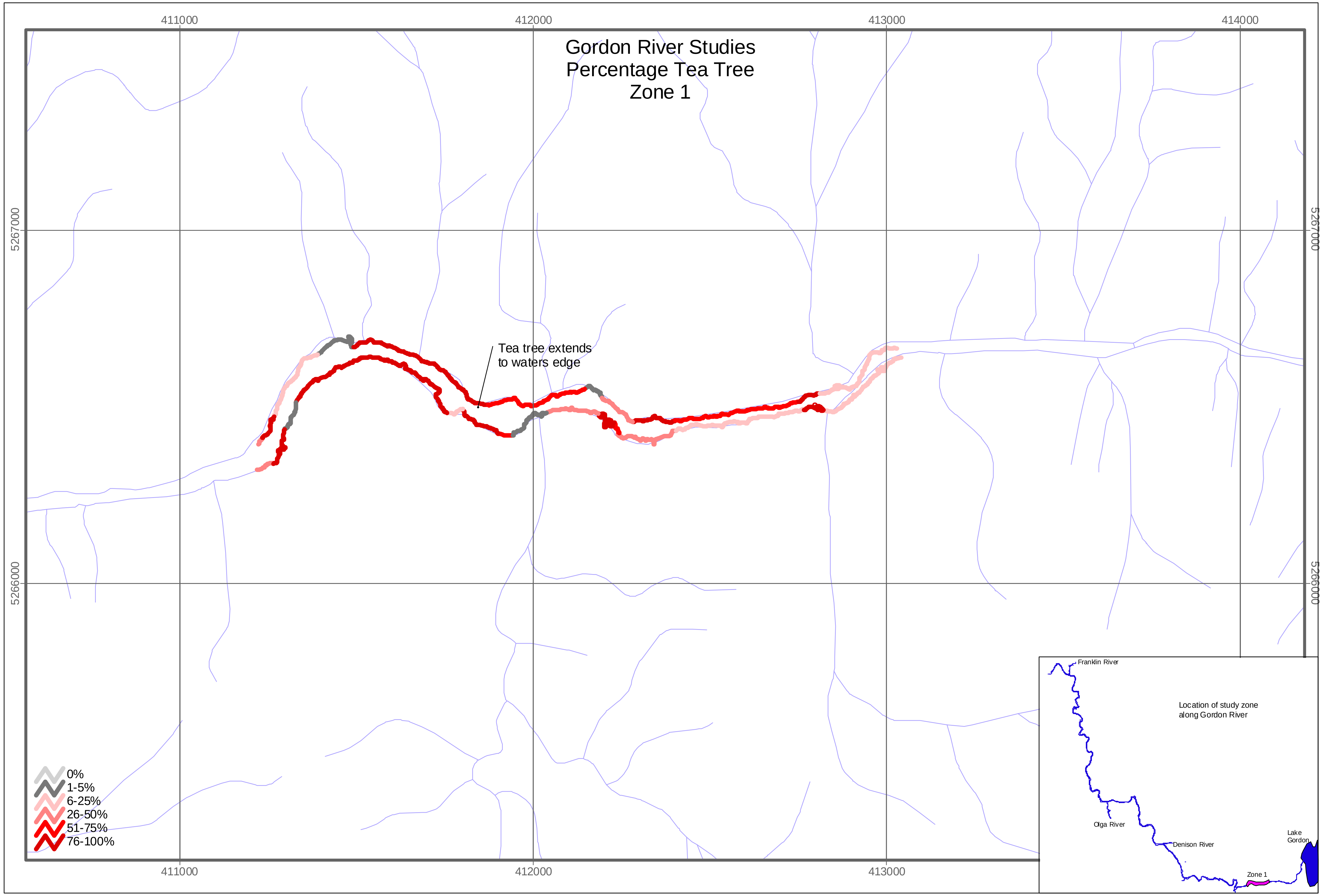
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION

N

Environmental Services



Hydro Tasmania

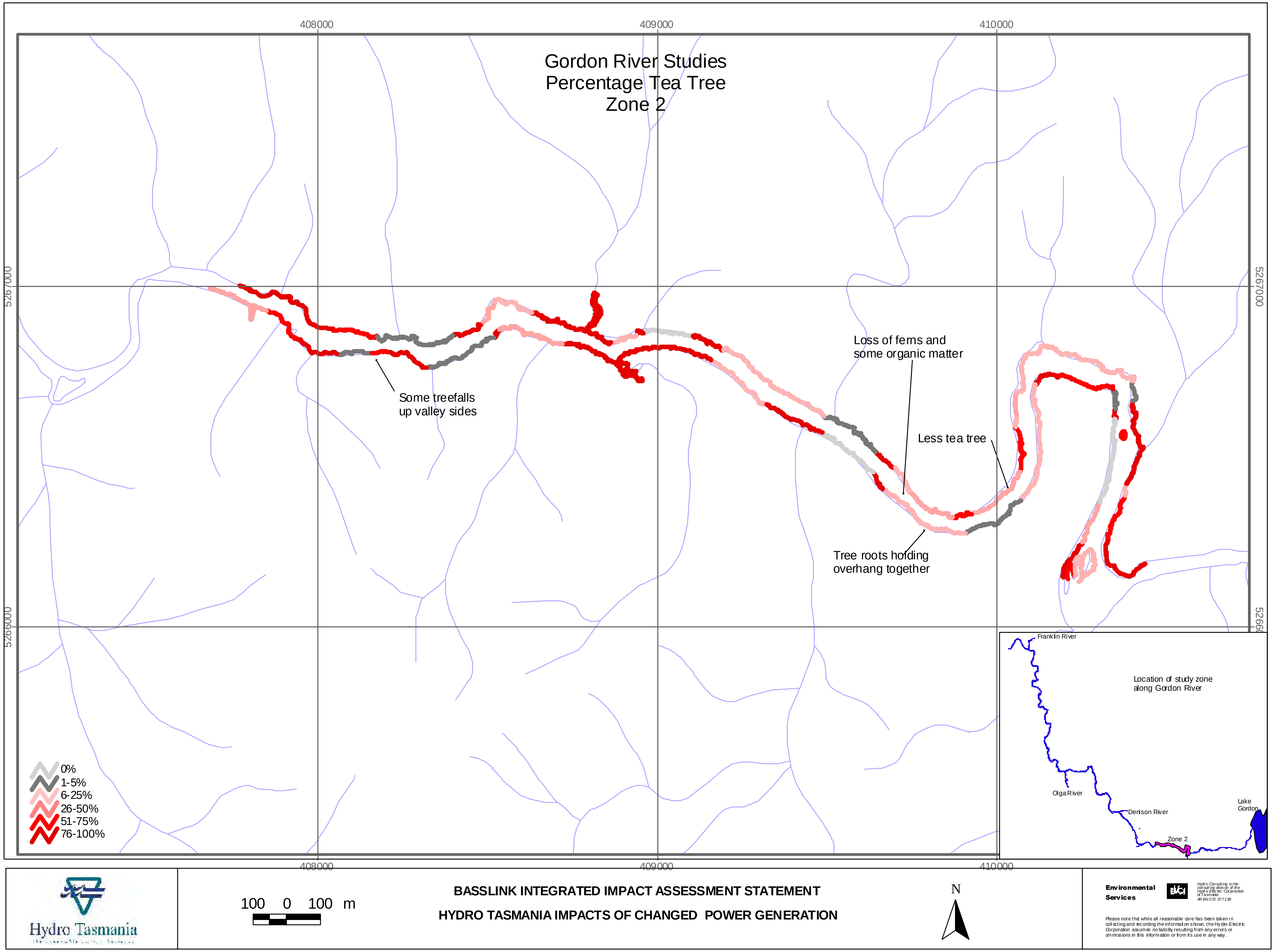
100 0 100 m

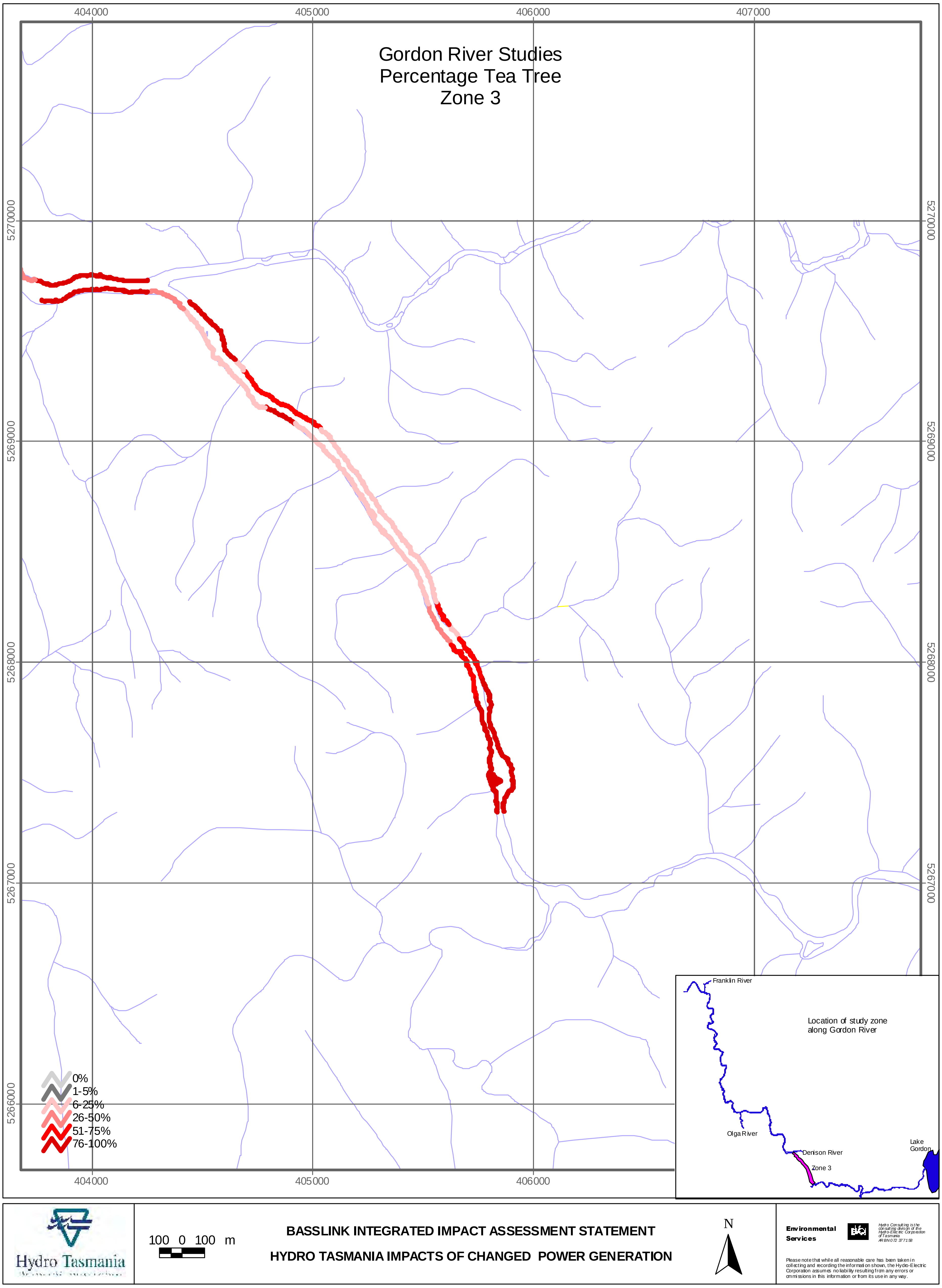
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT

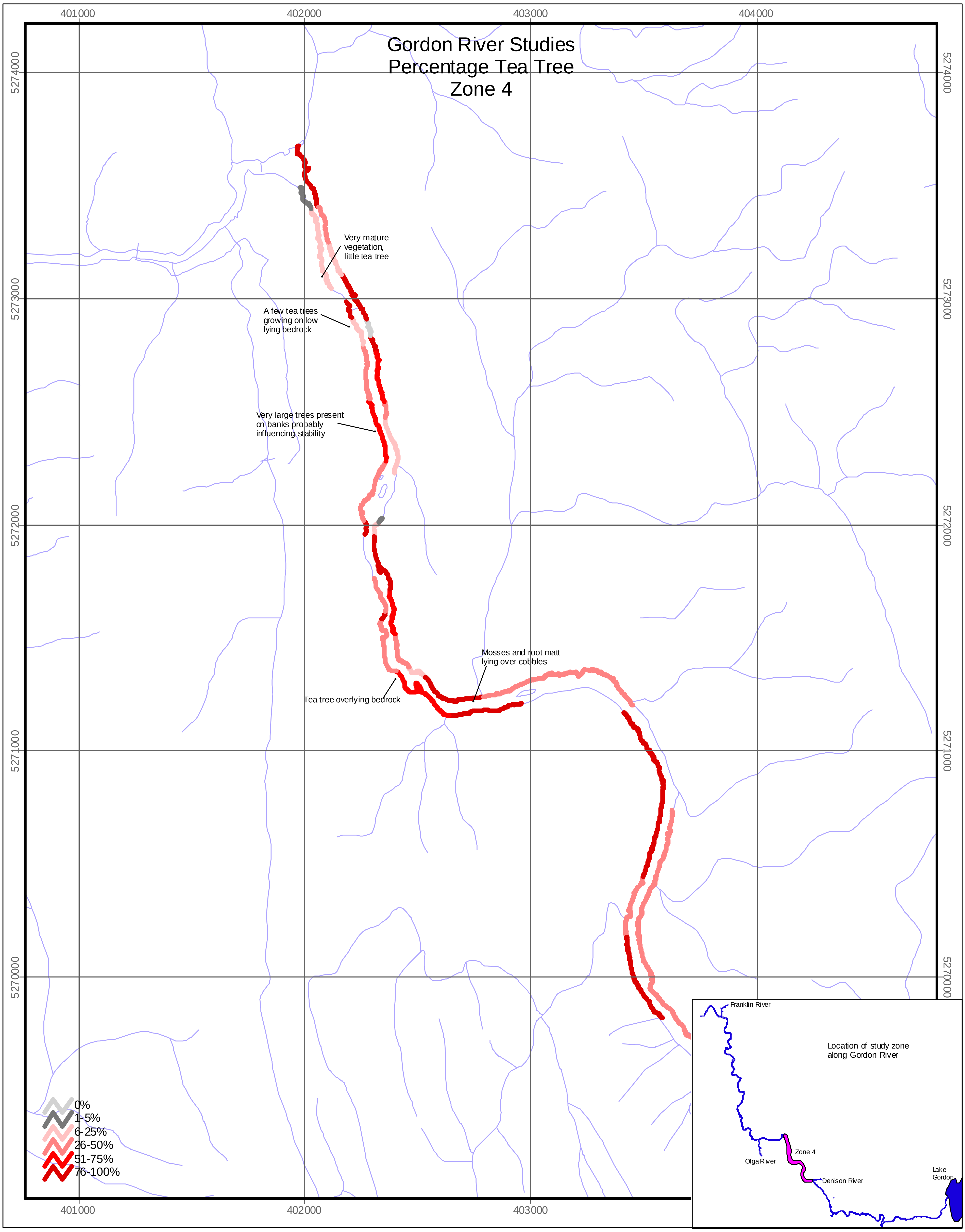
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION

N

Environmental Services


Gordon River Studies
Percentage Tea Tree
Zone 2
408000
409000
410000
5267000
5266000
Some treefalls
up valley sides
Loss of ferns and
some organic matter
Less tea tree
Tree roots holding
overhang together
0%
1-5%
6-25%
26-50%
51-75%
76-100%
Location of study zone
along Gordon River
Franklin River
Olga River
Denison River
Zone 2
Lake
Gordon
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
Environmental
Services


Gordon River Studies
Percentage Tea Tree
Zone 3
404000
405000
406000
407000
5270000
5269000
5268000
5267000
5266000
0%
1-5%
6-25%
26-50%
51-75%
76-100%
Franklin River
Location of study zone along Gordon River
Olga River
Denison River
Zone 3
Lake Gordon
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
Environmental Services



Hydro Tasmania

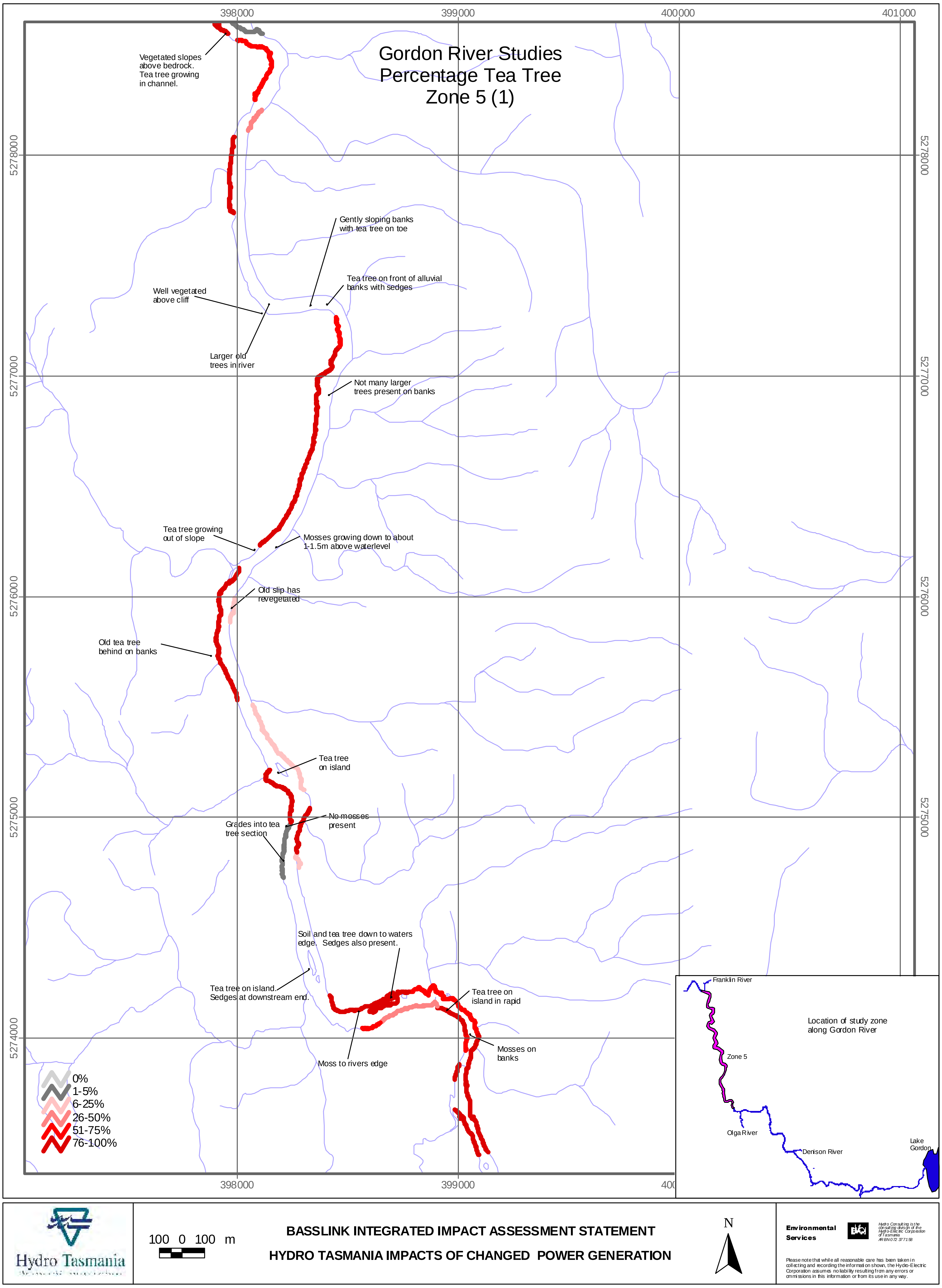
100 0 100 m

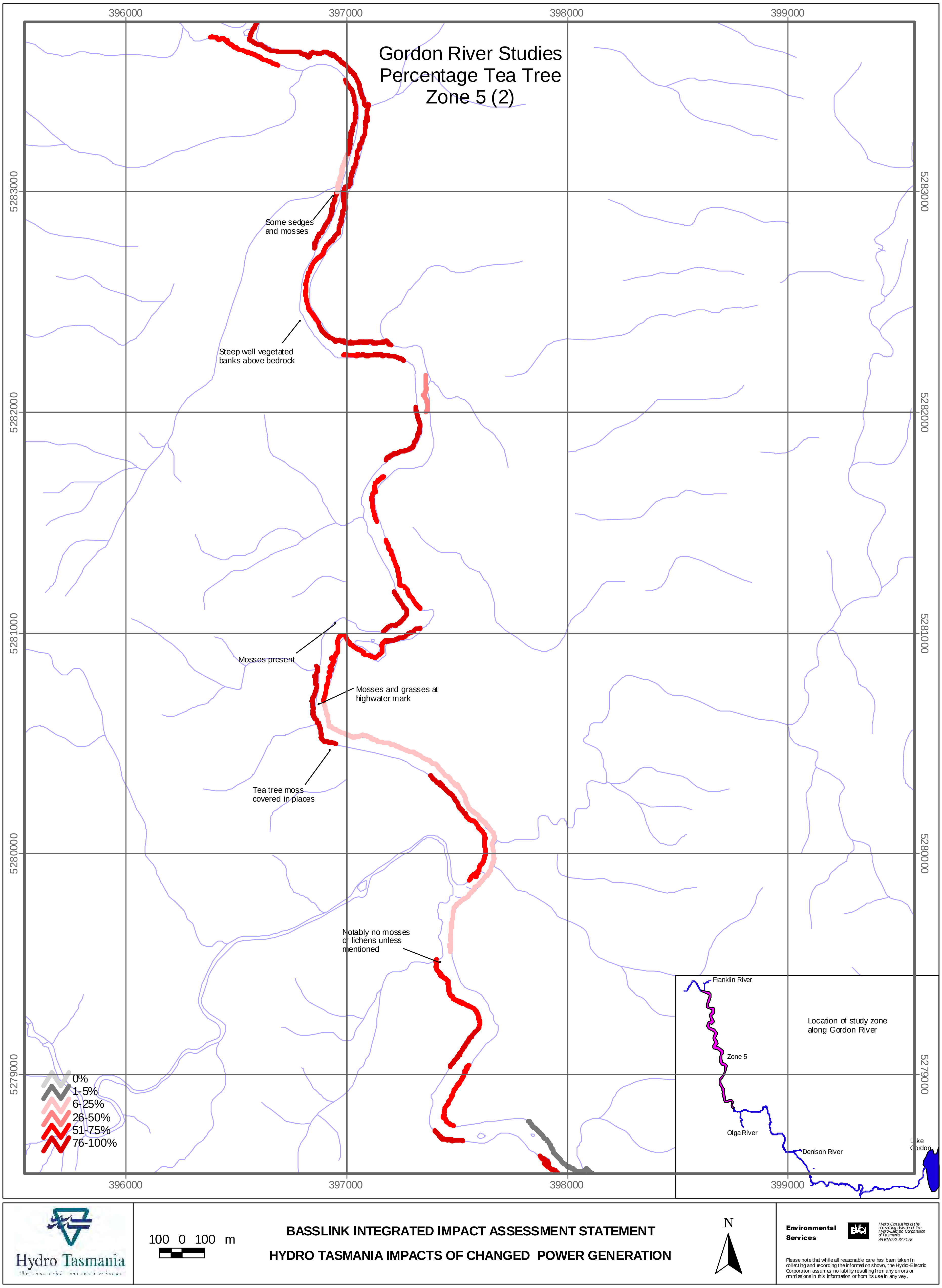
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT

HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION

N

Environmental Services


Gordon River Studies
Percentage Tea Tree
Zone 5 (1)
398000
399000
400000
401000
5278000
5277000
5276000
5275000
5274000
Vegetated slopes above bedrock. Tea tree growing in channel.
Gently sloping banks with tea tree on toe
Tea tree on front of alluvial banks with sedges
Well vegetated above cliff
Larger old trees in river
Not many larger trees present on banks
Tea tree growing out of slope
Mosses growing down to about 1-1.5m above waterlevel
Old slip has revegetated
Old tea tree behind on banks
Tea tree on island
Grades into tea tree section
No mosses present
Soil and tea tree down to waters edge. Sedges also present.
Tea tree on island. Sedges at downstream end.
Tea tree on island in rapid
Mosses on banks
Moss to rivers edge
0%
1-5%
6-25%
26-50%
51-75%
76-100%
Franklin River
Location of study zone along Gordon River
Zone 5
Olga River
Denison River
Lake Gordon
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
Environmental Services


Gordon River Studies
Percentage Tea Tree
Zone 5 (2)
396000
397000
398000
399000
5283000
5282000
5281000
5280000
5279000
Some sedges and mosses
Steep well vegetated banks above bedrock
Mosses present
Mosses and grasses at highwater mark
Tea tree moss covered in places
Notably no mosses or lichens unless mentioned
0%
1-5%
6-25%
26-50%
51-75%
76-100%
Franklin River
Location of study zone along Gordon River
Zone 5
Olga River
Denison River
Lake Gordon
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
Hydro Tasmania
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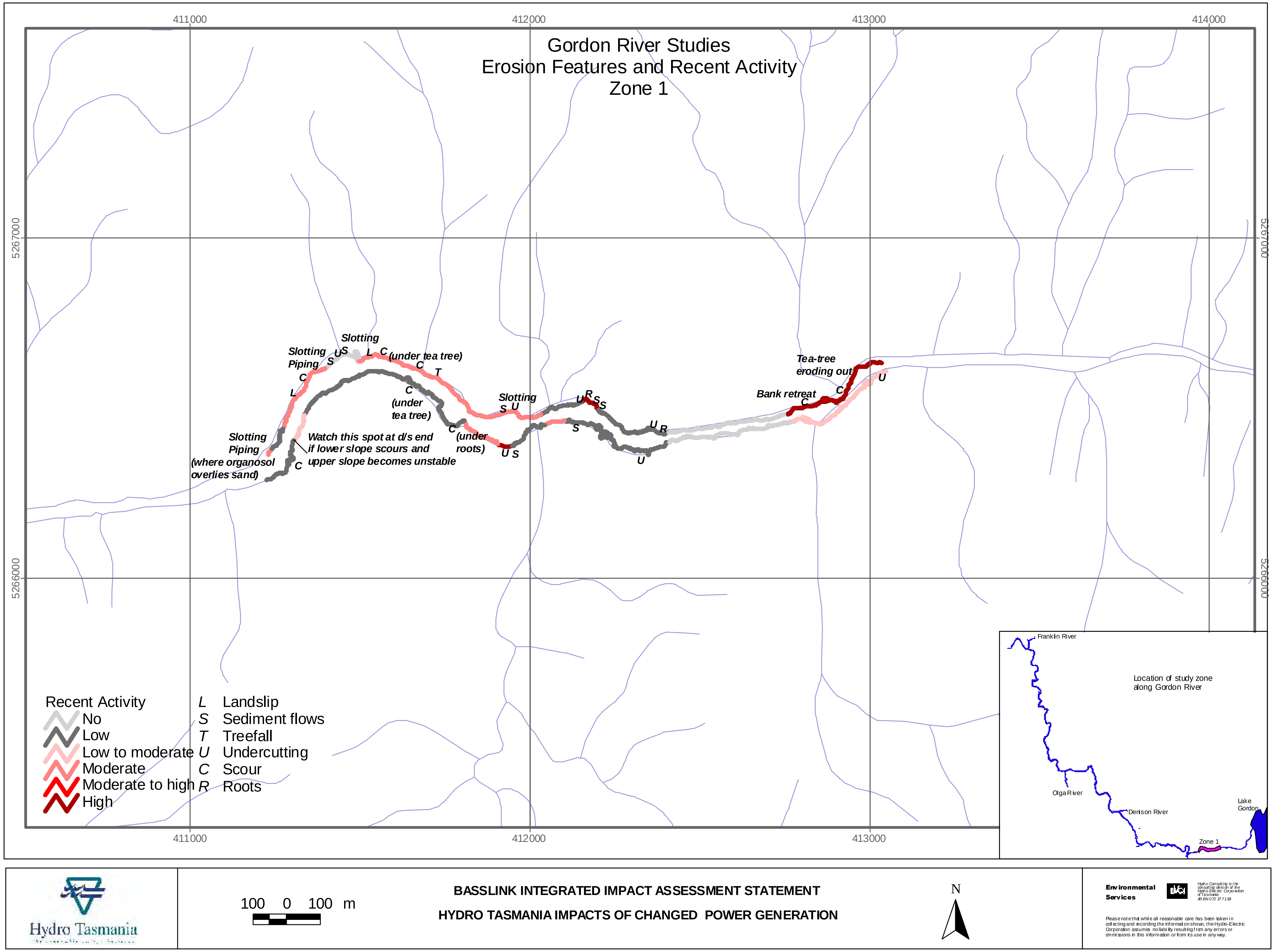
Gordon River Studies
Erosion Features and Recent Activity
Zone 1
411000
412000
413000
414000
5267000
5266000
Slotting
Slotting
Piping
U S
S
L C (under tea tree)
C
T
C
L
C
(under
tea tree)
Slotting
Piping
(where organosol
overlies sand)
Watch this spot at d/s end
if lower slope scours and
upper slope becomes unstable
C
C
(under
roots)
U S
Slotting
S U
U R S S
S
U R
U
Tea-tree
eroding out
Bank retreat
C
C
U
Recent Activity
No
Low
Low to moderate
Moderate
Moderate to high
High
L Landslip
S Sediment flows
T Treefall
U Undercutting
C Scour
R Roots
Franklin River
Location of study zone
along Gordon River
Olga River
Denison River
Lake
Gordon
Zone 1
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
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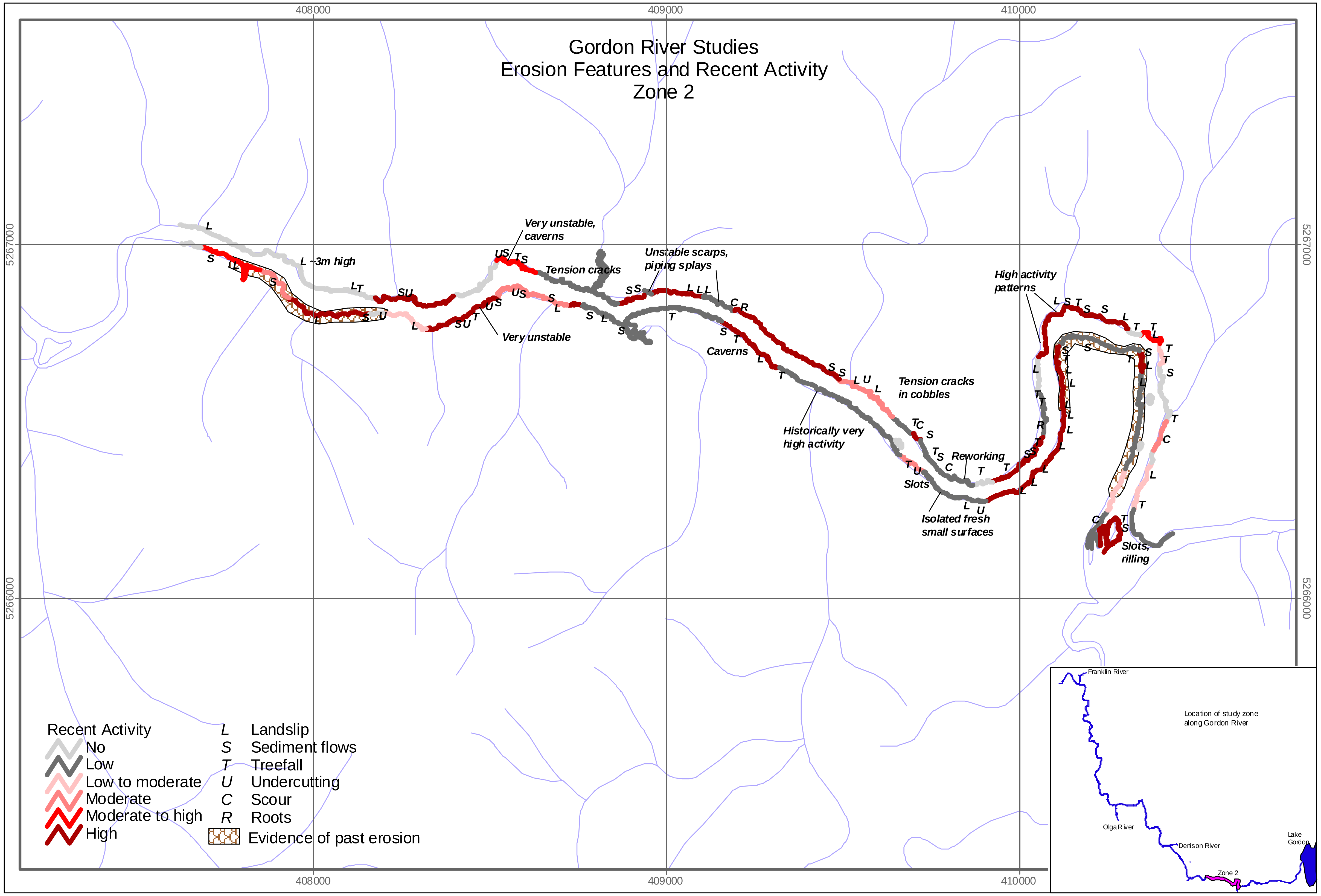

BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT

HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION

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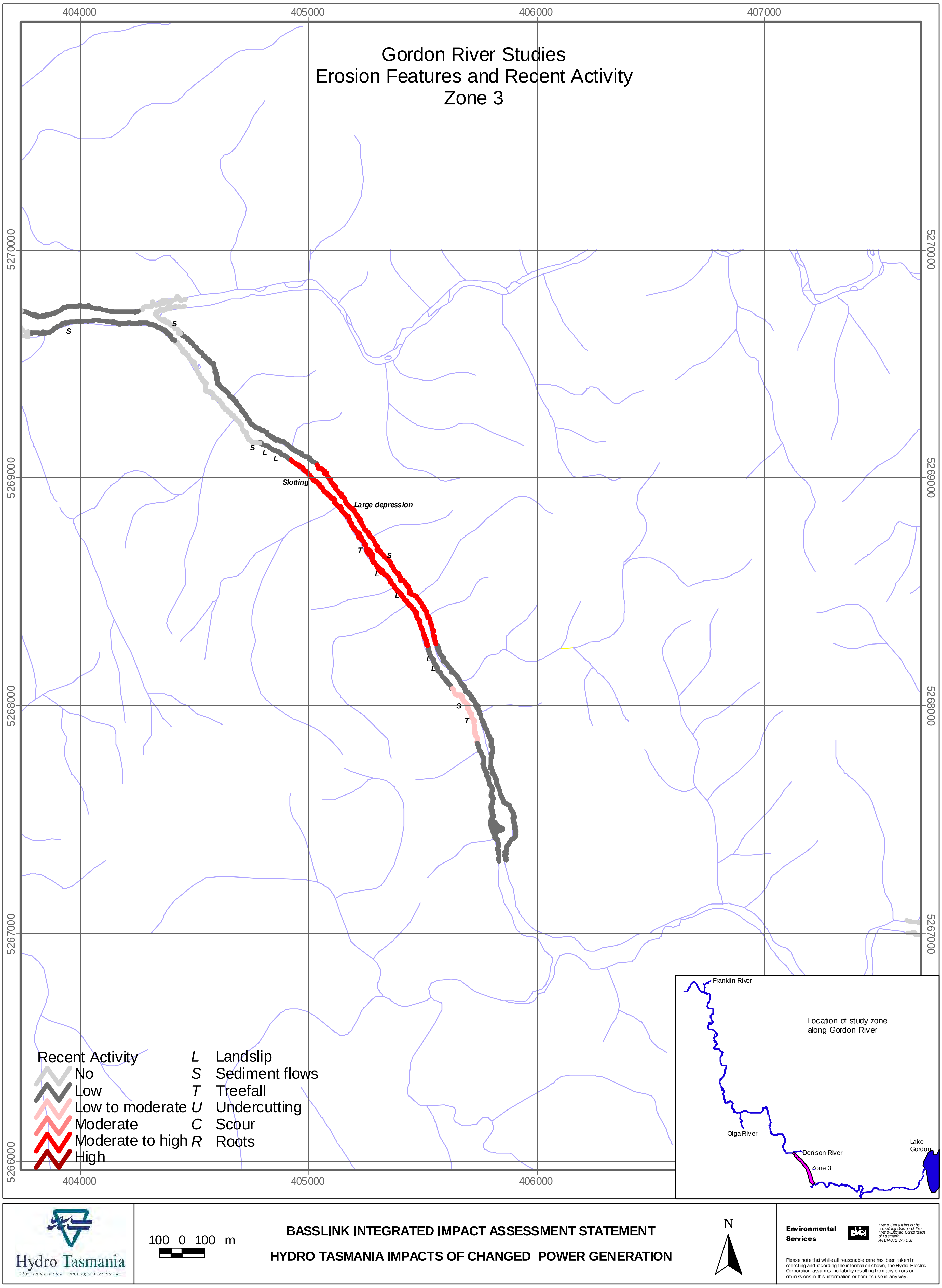
Gordon River Studies
Erosion Features and Recent Activity
Zone 3
404000
405000
406000
407000
5270000
5269000
5268000
5267000
5266000
S
L
Slotting
Large depression
T
Recent Activity
No
Low
Low to moderate
Moderate
Moderate to high
High
L Landslip
S Sediment flows
T Treefall
U Undercutting
C Scour
R Roots
Franklin River
Location of study zone
along Gordon River
Olga River
Denison River
Zone 3
Lake
Gordon
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
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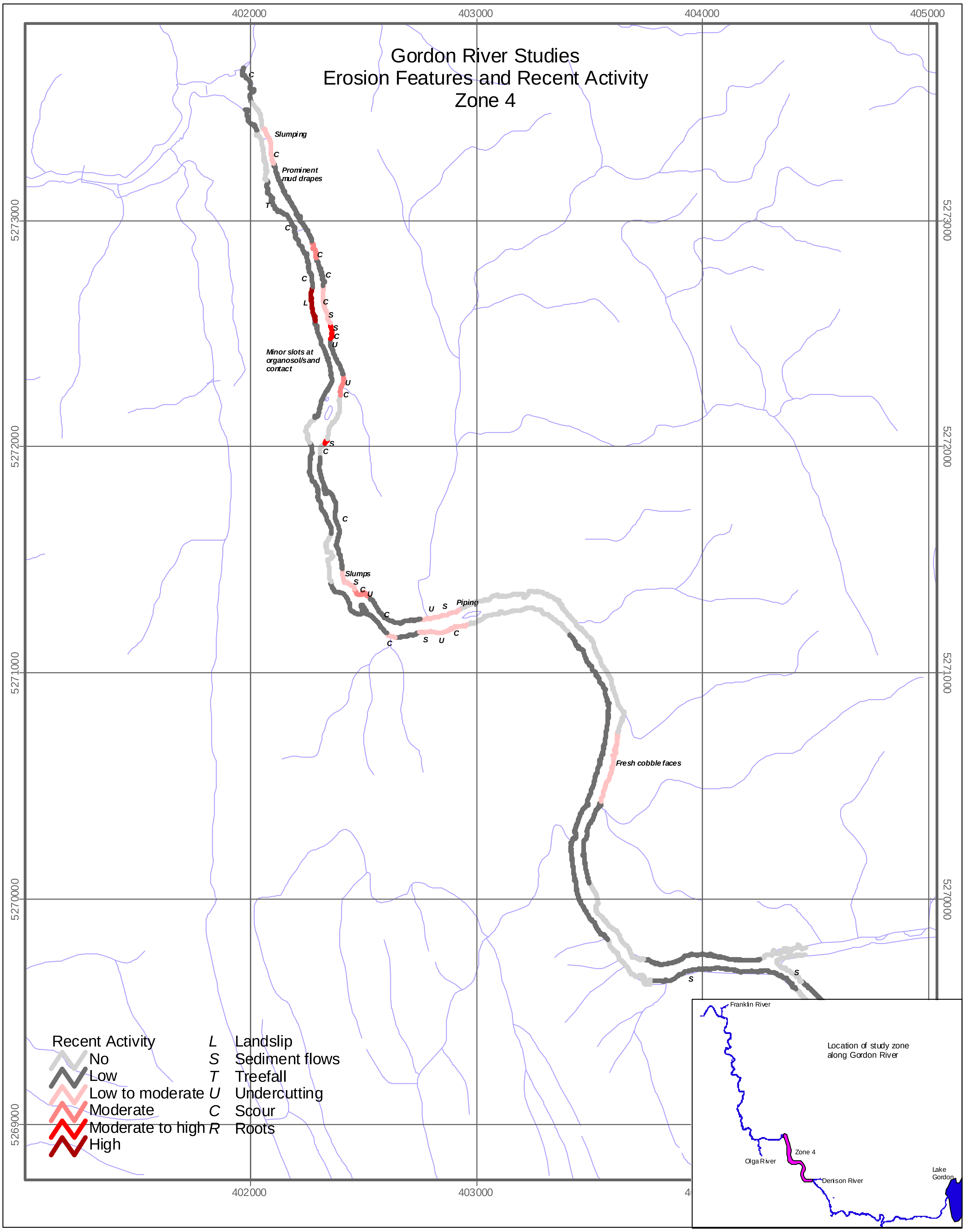


Hydro Tasmania

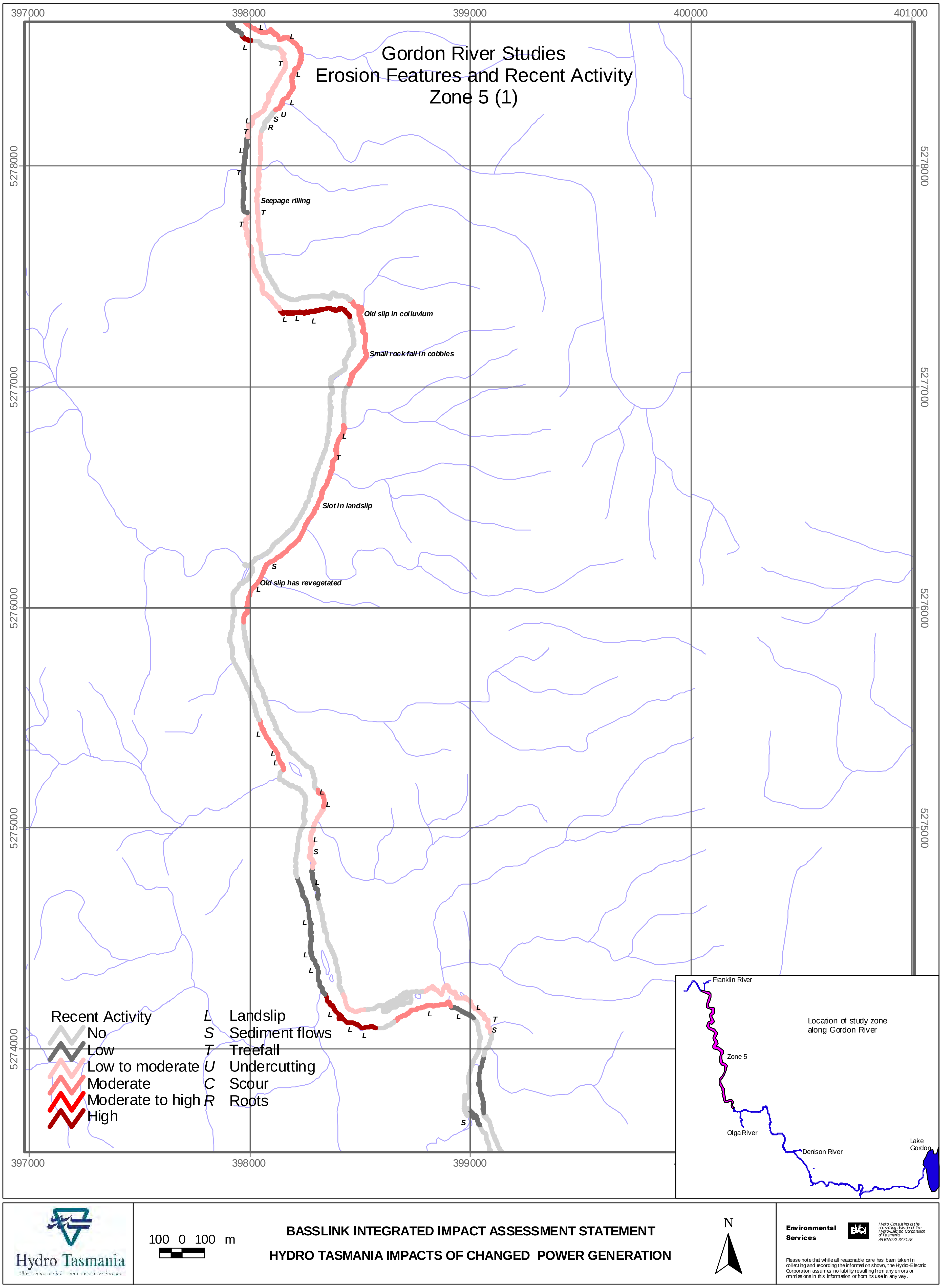
100 0 100 m

BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT

HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION

N

Environmental Services


Gordon River Studies
Erosion Features and Recent Activity
Zone 5 (1)
397000
398000
399000
400000
401000
5278000
5277000
5276000
5275000
5274000
Seepage rilling
Old slip in colluvium
Small rock fall in cobbles
Slot in landslip
Old slip has revegetated
Recent Activity
No
Low
Low to moderate
Moderate
Moderate to high
High
L Landslip
S Sediment flows
T Treefall
U Undercutting
C Scour
R Roots
Franklin River
Location of study zone along Gordon River
Zone 5
Olga River
Denison River
Lake Gordon
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
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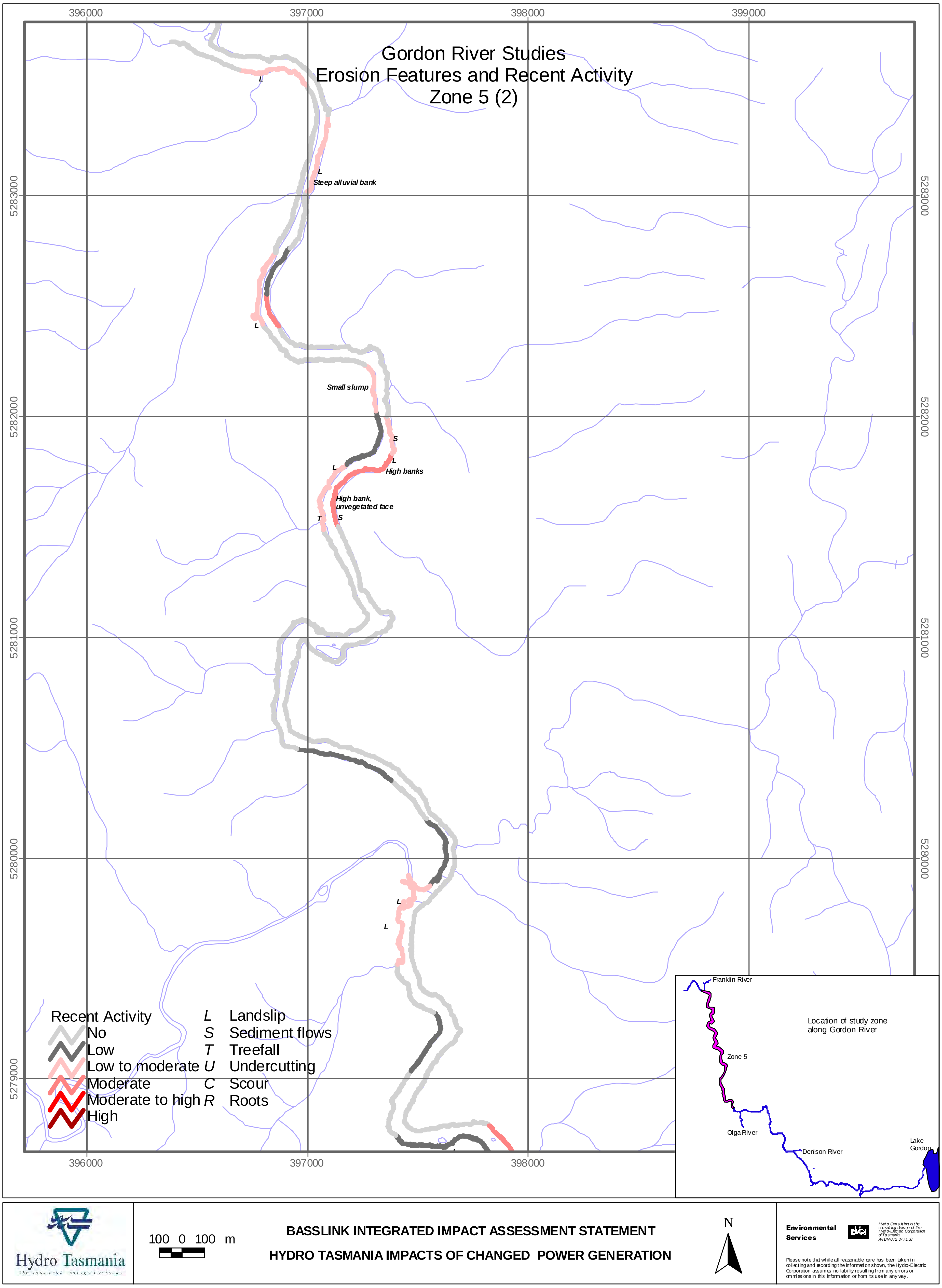
Gordon River Studies
Erosion Features and Recent Activity
Zone 5 (2)
396000
397000
398000
399000
5283000
5282000
5281000
5280000
5279000
Steep alluvial bank
Small slump
High banks
High bank, unvegetated face
L
S
T
Recent Activity
No
Low
Low to moderate
Moderate
Moderate to high
High
L Landslip
S Sediment flows
T Treefall
U Undercutting
C Scour
R Roots
Franklin River
Location of study zone along Gordon River
Zone 5
Olga River
Denison River
Lake Gordon
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
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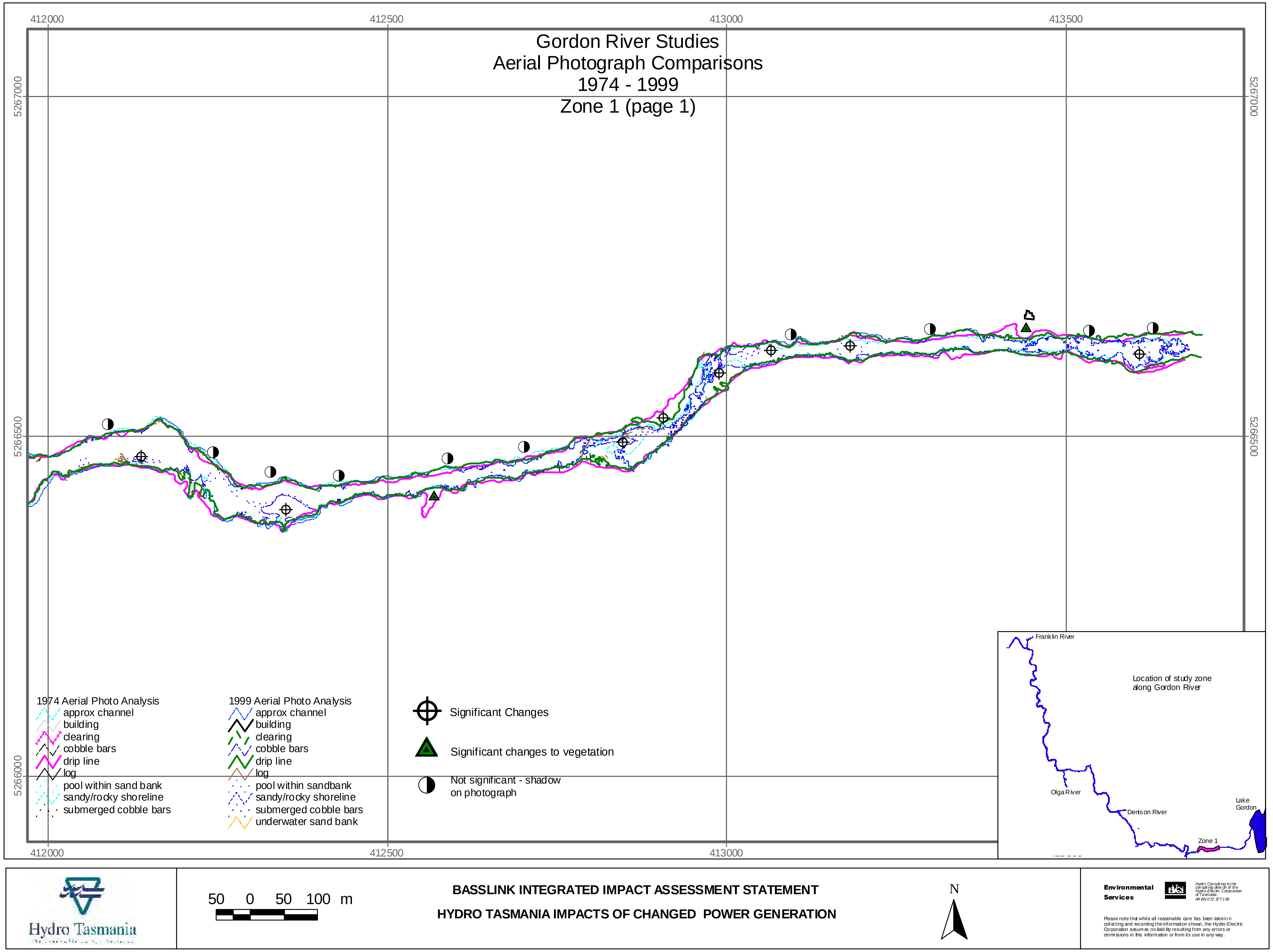
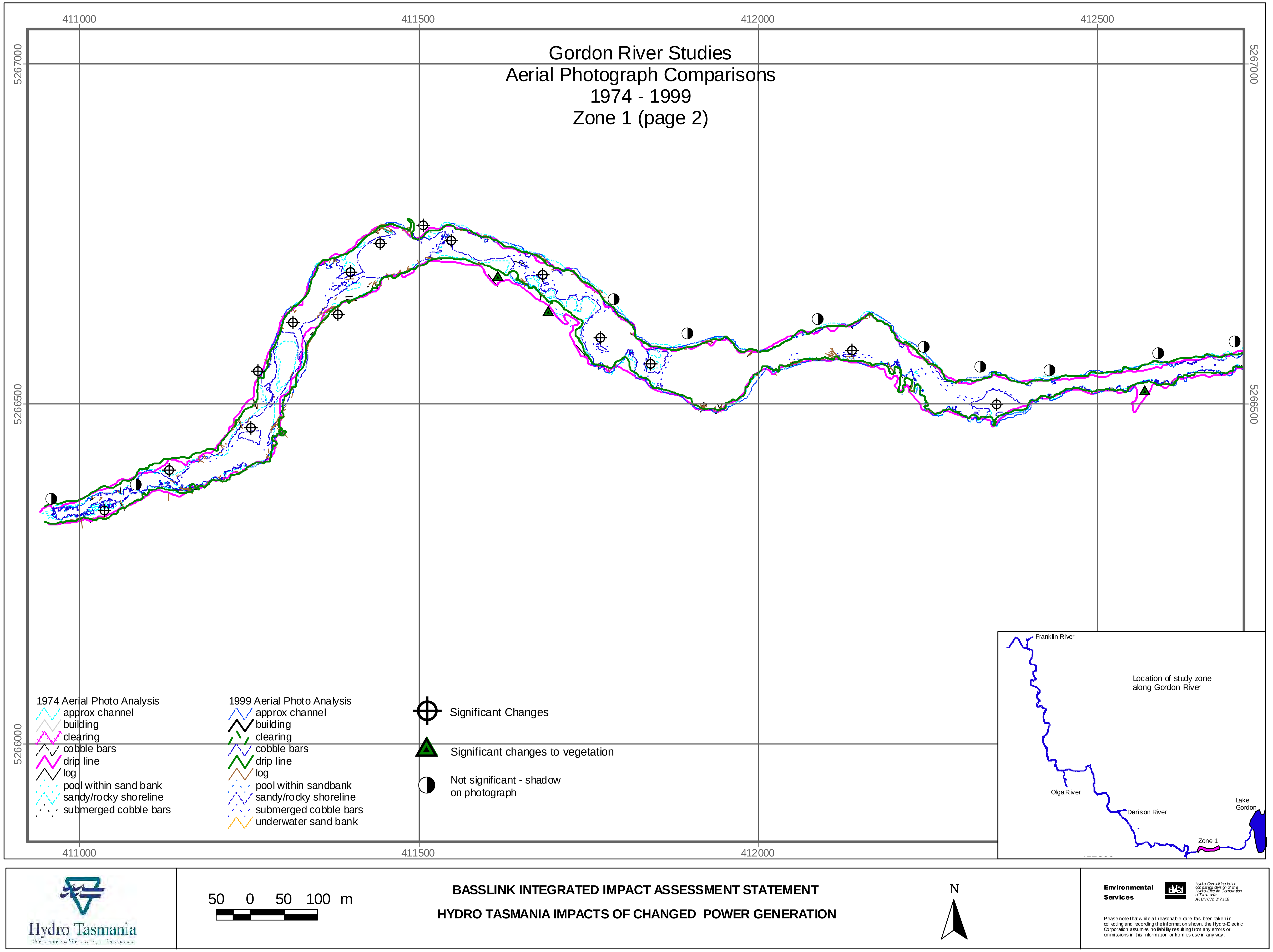
ATTACHMENT 7

MAPS OF AERIAL PHOTO COMPARISON

1974 AND 1999


Gordon River Studies
Aerial Photograph Comparisons
1974 - 1999
Zone 1 (page 1)
412000
412500
413000
413500
5267000
5266500
5266000
1974 Aerial Photo Analysis
approx channel
building
clearing
cobble bars
drip line
log
pool within sand bank
sandy/rocky shoreline
submerged cobble bars
1999 Aerial Photo Analysis
approx channel
building
clearing
cobble bars
drip line
log
pool within sandbank
sandy/rocky shoreline
submerged cobble bars
underwater sand bank
Significant Changes
Significant changes to vegetation
Not significant - shadow
on photograph
Location of study zone
along Gordon River
Franklin River
Olga River
Denison River
Lake Gordon
Zone 1
Hydro Tasmania
50 0 50 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
Environmental Services


Gordon River Studies
Aerial Photograph Comparisons
1974 - 1999
Zone 1 (page 2)
411000
411500
412000
412500
5267000
5266500
5266000
1974 Aerial Photo Analysis
approx channel
building
clearing
cobble bars
drip line
log
pool within sand bank
sandy/rocky shoreline
submerged cobble bars
1999 Aerial Photo Analysis
approx channel
building
clearing
cobble bars
drip line
log
pool within sandbank
sandy/rocky shoreline
submerged cobble bars
underwater sand bank
Significant Changes
Significant changes to vegetation
Not significant - shadow on photograph
Location of study zone along Gordon River
Franklin River
Olga River
Denison River
Lake Gordon
Zone 1
Hydro Tasmania
50 0 50 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
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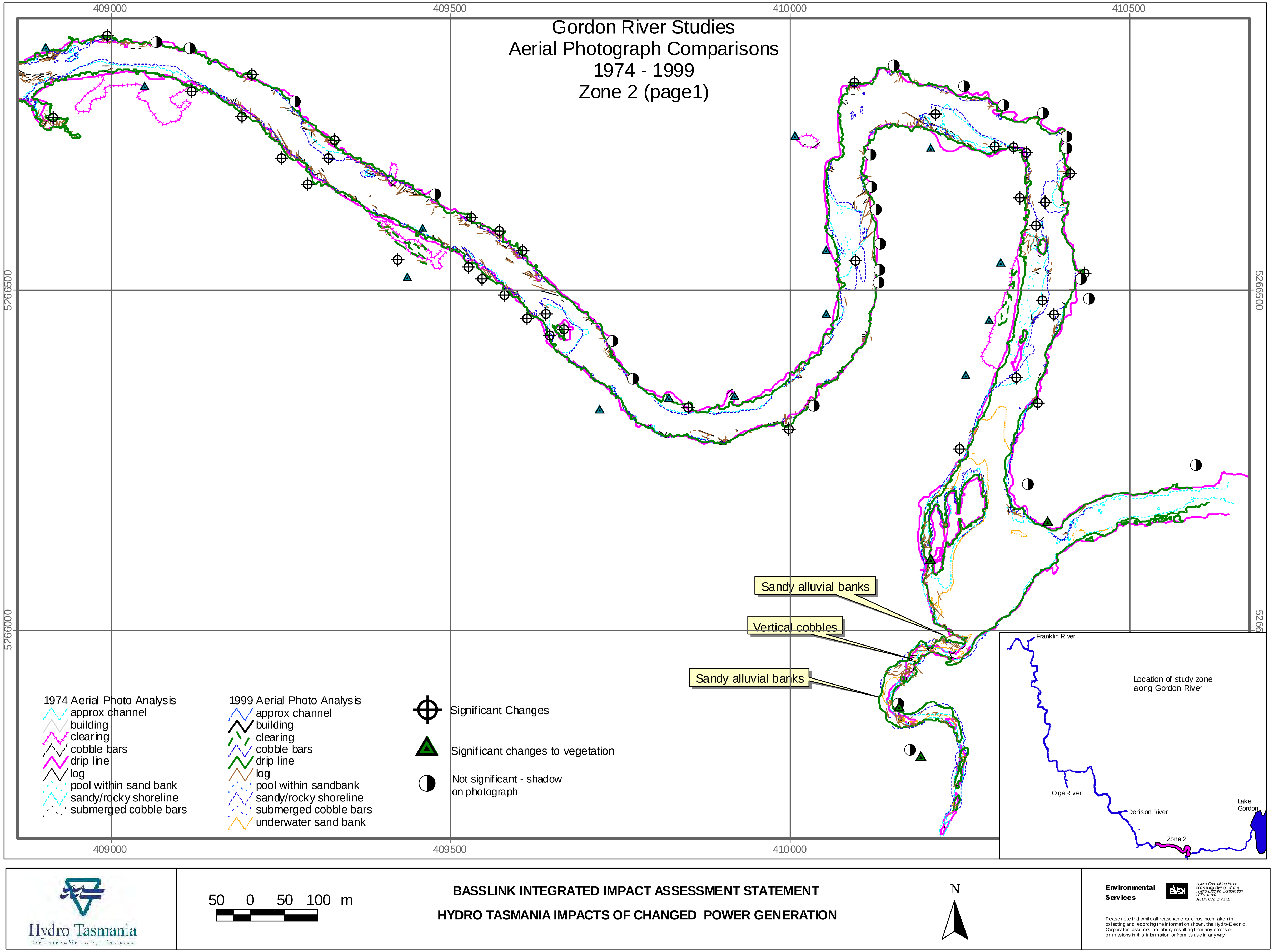
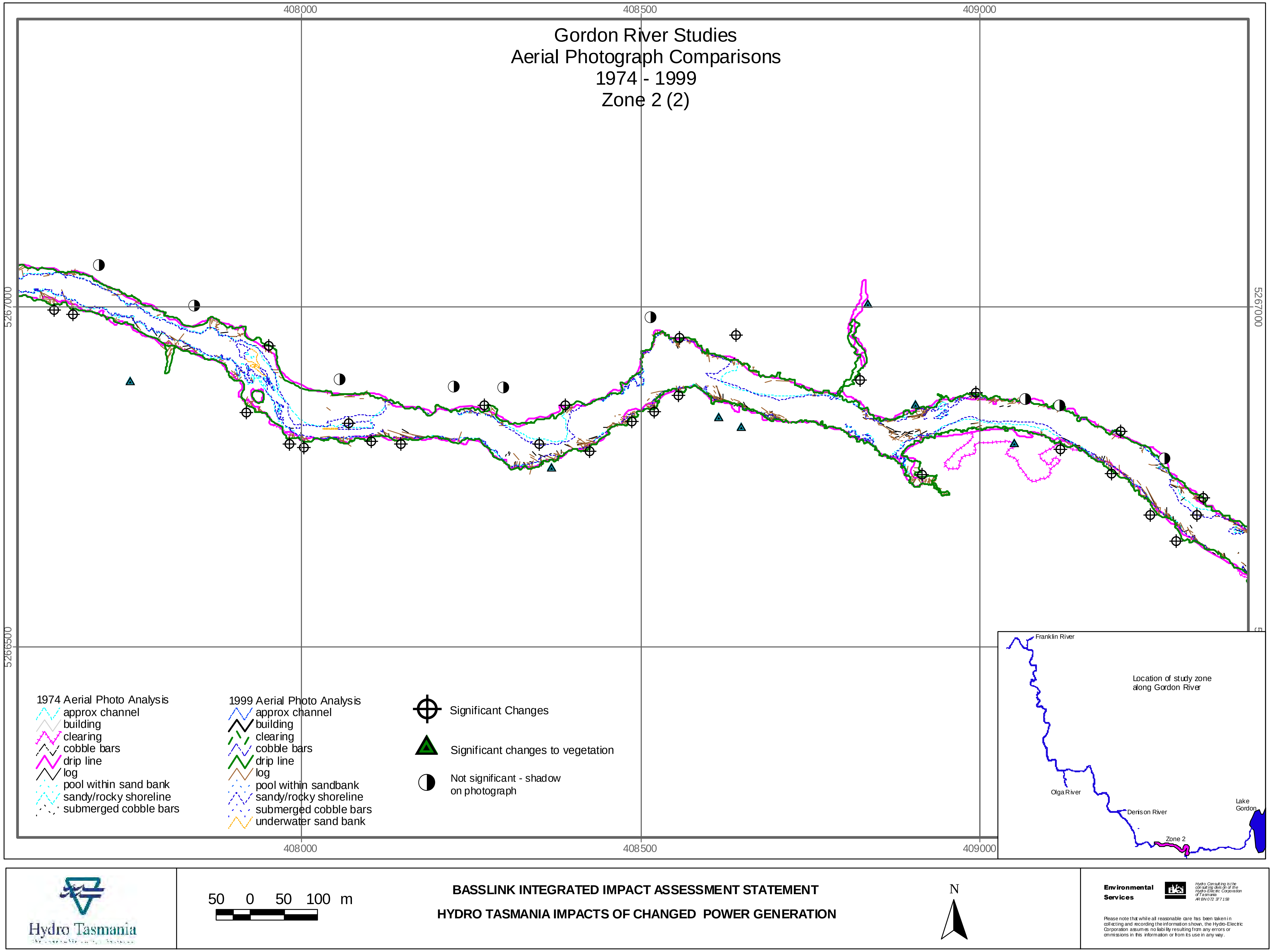
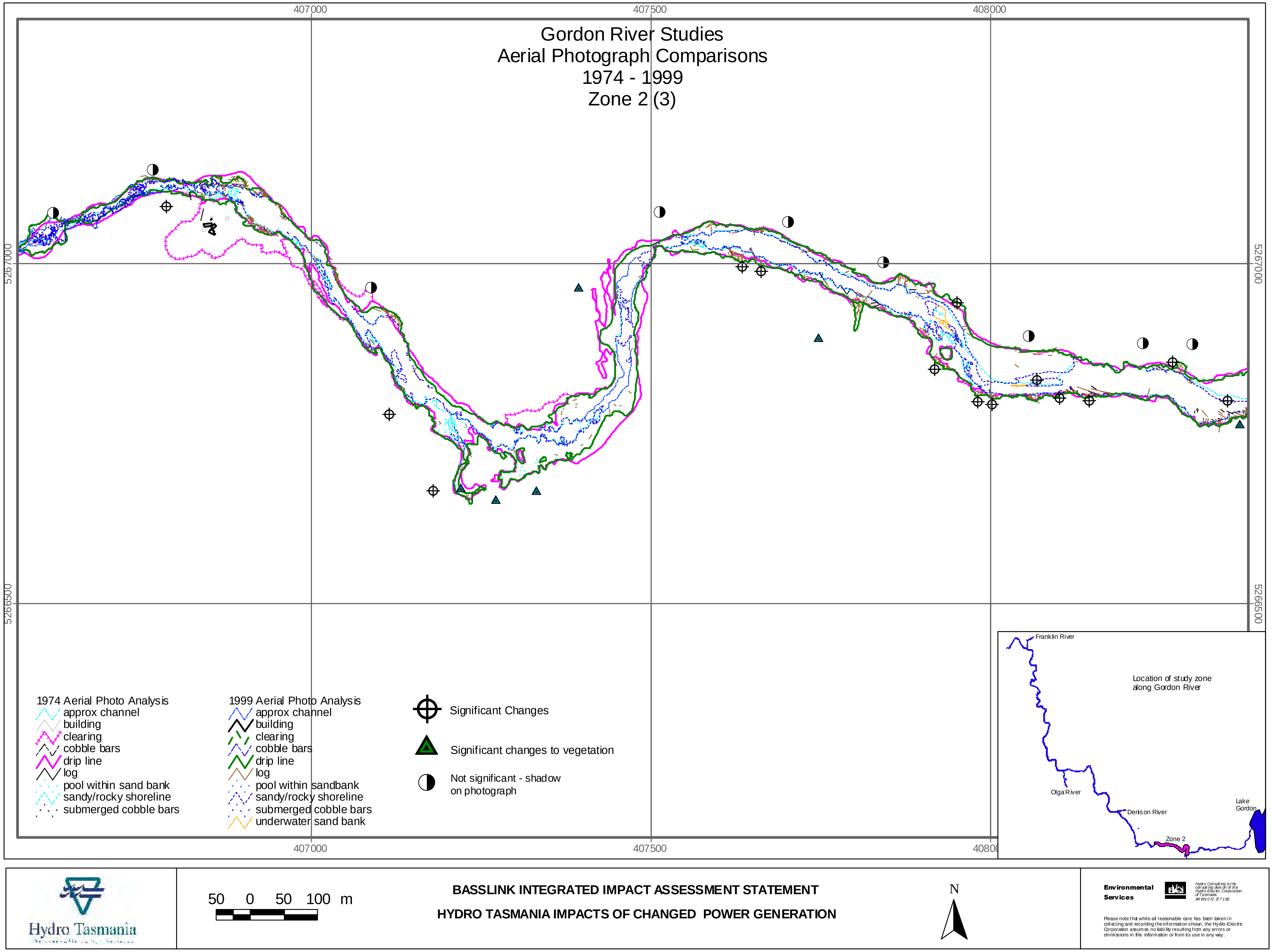
Environmental Services


Gordon River Studies
Aerial Photograph Comparisons
1974 - 1999
Zone 2 (page1)
409000
409500
410000
410500
5266500
5266000
Sandy alluvial banks
Vertical cobbles
Sandy alluvial banks
1974 Aerial Photo Analysis
approx channel
building
clearing
cobble bars
drip line
log
pool within sand bank
sandy/rocky shoreline
submerged cobble bars
1999 Aerial Photo Analysis
approx channel
building
clearing
cobble bars
drip line
log
pool within sandbank
sandy/rocky shoreline
submerged cobble bars
underwater sand bank
Significant Changes
Significant changes to vegetation
Not significant - shadow
on photograph
Franklin River
Location of study zone
along Gordon River
Olga River
Denison River
Lake
Gordon
Zone 2
Hydro Tasmania
50 0 50 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
Environmental
Services


Gordon River Studies
Aerial Photograph Comparisons
1974 - 1999
Zone 2 (2)
408000
408500
409000
5267000
5266500
1974 Aerial Photo Analysis
approx channel
building
clearing
cobble bars
drip line
log
pool within sand bank
sandy/rocky shoreline
submerged cobble bars
1999 Aerial Photo Analysis
approx channel
building
clearing
cobble bars
drip line
log
pool within sandbank
sandy/rocky shoreline
submerged cobble bars
underwater sand bank
Significant Changes
Significant changes to vegetation
Not significant - shadow
on photograph
Location of study zone
along Gordon River
Franklin River
Olga River
Denison River
Lake
Gordon
Zone 2
Hydro Tasmania
50 0 50 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
Environmental
Services


Gordon River Studies
Aerial Photograph Comparisons
1974 - 1999
Zone 2 (3)
407000
407500
408000
5267000
5266500
1974 Aerial Photo Analysis
approx channel
building
clearing
cobble bars
drip line
log
pool within sand bank
sandy/rocky shoreline
submerged cobble bars
1999 Aerial Photo Analysis
approx channel
building
clearing
cobble bars
drip line
log
pool within sandbank
sandy/rocky shoreline
submerged cobble bars
underwater sand bank
Significant Changes
Significant changes to vegetation
Not significant - shadow
on photograph
Location of study zone
along Gordon River
Franklin River
Olga River
Denison River
Zone 2
Lake
Gordon
Hydro Tasmania
50 0 50 100 m
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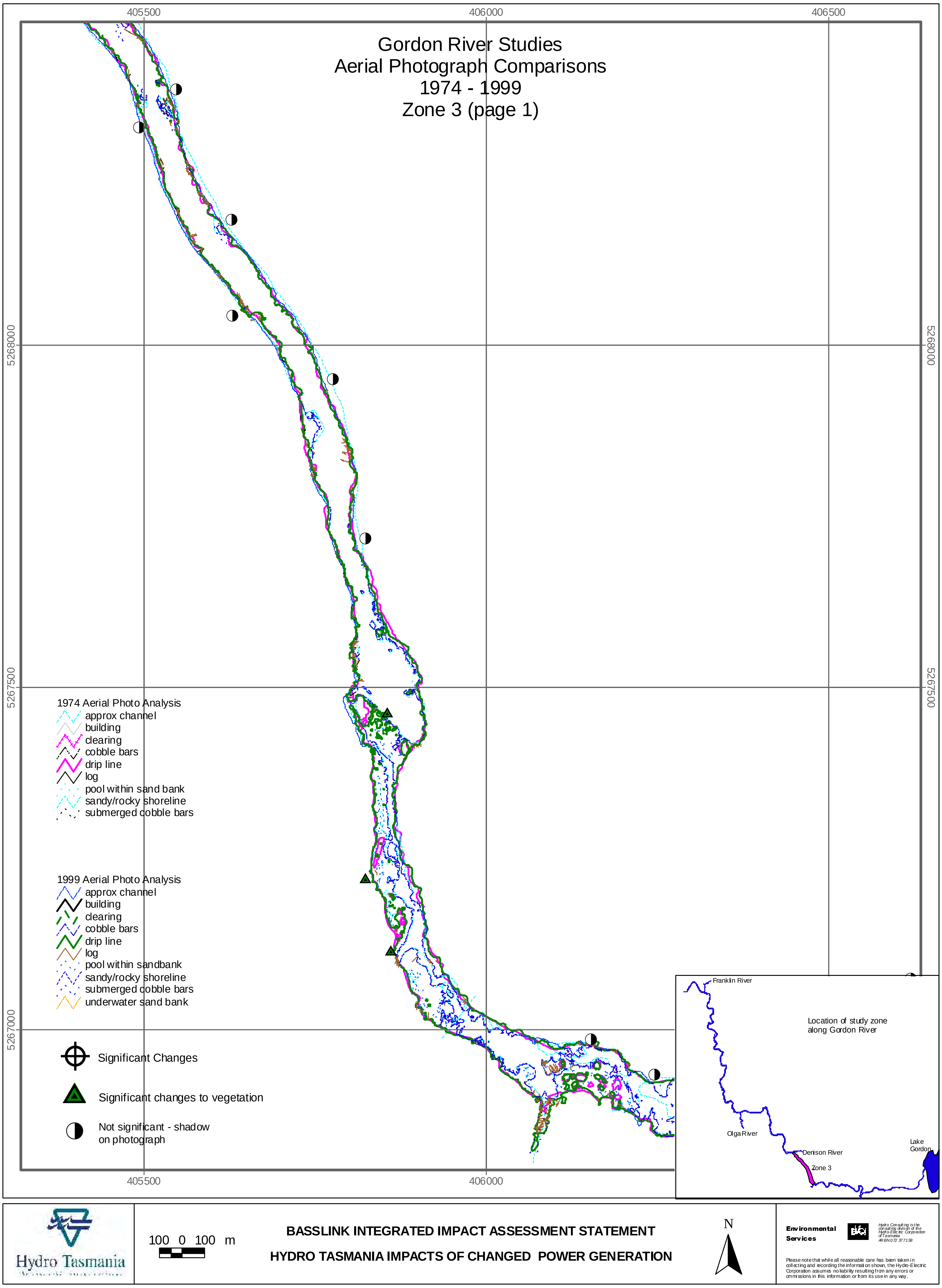
Environmental
Services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approx channel
building
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cobble bars
drip line
log
pool within sand bank
sandy/rocky shoreline
submerged cobble bars
1999 Aerial Photo Analysis
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building
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drip line
log
pool within sandbank
sandy/rocky shoreline
submerged cobble bars
underwater sand bank
Significant Changes
Significant changes to vegetation
Not significant - shadow
on photograph
Franklin River
Location of study zone
along Gordon River
Olga River
Denison River
Lake
Gordon
Zone 3
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Environmental
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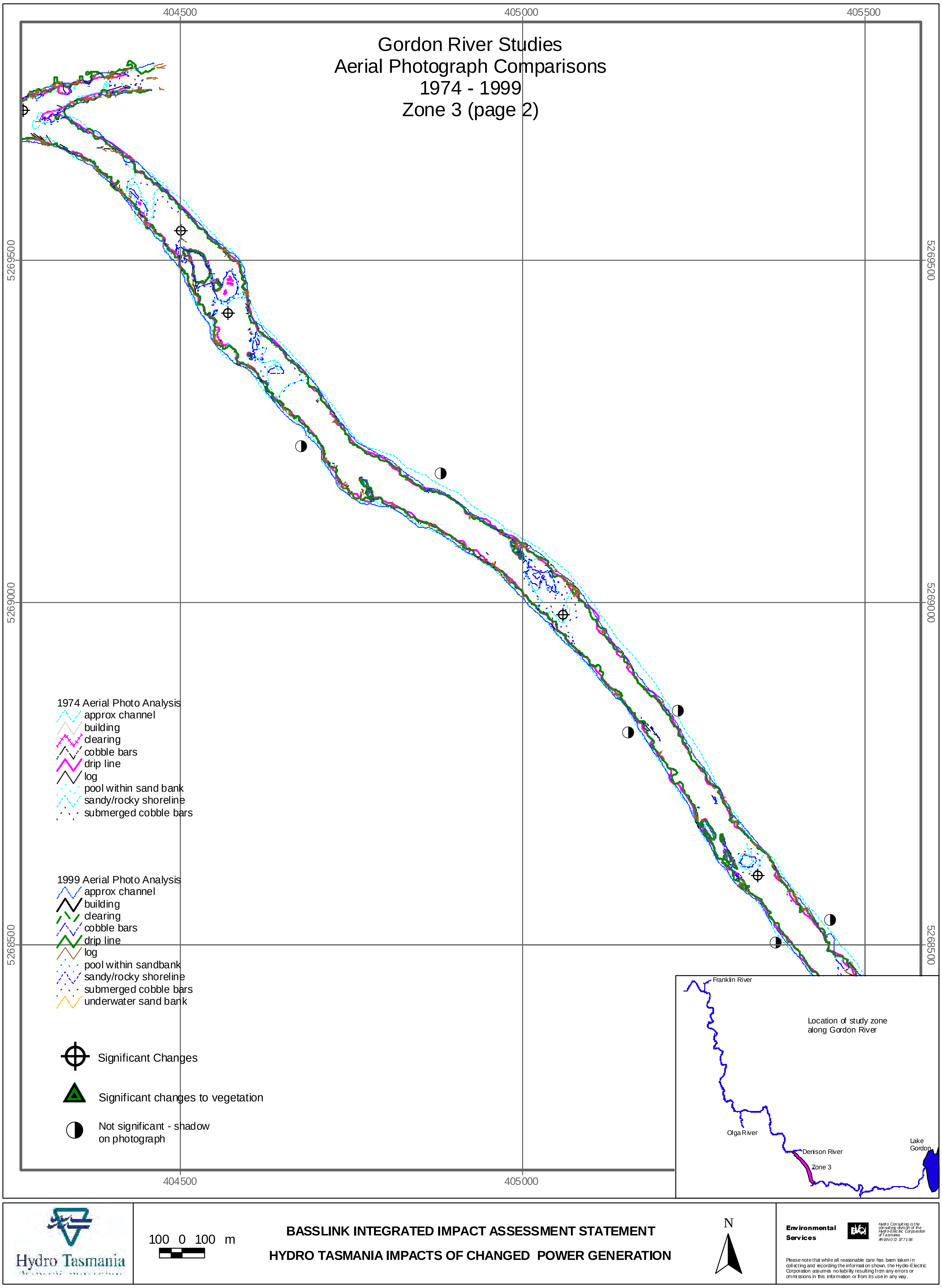
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underwater sand bank
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Olga River
Denison River
Zone 3
Lake
Gordon
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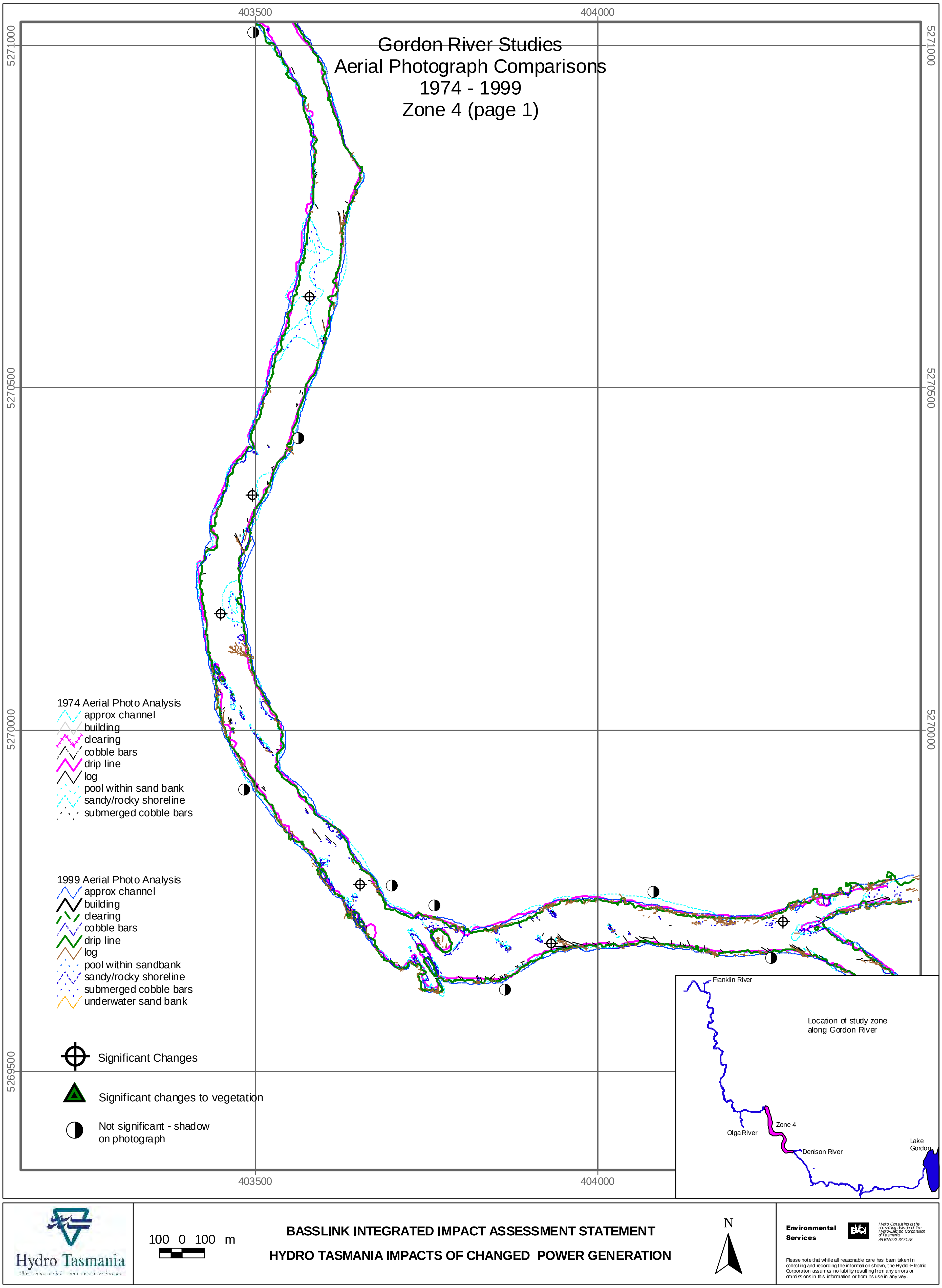
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log
pool within sand bank
sandy/rocky shoreline
submerged cobble bars
1999 Aerial Photo Analysis
approx channel
building
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cobble bars
drip line
log
pool within sandbank
sandy/rocky shoreline
submerged cobble bars
underwater sand bank
Significant Changes
Significant changes to vegetation
Not significant - shadow
on photograph
Franklin River
Location of study zone
along Gordon River
Zone 4
Olga River
Denison River
Lake
Gordon
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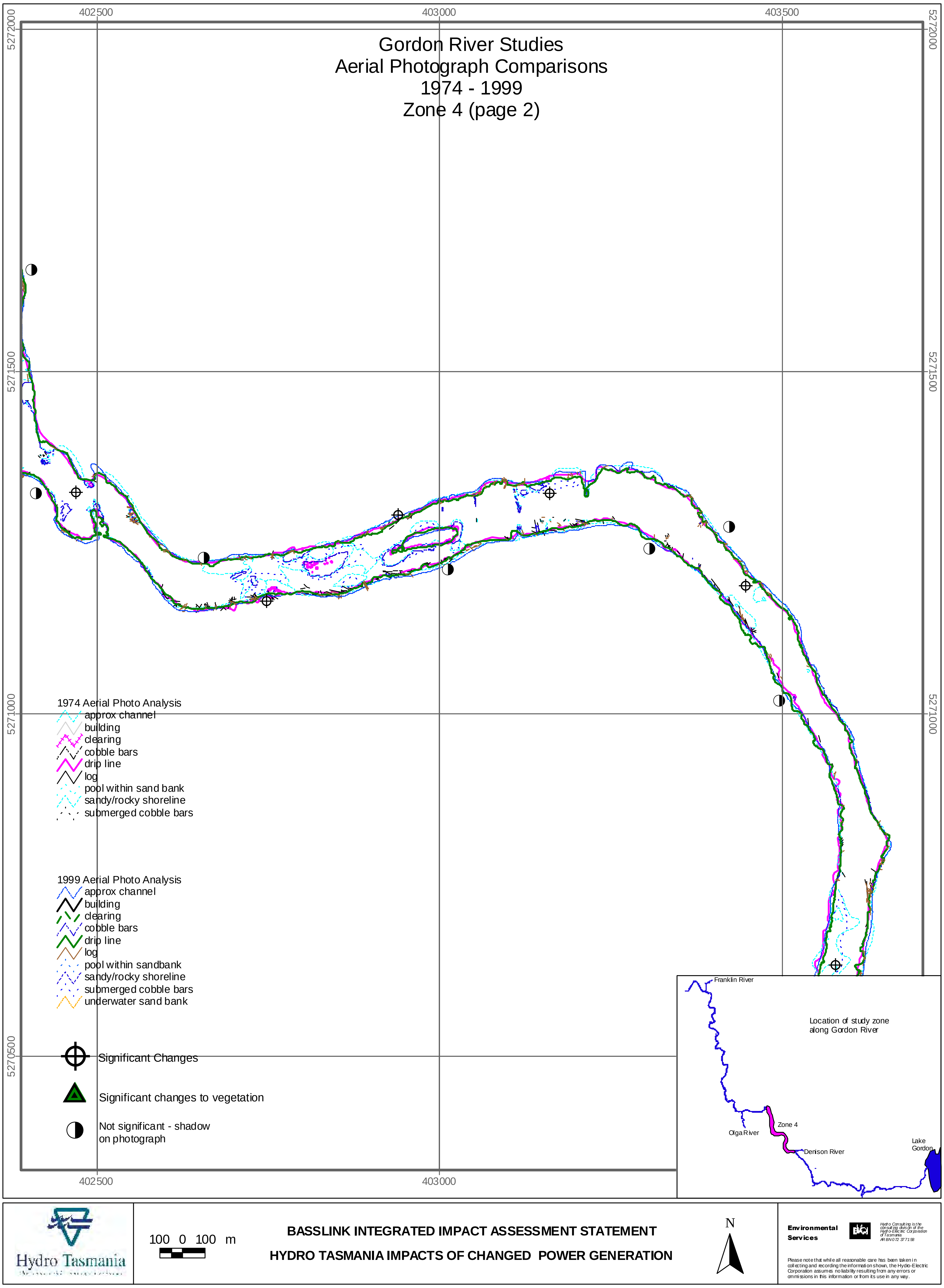
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pool within sand bank
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submerged cobble bars
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drip line
log
pool within sandbank
sandy/rocky shoreline
submerged cobble bars
underwater sand bank
Significant Changes
Significant changes to vegetation
Not significant - shadow
on photograph
Franklin River
Location of study zone
along Gordon River
Zone 4
Olga River
Denison River
Lake
Gordon
Hydro Tasmania
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Environmental
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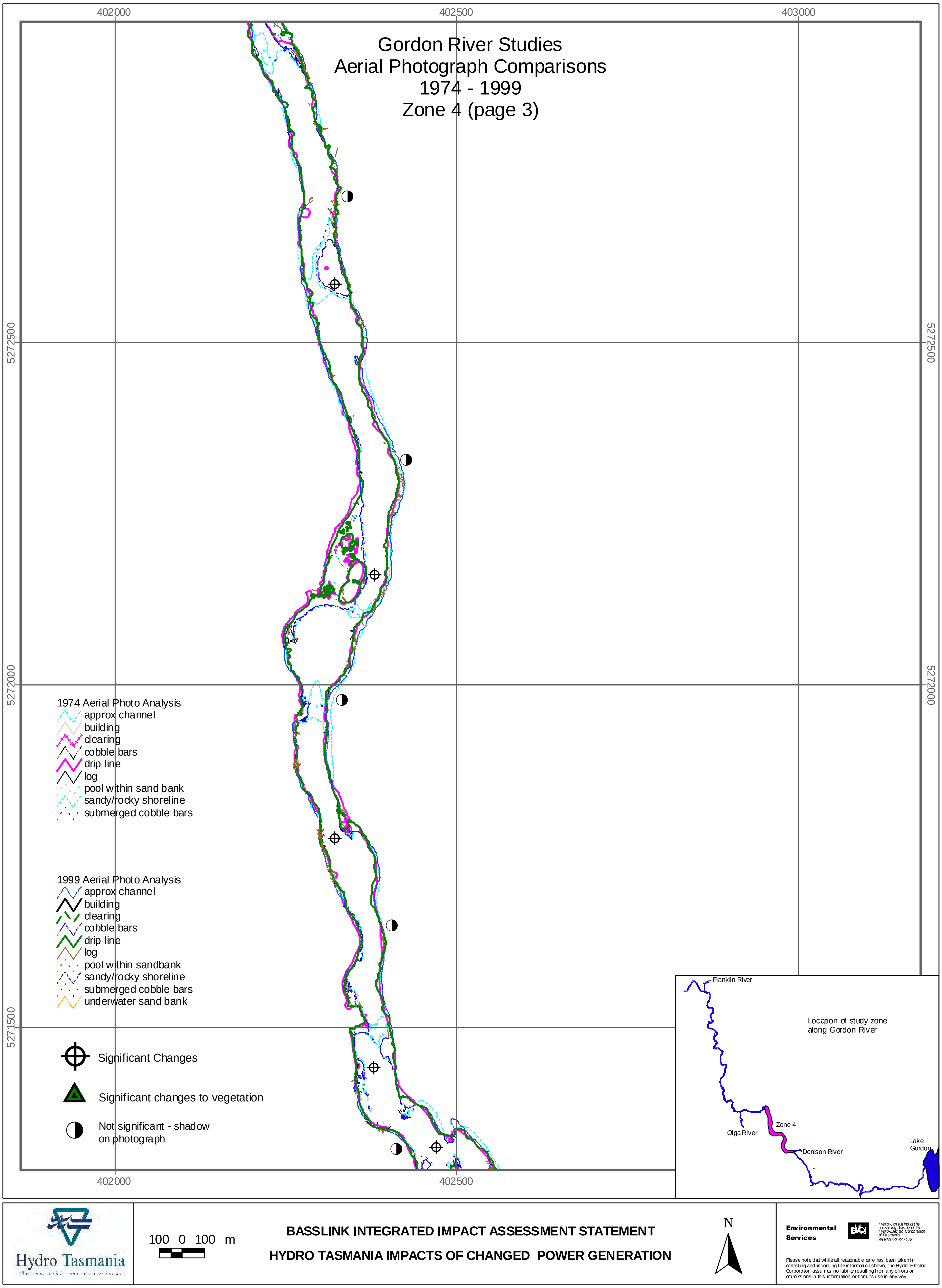
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submerged cobble bars
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clearing
cobble bars
drip line
log
pool within sandbank
sandy/rocky shoreline
submerged cobble bars
underwater sand bank
Significant Changes
Significant changes to vegetation
Not significant - shadow on photograph
Franklin River
Location of study zone along Gordon River
Olga River
Zone 4
Denison River
Lake Gordon
Hydro Tasmania
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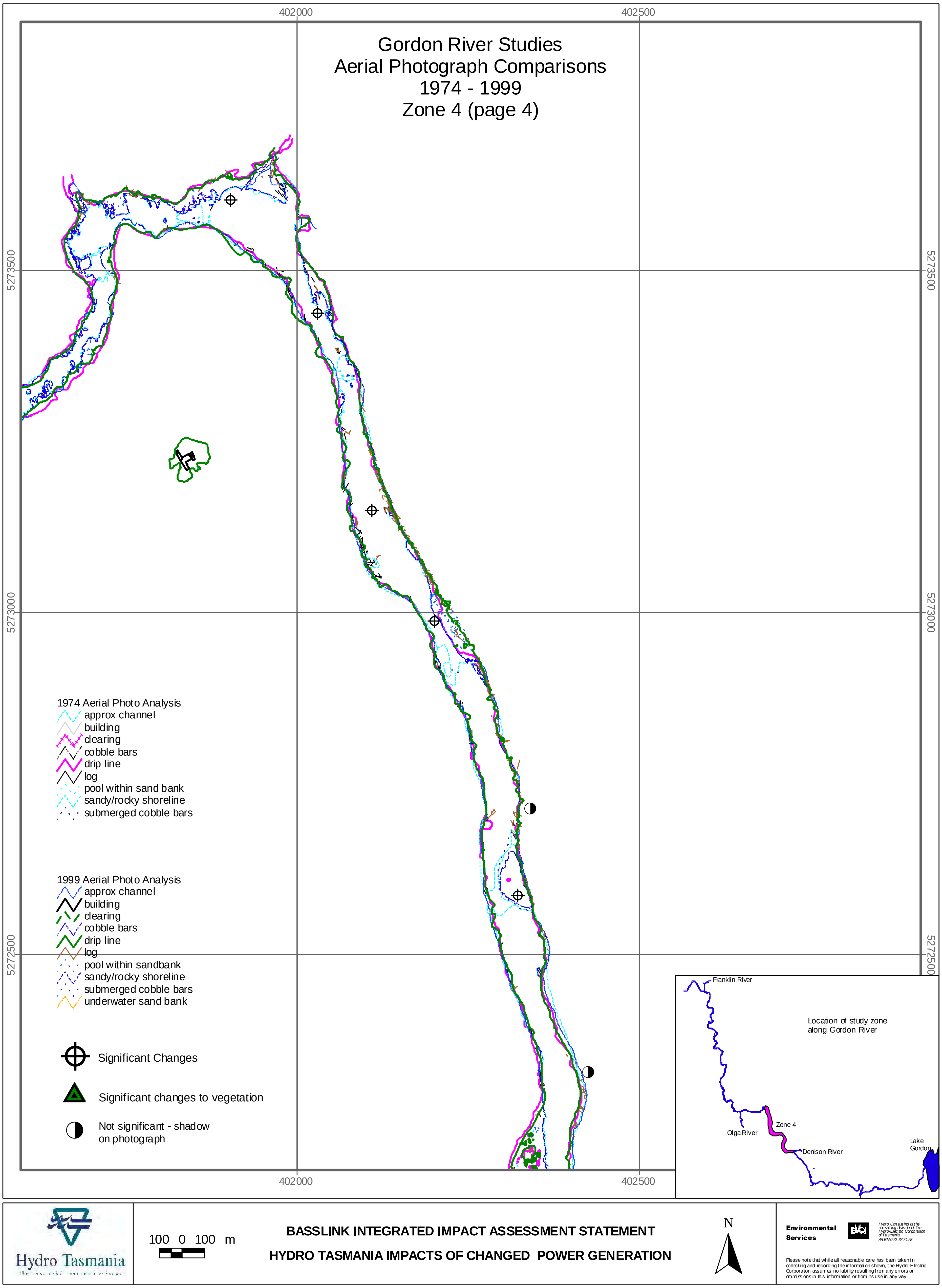
Environmental Services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cobble bars
drip line
log
pool within sand bank
sandy/rocky shoreline
submerged cobble bars
1999 Aerial Photo Analysis
approx channel
building
clearing
cobble bars
drip line
log
pool within sandbank
sandy/rocky shoreline
submerged cobble bars
underwater sand bank
Significant Changes
Significant changes to vegetation
Not significant - shadow on photograph
Franklin River
Location of study zone along Gordon River
Zone 4
Olga River
Denison River
Lake Gordon
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
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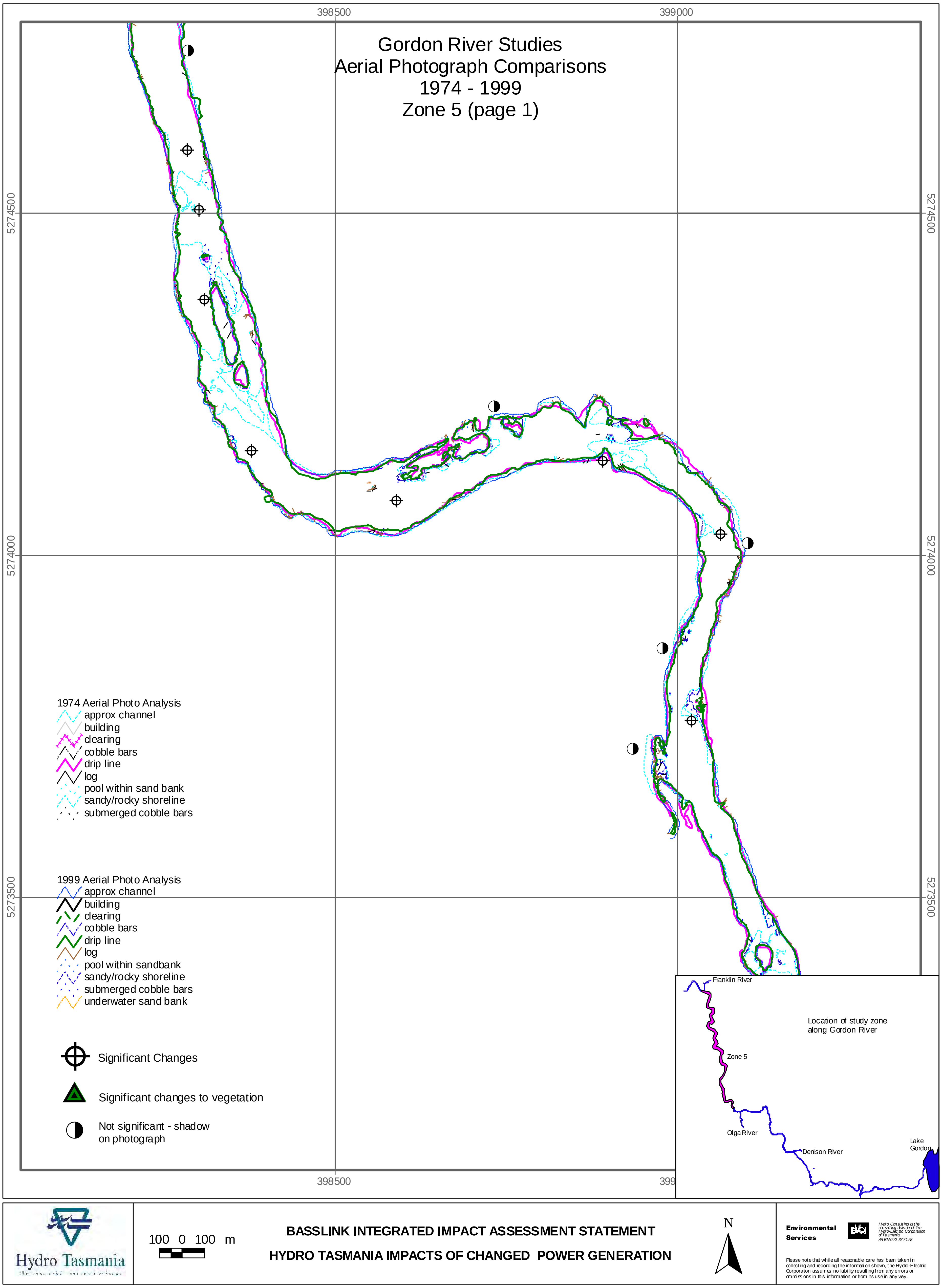
Please note that while all reasonable care has been taken in collecting and recording the information shown, the Hydro-Electric Corporation assumes no liability resulting from any errors or omissions in this information or from its use in any way.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clearing
cobble bars
drip line
log
pool within sand bank
sandy/rocky shoreline
submerged cobble bars
1999 Aerial Photo Analysis
approx channel
building
clearing
cobble bars
drip line
log
pool within sandbank
sandy/rocky shoreline
submerged cobble bars
underwater sand bank
Significant Changes
Significant changes to vegetation
Not significant - shadow
on photograph
Franklin River
Location of study zone
along Gordon River
Zone 5
Olga River
Denison River
Lake
Gordon
Hydro Tasmania
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BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
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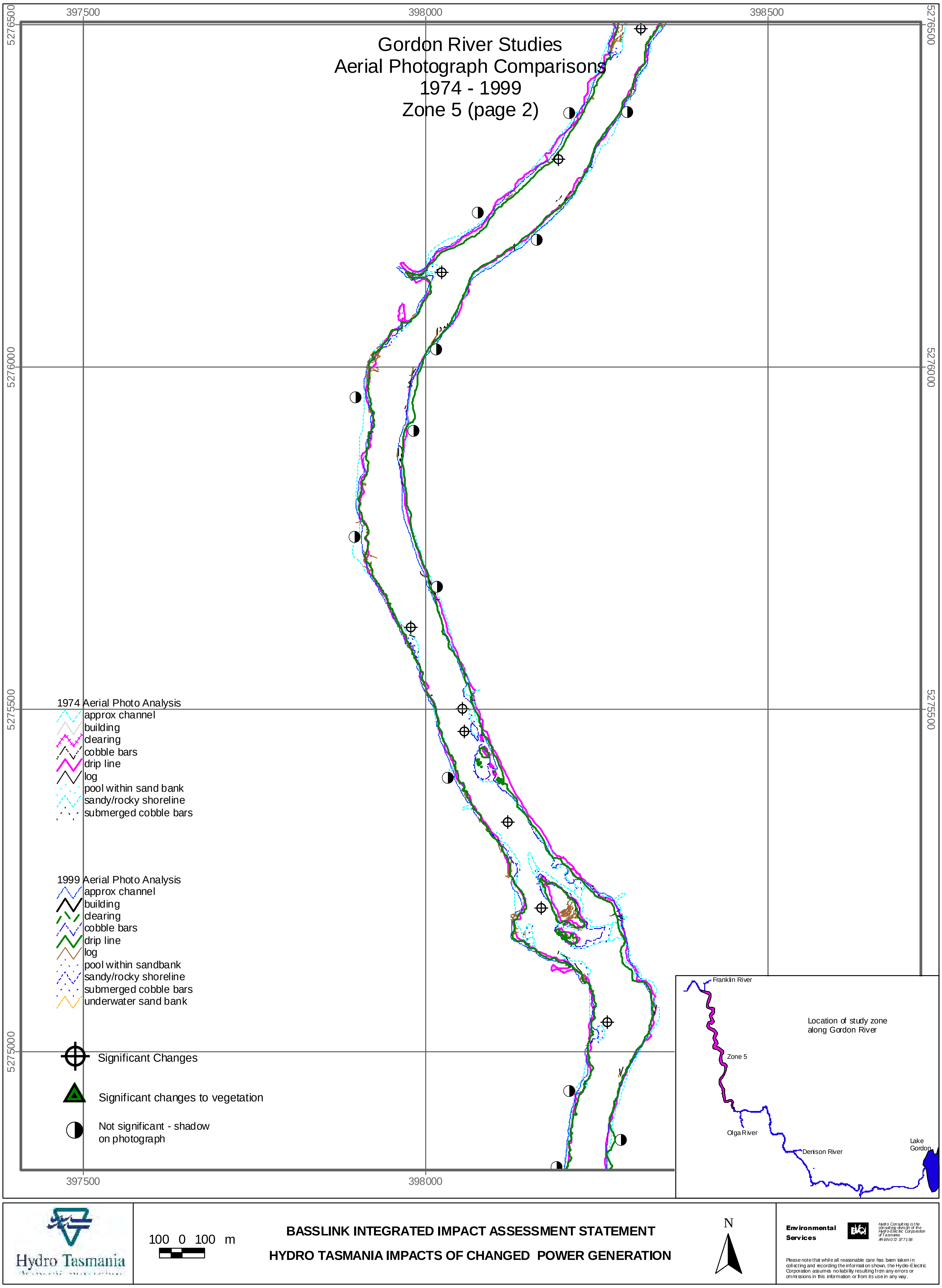
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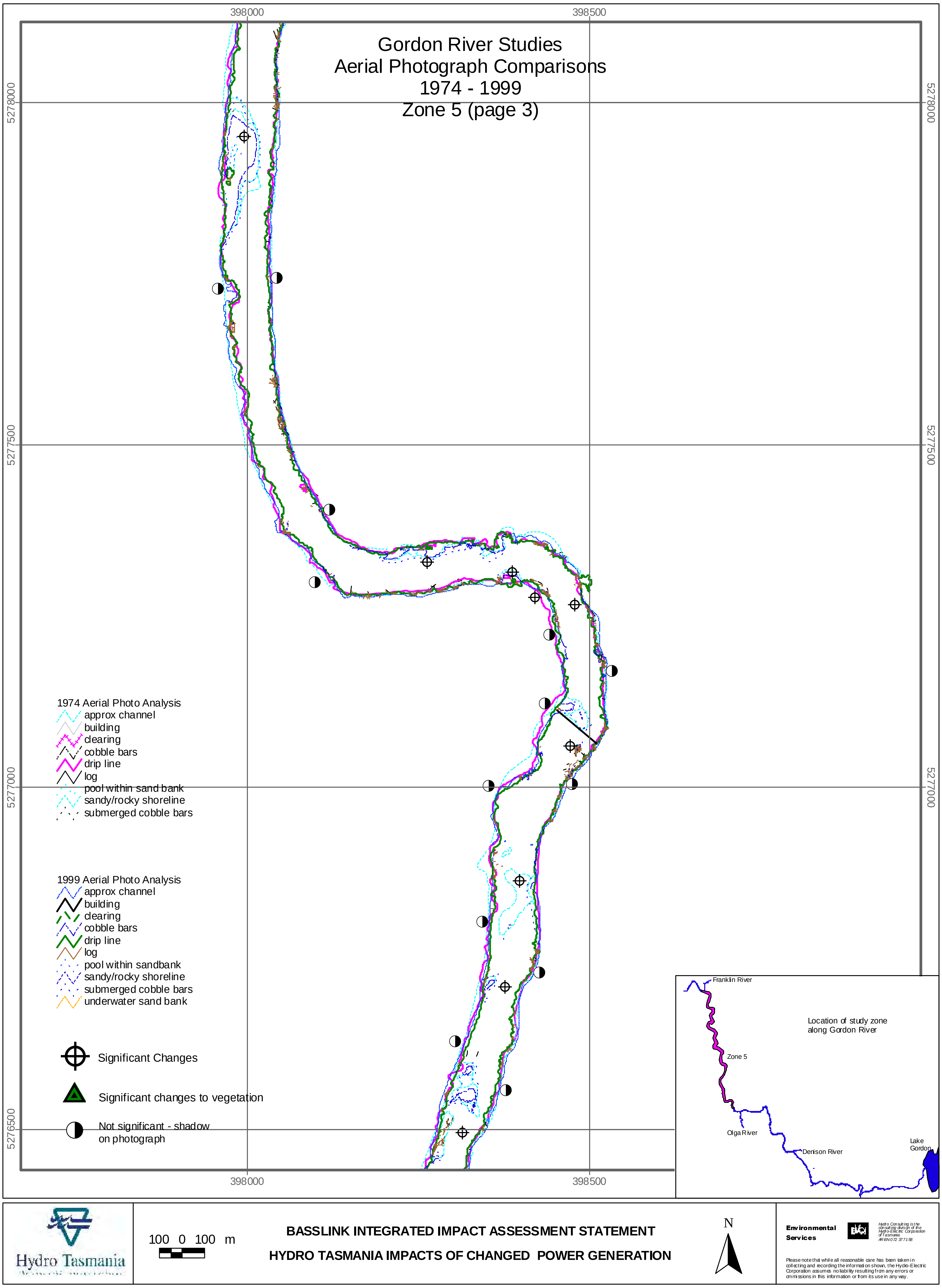
drip line
log
pool within sand bank
sandy/rocky shoreline
submerged cobble bars
1999 Aerial Photo Analysis
approx channel
building
clearing
cobble bars
drip line
log
pool within sandbank
sandy/rocky shoreline
submerged cobble bars
underwater sand bank
Significant Changes
Significant changes to vegetation
Not significant - shadow
on photograph
Franklin River
Location of study zone
along Gordon River
Zone 5
Olga River
Denison River
Lake
Gordon
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
Hydro Tasmania
Environmental
Services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Aerial Photograph Comparisons
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approx channel
building
clearing
cobble bars
drip line
log
pool within sand bank
sandy/rocky shoreline
submerged cobble bars
1999 Aerial Photo Analysis
approx channel
building
clearing
cobble bars
drip line
log
pool within sandbank
sandy/rocky shoreline
submerged cobble bars
underwater sand bank
Significant Changes
Significant changes to vegetation
Not significant - shadow on photograph
Franklin River
Location of study zone along Gordon River
Zone 5
Olga River
Denison River
Lake Gordon
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
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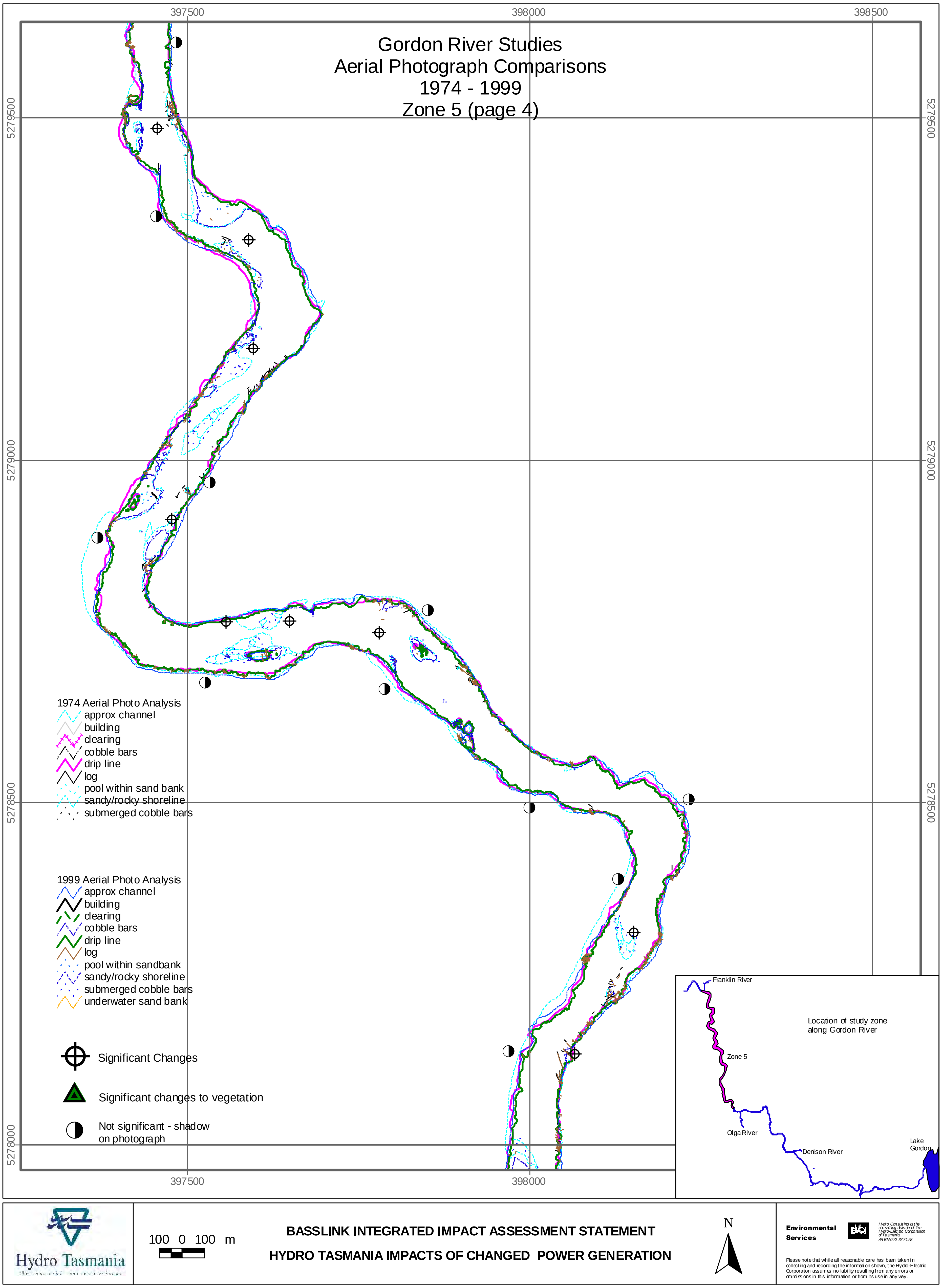
Environmental Services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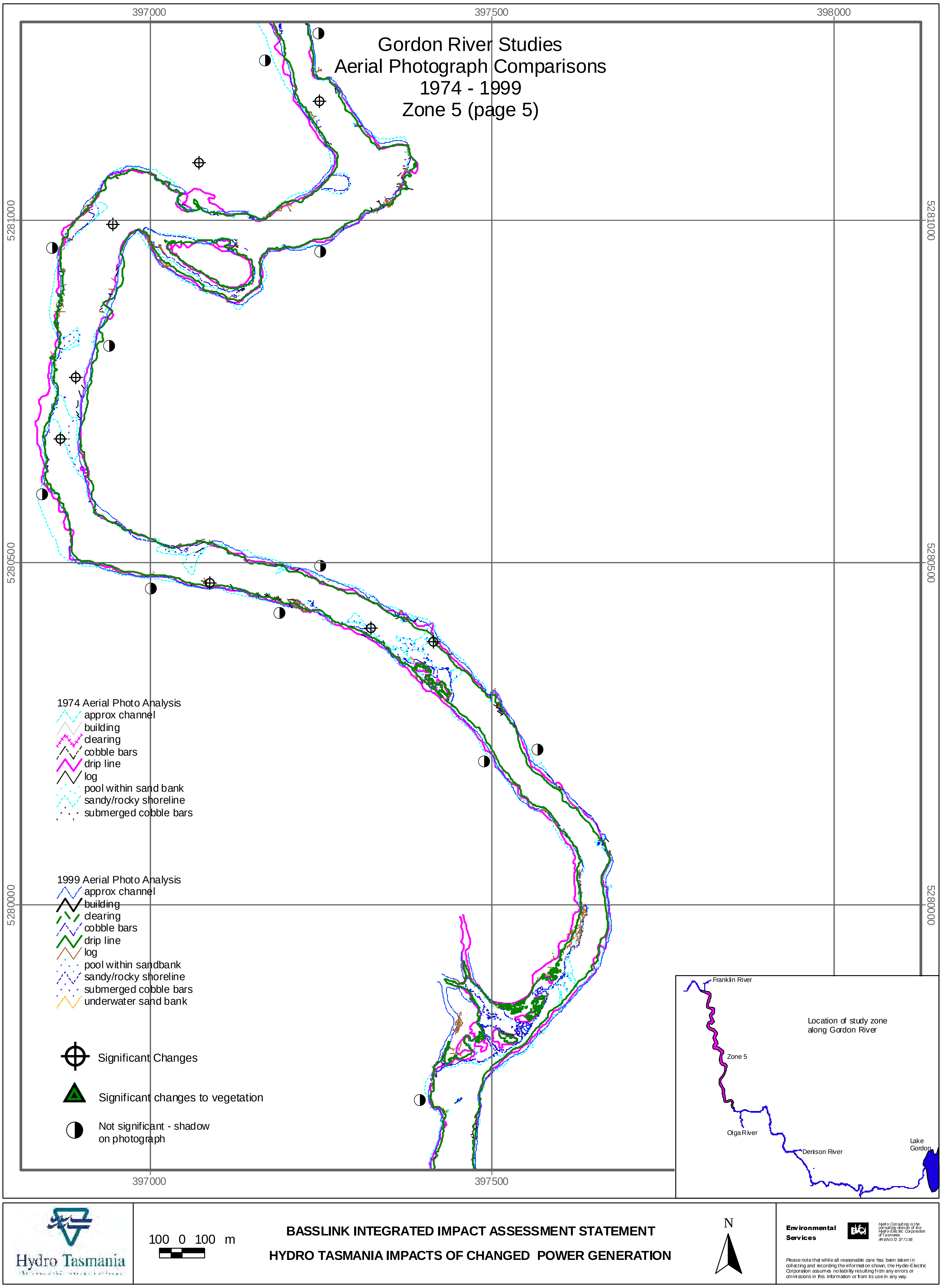
1974 Aerial Photo Analysis
approx channel
building
clearing
cobble bars
drip line
log
pool within sand bank
sandy/rocky shoreline
submerged cobble bars
1999 Aerial Photo Analysis
approx channel
building
clearing
cobble bars
drip line
log
pool within sandbank
sandy/rocky shoreline
submerged cobble bars
underwater sand bank
Significant Changes
Significant changes to vegetation
Not significant - shadow on photograph
Franklin River
Location of study zone along Gordon River
Zone 5
Olga River
Denison River
Lake Gordon
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
Environmental Services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approx channel
building
clearing
cobble bars
drip line
log
pool within sand bank
sandy/rocky shoreline
submerged cobble bars
1999 Aerial Photo Analysis
approx channel
building
clearing
cobble bars
drip line
log
pool within sandbank
sandy/rocky shoreline
submerged cobble bars
underwater sand bank
Significant Changes
Significant changes to vegetation
Not significant - shadow on photograph
Franklin River
Location of study zone along Gordon River
Zone 5
Olga River
Denison River
Lake Gordon
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
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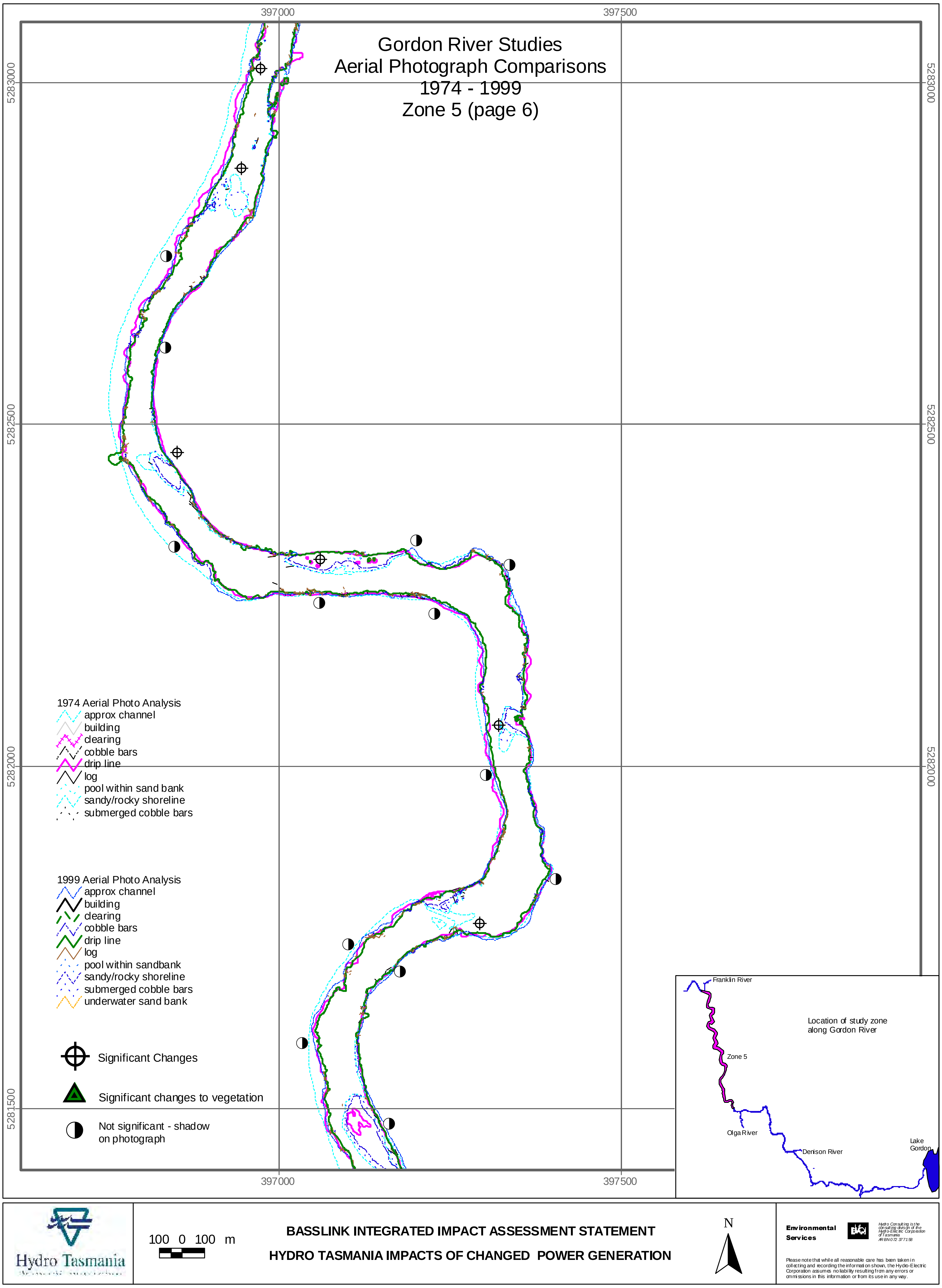
Environmental Services


Gordon River Studies
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1974 - 1999
Zone 5 (page 6)
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5283000
5282500
5282000
5281500
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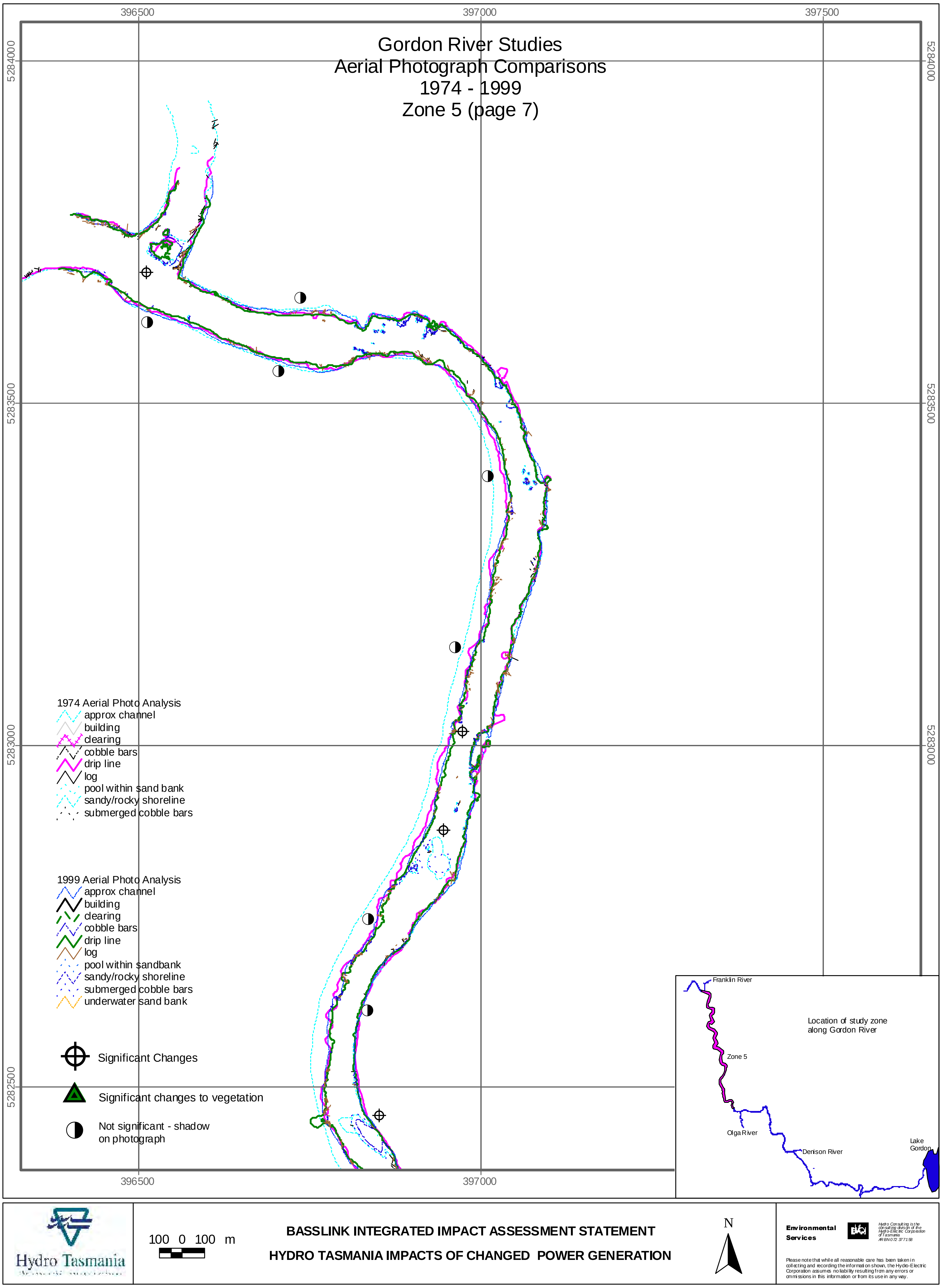
approx channel
building
clearing
cobble bars
drip line
log
pool within sand bank
sandy/rocky shoreline
submerged cobble bars
1999 Aerial Photo Analysis
approx channel
building
clearing
cobble bars
drip line
log
pool within sandbank
sandy/rocky shoreline
submerged cobble bars
underwater sand bank
Significant Changes
Significant changes to vegetation
Not significant - shadow on photograph
Franklin River
Location of study zone along Gordon River
Zone 5
Olga River
Denison River
Lake Gordon
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
Environmental Services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Aerial Photograph Comparisons
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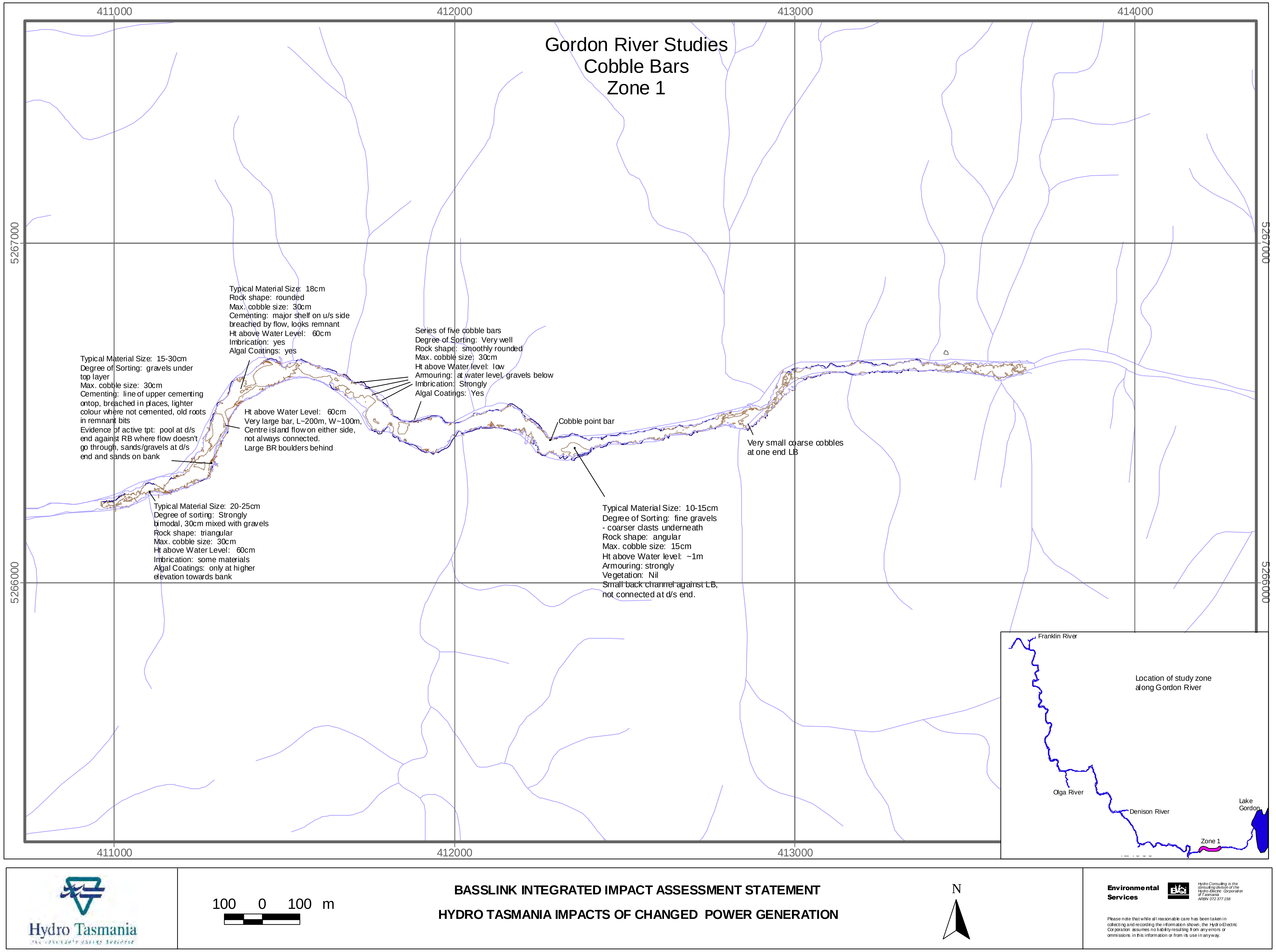
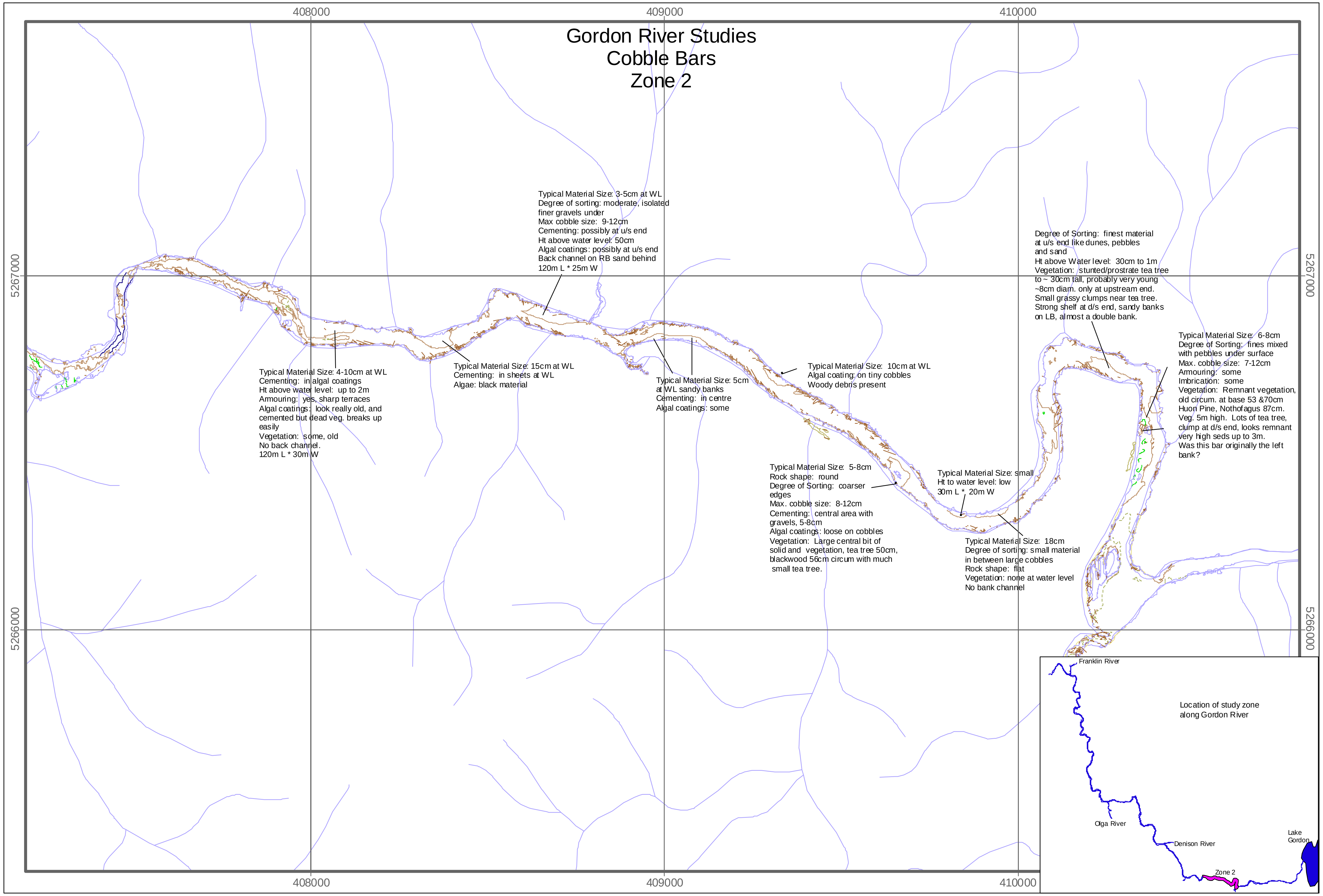
approx channel
building
clearing
cobble bars
drip line
log
pool within sand bank
sandy/rocky shoreline
submerged cobble bars
1999 Aerial Photo Analysis
approx channel
building
clearing
cobble bars
drip line
log
pool within sandbank
sandy/rocky shoreline
submerged cobble bars
underwater sand bank
Significant Changes
Significant changes to vegetation
Not significant - shadow on photograph
Franklin River
Location of study zone along Gordon River
Zone 5
Olga River
Denison River
Lake Gordon
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
Environmental Services

ATTACHMENT 8

COBBLE BAR FEATURES


Gordon River Studies
Cobble Bars
Zone 1
411000
412000
413000
414000
5267000
5266000
Typical Material Size: 18cm
Rock shape: rounded
Max. cobble size: 30cm
Cementing: major shelf on u/s side breached by flow, looks remnant
Ht above Water Level: 60cm
Imbrication: yes
Algal Coatings: yes
Series of five cobble bars
Degree of Sorting: Very well
Rock shape: smoothly rounded
Max. cobble size: 30cm
Ht above Water level: low
Armouring: at water level, gravels below
Imbrication: Strongly
Algal Coatings: Yes
Typical Material Size: 15-30cm
Degree of Sorting: gravels under top layer
Max. cobble size: 30cm
Cementing: line of upper cementing ontop, breached in places, lighter colour where not cemented, old roots in remnant bits
Evidence of active tpt: pool at d/s end against RB where flow doesn't go through, sands/gravels at d/s end and sands on bank
Ht above Water Level: 60cm
Very large bar, L~200m, W~100m,
Centre island flow on either side, not always connected.
Large BR boulders behind
Cobble point bar
Very small coarse cobbles at one end LB
Typical Material Size: 20-25cm
Degree of sorting: Strongly bimodal, 30cm mixed with gravels
Rock shape: triangular
Max. cobble size: 30cm
Ht above Water Level: 60cm
Imbrication: some materials
Algal Coatings: only at higher elevation towards bank
Typical Material Size: 10-15cm
Degree of Sorting: fine gravels - coarser clasts underneath
Rock shape: angular
Max. cobble size: 15cm
Ht above Water level: ~1m
Armouring: strongly
Vegetation: Nil
Small back channel against LB, not connected at d/s end.
Franklin River
Location of study zone along Gordon River
Olga River
Denison River
Lake Gordon
Zone 1
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
Environmental Services



Hydro Tasmania

100 0 100 m

BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT

HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION

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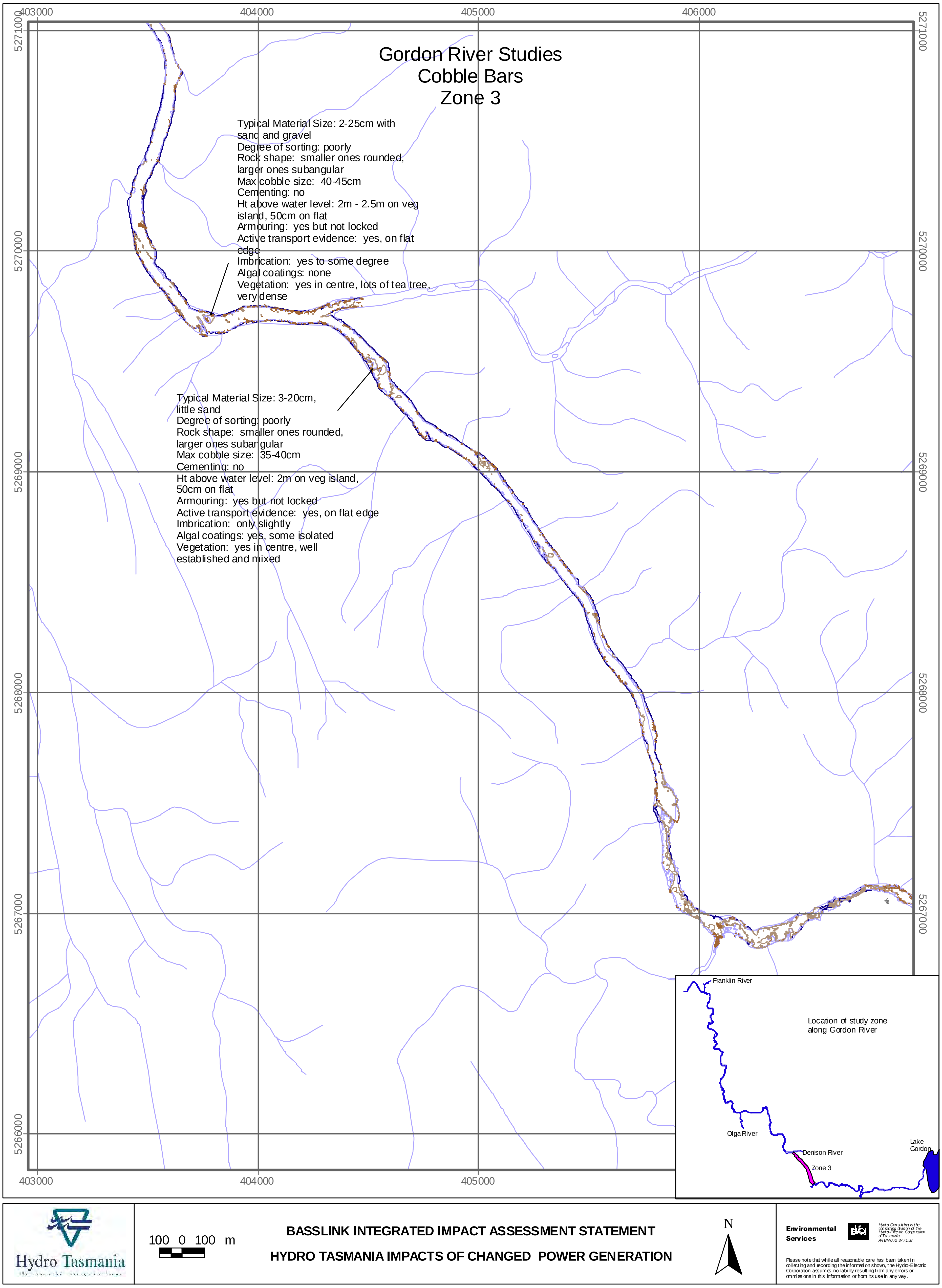
Environmental Services


Gordon River Studies
Cobble Bars
Zone 3
Typical Material Size: 2-25cm with sand and gravel
Degree of sorting: poorly
Rock shape: smaller ones rounded, larger ones subangular
Max cobble size: 40-45cm
Cementing: no
Ht above water level: 2m - 2.5m on veg island, 50cm on flat
Armouring: yes but not locked
Active transport evidence: yes, on flat edge
Imbrication: yes to some degree
Algal coatings: none
Vegetation: yes in centre, lots of tea tree, very dense
Typical Material Size: 3-20cm, little sand
Degree of sorting: poorly
Rock shape: smaller ones rounded, larger ones subangular
Max cobble size: 35-40cm
Cementing: no
Ht above water level: 2m on veg island, 50cm on flat
Armouring: yes but not locked
Active transport evidence: yes, on flat edge
Imbrication: only slightly
Algal coatings: yes, some isolated
Vegetation: yes in centre, well established and mixed
403000
404000
405000
406000
5271000
5270000
5269000
5268000
5267000
5266000
Franklin River
Location of study zone along Gordon River
Olga River
Denison River
Zone 3
Lake Gordon
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
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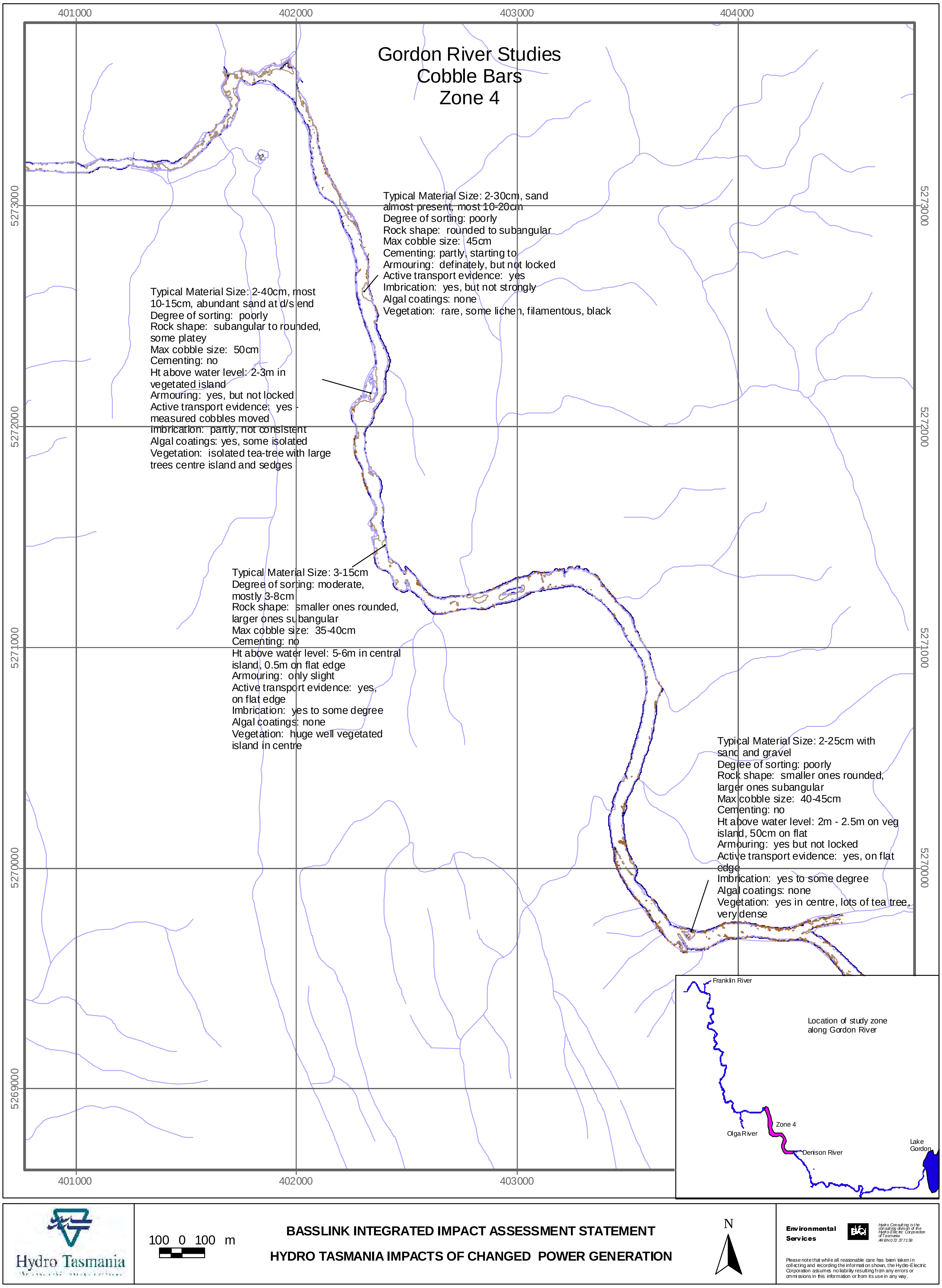
Environmental Services


Gordon River Studies
Cobble Bars
Zone 4
401000
402000
403000
404000
5273000
5272000
5271000
5270000
5269000
Typical Material Size: 2-30cm, sand almost present, most 10-20cm
Degree of sorting: poorly
Rock shape: rounded to subangular
Max cobble size: 45cm
Cementing: partly, starting to
Armouring: definately, but not locked
Active transport evidence: yes
Imbrication: yes, but not strongly
Algal coatings: none
Vegetation: rare, some lichen, filamentous, black
Typical Material Size: 2-40cm, most 10-15cm, abundant sand at d/s end
Degree of sorting: poorly
Rock shape: subangular to rounded, some platey
Max cobble size: 50cm
Cementing: no
Ht above water level: 2-3m in vegetated island
Armouring: yes, but not locked
Active transport evidence: yes - measured cobbles moved
Imbrication: partly, not consistent
Algal coatings: yes, some isolated
Vegetation: isolated tea-tree with large trees centre island and sedges
Typical Material Size: 3-15cm
Degree of sorting: moderate, mostly 3-8cm
Rock shape: smaller ones rounded, larger ones subangular
Max cobble size: 35-40cm
Cementing: no
Ht above water level: 5-6m in central island, 0.5m on flat edge
Armouring: only slight
Active transport evidence: yes, on flat edge
Imbrication: yes to some degree
Algal coatings: none
Vegetation: huge well vegetated island in centre
Typical Material Size: 2-25cm with sand and gravel
Degree of sorting: poorly
Rock shape: smaller ones rounded, larger ones subangular
Max cobble size: 40-45cm
Cementing: no
Ht above water level: 2m - 2.5m on veg island, 50cm on flat
Armouring: yes but not locked
Active transport evidence: yes, on flat edge
Imbrication: yes to some degree
Algal coatings: none
Vegetation: yes in centre, lots of tea tree, very dense
Franklin River
Location of study zone along Gordon River
Zone 4
Olga River
Denison River
Lake Gordon
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
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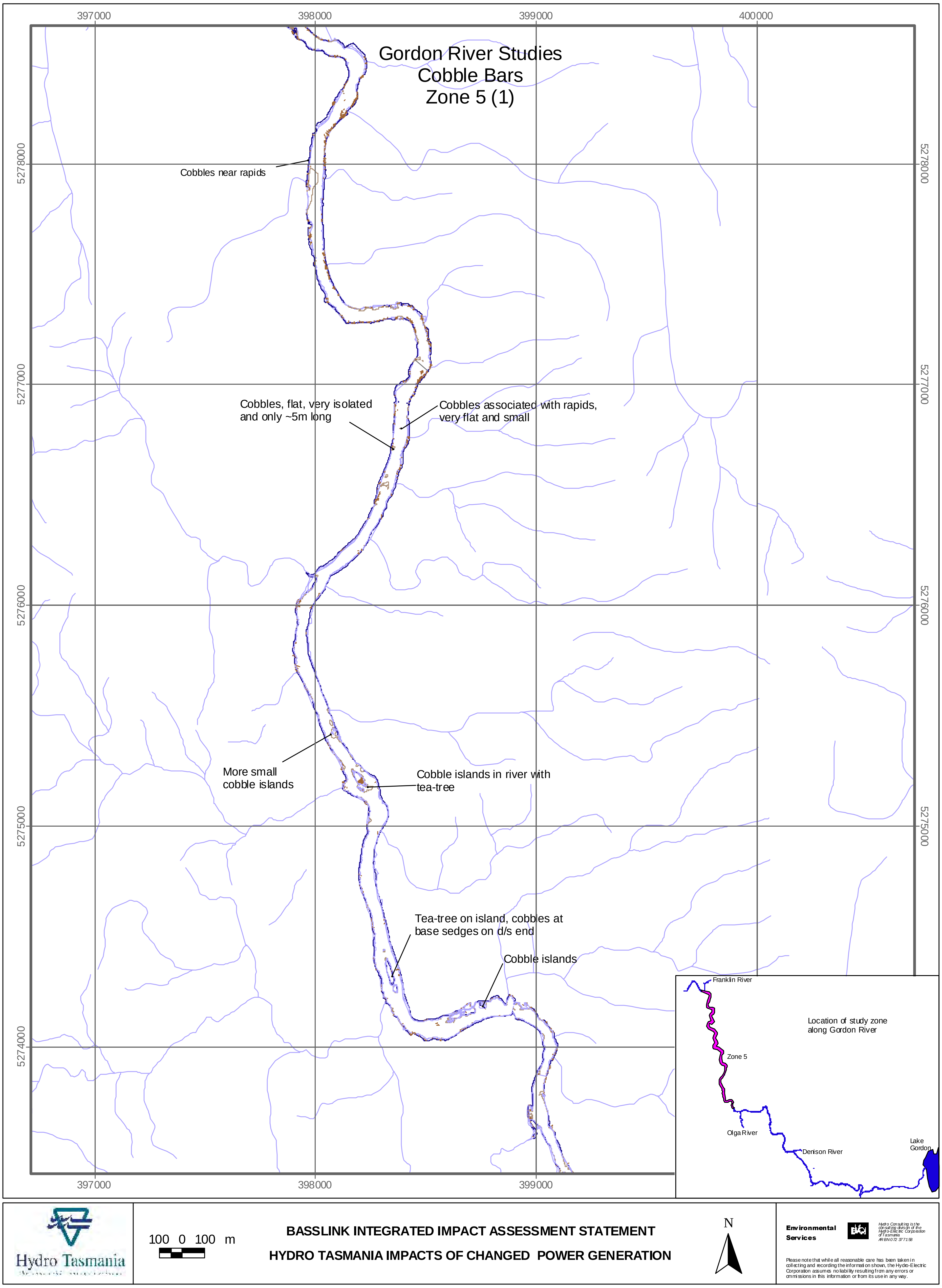
Environmental Services


Gordon River Studies
Cobble Bars
Zone 5 (1)
397000
398000
399000
400000
5278000
5277000
5276000
5275000
5274000
Cobbles near rapids
Cobbles, flat, very isolated and only ~5m long
Cobbles associated with rapids, very flat and small
More small cobble islands
Cobble islands in river with tea-tree
Tea-tree on island, cobbles at base sedges on d/s end
Cobble islands
Franklin River
Location of study zone along Gordon River
Zone 5
Olga River
Denison River
Lake Gordon
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
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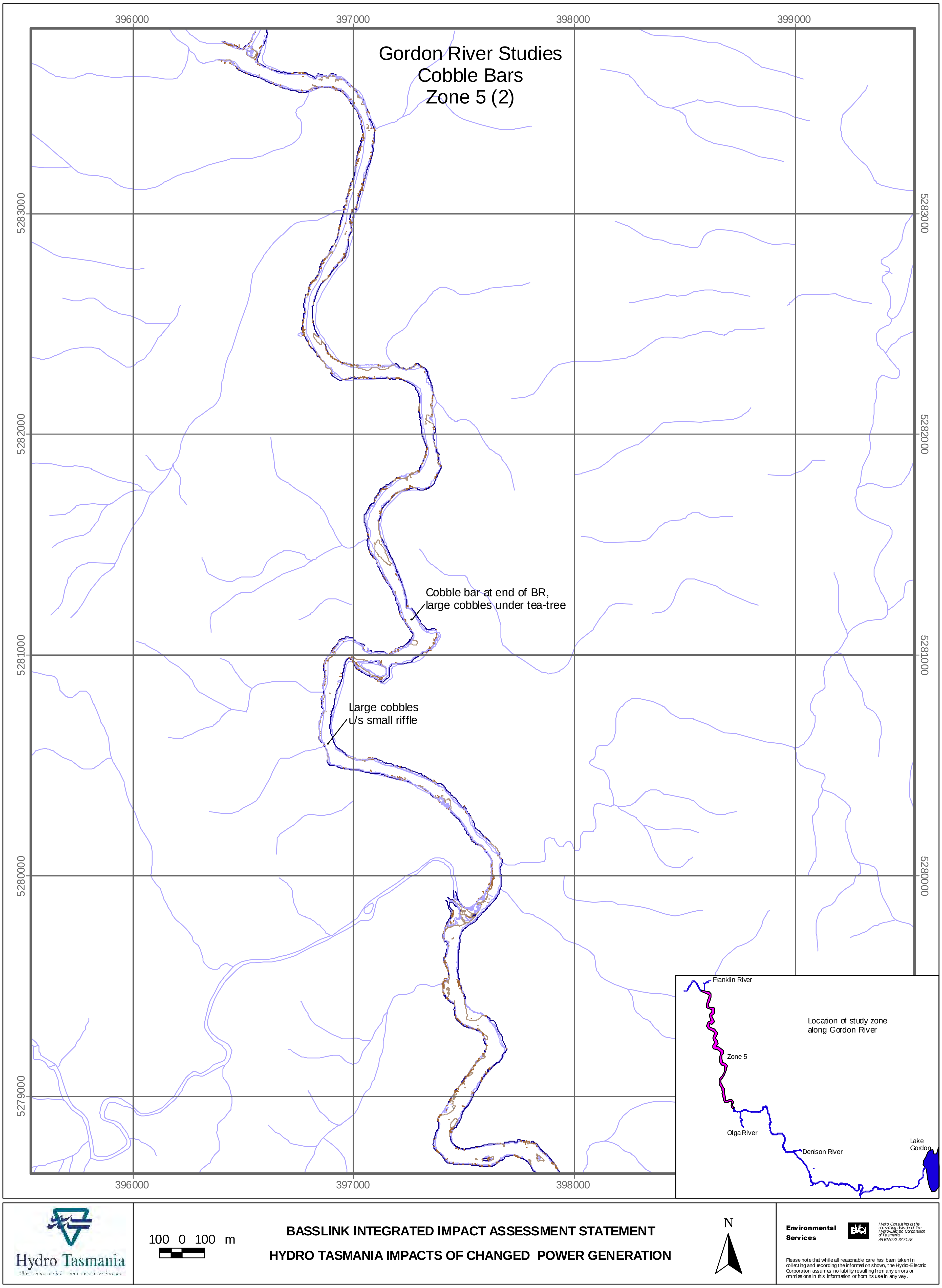
Gordon River Studies
Cobble Bars
Zone 5 (2)
396000
397000
398000
399000
5283000
5282000
5281000
5280000
5279000
Cobble bar at end of BR,
large cobbles under tea-tree
Large cobbles
u/s small riffle
Franklin River
Location of study zone
along Gordon River
Zone 5
Olga River
Denison River
Lake
Gordon
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
Environmental
Services

ATTACHMENT 9

SEDIMENT TRANSPORT CAPACITY ANALYSIS

POTENTIAL IMPACT OF BASSLINK ON THE TIME-AVERAGED SEDIMENT TRANSPORT RATE IN THE GORDON RIVER

- USING UPDATED FLOW DURATION CURVES

Scott Wilkinson and Ian Rutherfurd, April 2001

Introduction

This study repeated the analysis previously carried out in March 2001 on the sediment transport impact of the proposed Basslink flow regime in the Gordon River. The analysis was repeated using updated hourly flow duration curves, as used in reports of the hydrologic impact of Basslink (Peterson pers comm.). These curves were generated using data from the period 1997-1998. This sediment transport analysis provided a more accurate estimate of the impact of Basslink on the sediment transport rate in the Gordon River.

The same methodology was applied as previously and summarised below, with the result being estimates of the time averaged sediment transport rate under natural, present and Basslink flow regimes at three sites, Geo1, Geo2B and Geo4. These estimates were then compared to determine the percentage change in sediment transport over time associated with the change to the Basslink flow regime. A comparison between the natural and present flow regimes was also made. The accuracy of the results was quantified using the sensitivity analysis performed previously.

Method

The method used to compare the sediment transport capacity between different flow regimes had three stages. Firstly, the hydraulic parameters affecting sediment transport at the bank toe, including shear stress, were calculated for a number of flowrates. Secondly, the relationship between sediment transport capacity and flowrate was determined using the updated Ackers-White sediment transport equation. Thirdly a time average of the sediment transport capacity was calculated using the flow duration curves provided.

To determine the shear stress (τ)at the bank toe, the following equation was used:

$\tau = \gamma y S$ where γ = unit weight of water
y = depth at bank toe
S = water surface slope.

[Henderson, 1966]

The bank toe was defined as the point on the bank just submerged at a flowrate of 50 m^3/s.

Water surface slope

The water surface slopes used in the analysis were provided from previous field work. Where both high and low flow water surface slopes were provided, the low flow slope was applied to flows <50

m^3/s (power station off) and the high flow slope was applied to flows >200 m^3/s. The slope at flows between these values was interpolated. A uniform slope of 0.005 was applied to site Geo1. This was higher than the reach average slope of 0.003, to reflect the confined, rocky nature of the site. It was lower than some of the estimated slopes provided, as they required unrealistic channel roughness to match the rating curve provided. Uniform flow was assumed due to the limited survey information. A one-dimensional numerical backwater model, Hec-Ras [US Army Corps of Engineers, 1998], was used to support the calculations and calibrate the discharge-stage curve against those provided for each site.

Sediment data

Bank material samples have been collected for the Basslink investigations (Brook, 2000), and grain-size distributions from the banks nearest to three cross-section sites were used for this analysis. For sediment transport analysis, the median particle diameter (d_{50}) of the sediment was determined for the bank toe at each site. Sediment samples were selected that best represented the sediment at the bank toe. At Geo1, the average of all samples taken was used. At Geo2B only the samples more than 1m below the surface were used. This was more representative of the bank toe, at 3-4m below the floodplain surface. Only three samples were collected in Zone 4, so the average of all of these was used at Geo4.

The bank material at the toe of the sample sites was predominantly sandy (Figure 1, Table 1). The median grain size ranges from 0.25mm at site Geo1, to 0.1mm at Geo4. Predictable, the material becomes finer downstream. The coarsest particles found on the bank face are typically around 3mm (fine gravels).

When sediment is transported, the fraction below 20 micron is transported as wash load, which does not have a functional relationship with flowrate [Raudkivi, 1998]. Therefore, this fraction was neglected when calculating the grain size for sediment transport calculations.

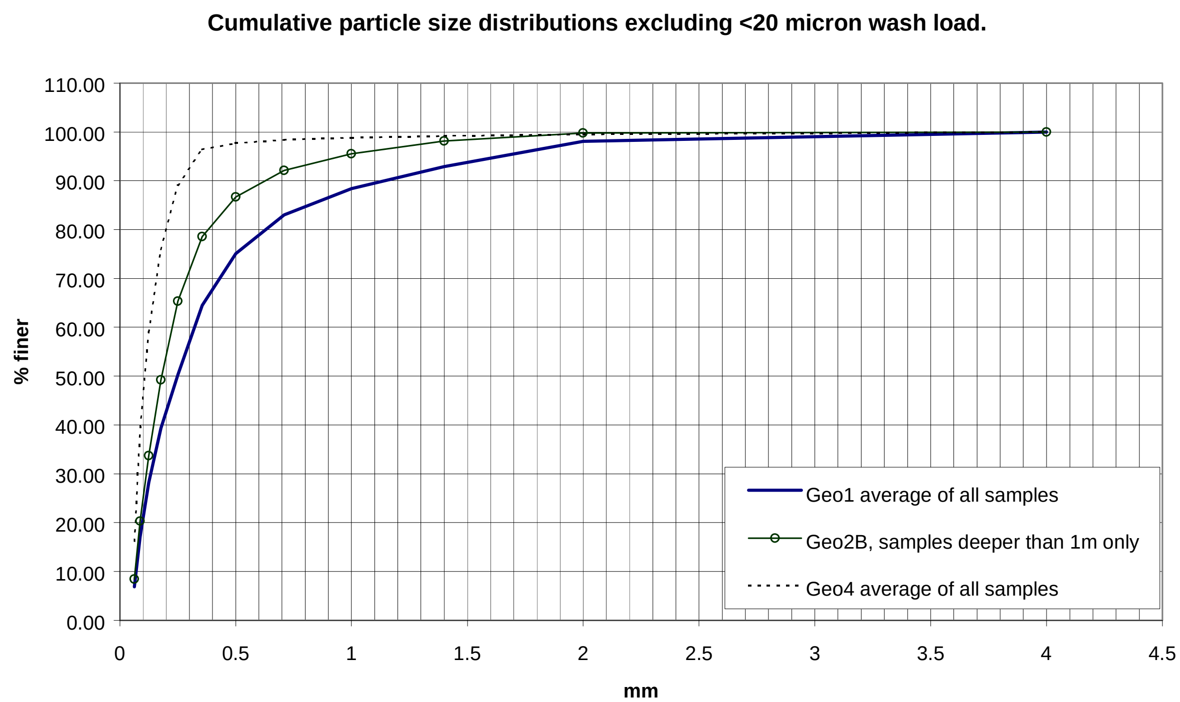

Figure 1; Cumulative particle size distributions for bank toe sediment at the three sites.

Comparison of the flow duration curves

The sediment transport analysis reported here produces a long term average of the sediment transport capacity of the stream. This is achieved by calculating the sediment transport rate occurring at each flowrate. The long term average sediment transport rate is the mean of these rates, weighted for the proportion of time that that flowrate occurs. The analysis therefore relies on detailed information of the proportion of time that each flowrate occurs within the overall regime. As a result, the updated flow duration curves were inspected before the sediment transport analysis was performed.

The updated flow duration curves were compared with those used in the previous analysis, to determine whether significant changes in the sediment transport rate were to be expected. The updated flow duration curves were significantly different to those used previously, the previous curves having been sourced from an earlier hydrologic analysis using daily flow information.

The main points of comparison are summarised as follows:

1. The updated natural and present flow duration curves were similar to that obtained previously, generally within 20 m^3/s.
2. The updated Basslink flow duration curves showed a higher probability of higher flowrates and a lower probability of lower flowrates than previous curves. This has two likely causes:

- ♦ The powerstation being operated at a higher flowrate but for a smaller proportion of the time than the previous curves indicated.
- ♦ The power station being operated at partial capacity for a smaller proportion of time than the previous curves indicated.

3. At Geo4, and to a lesser extent at Geo2B, the updated curves for all flow regimes were higher, indicating a larger total flow volume, probably due to a greater allowance for natural inflows than the previous flow duration curves.

The updated flow duration curves are compared with those used previously in the following figures, with dashed lines representing the previous curves and solid lines the updated curves.

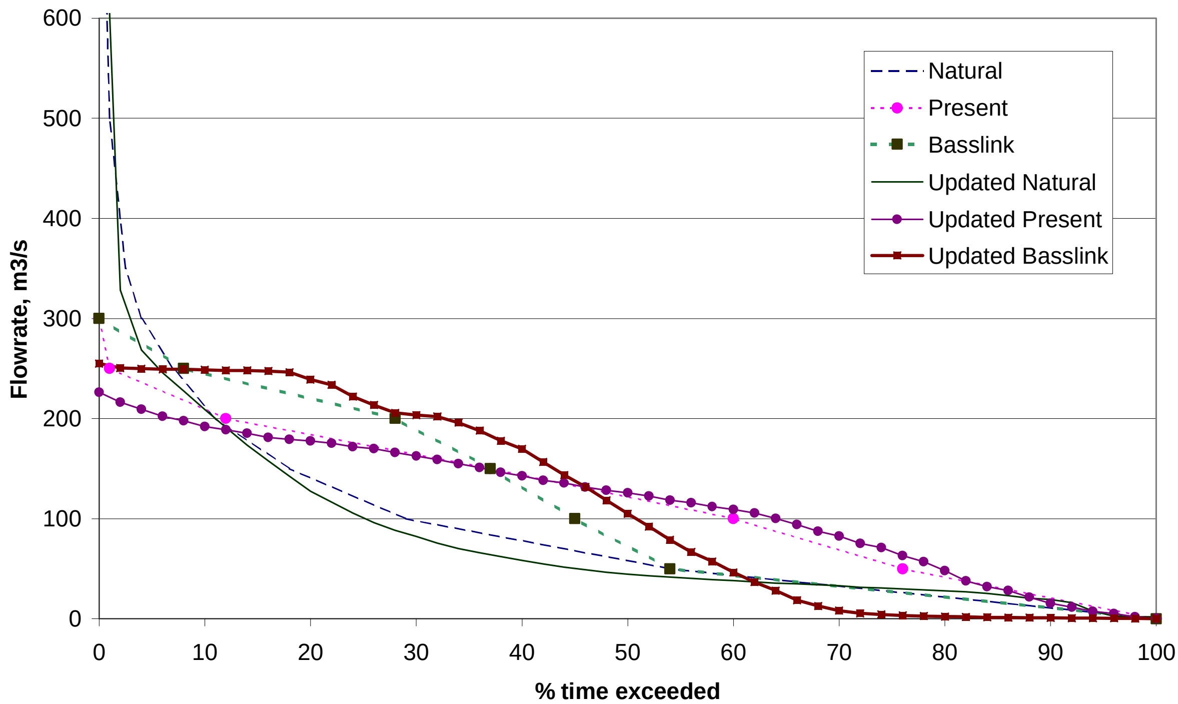

Figure 2; Comparison of updated flow duration curves for Geo1 with those used previously

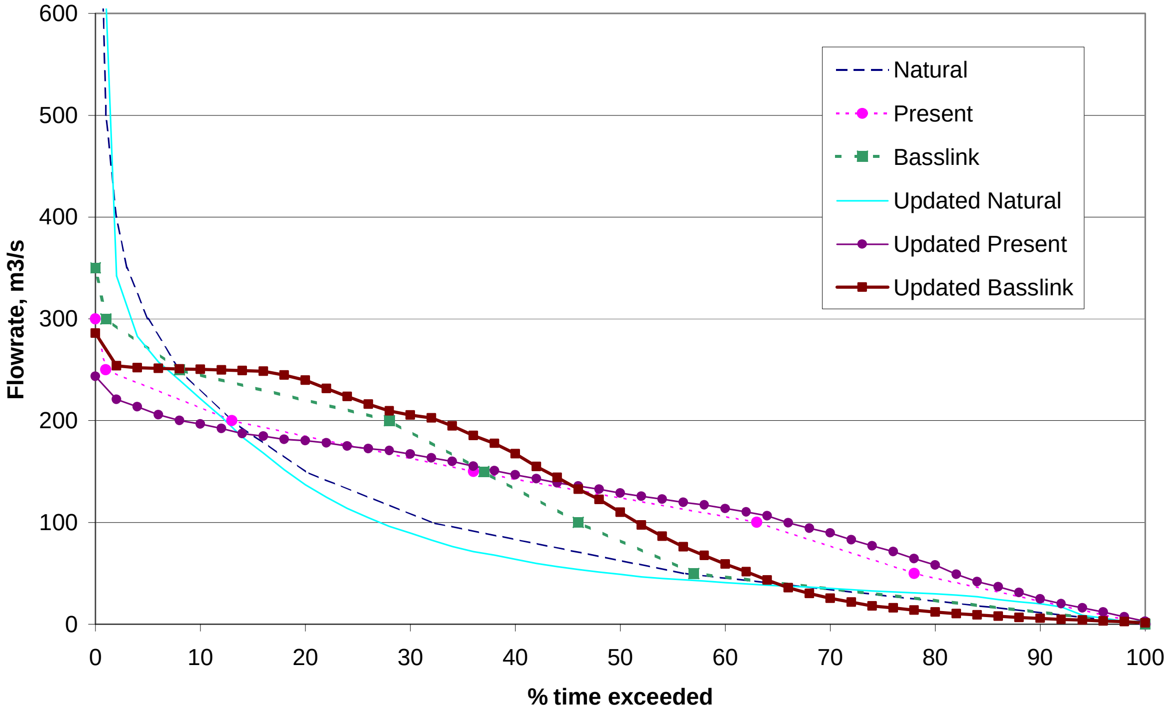

Figure 3; Comparison of updated flow duration curves for Geo2B with those used previously

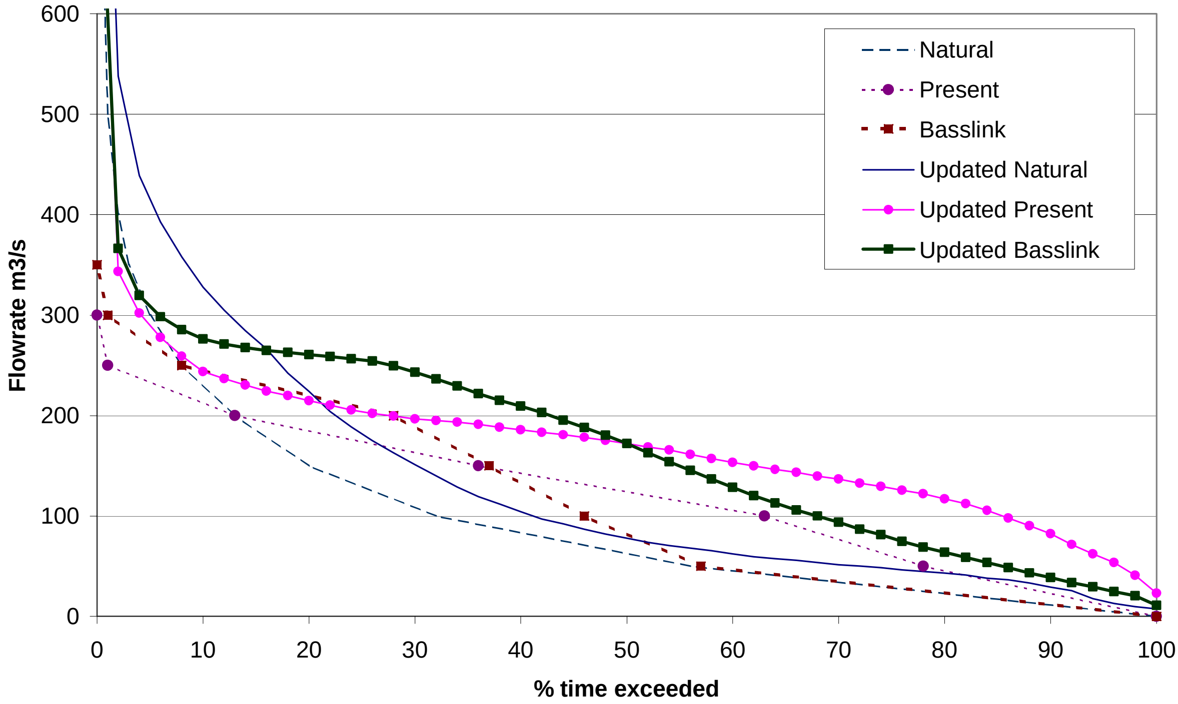

Figure 4; Comparison of updated flow duration curves for Geo4 with those used previously

Sediment rating curve

The sediment rating curves previously constructed for each site were extended to cover the larger flows included in the updated natural flow regime. The updated curves are in Figure 5. Note that it is the non-linearity of the sediment rating curves that results in the different flow regimes having different time averaged sediment transport rates, with larger flows having a progressively larger impact on sediment transport capacity.

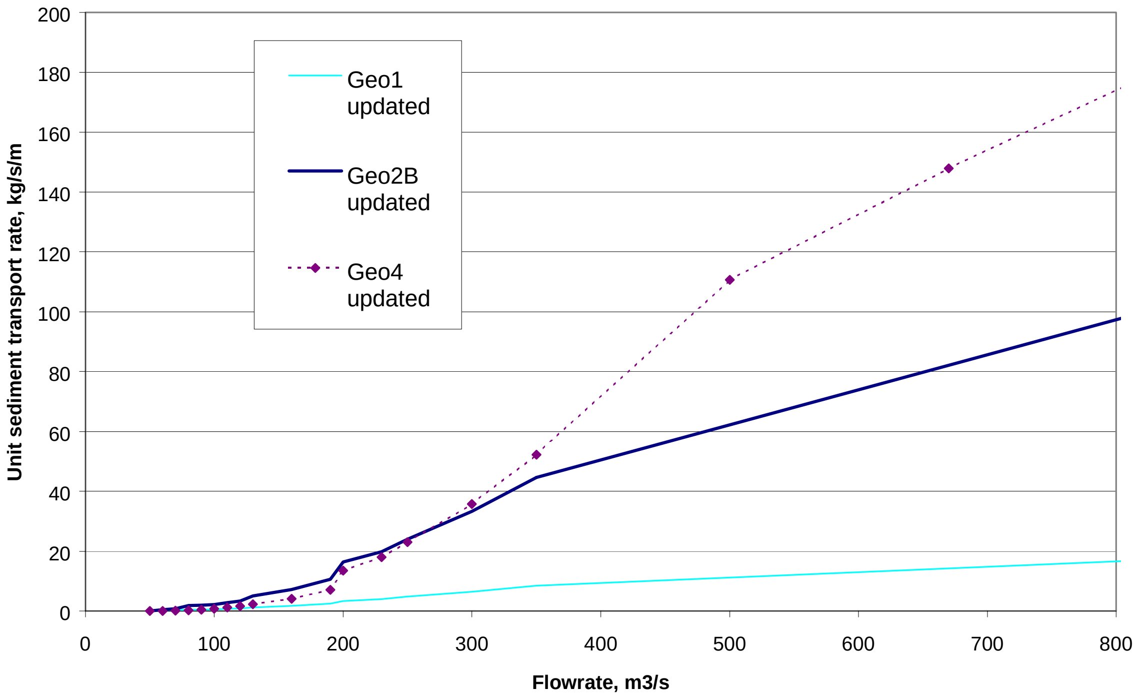

Figure 5; Sediment rating curves for Geo1, Geo2B and Geo4. Curves are shown only to 800 m3/s to highlight the non-linear nature of the curves between 50 and 500 m3/s

Impact of Basslink from updated sediment transport analysis

The time-averaged sediment transport rates were calculated using the updated flow duration curves and sediment rating curves. The accuracy of the results was also improved by analysing a greater number of flowrates than previously.

An increase in the sediment transport rate was predicted for the Basslink flow regime, as in the previous analysis. The size of the increase in sediment transport capacity increased at sites Geo1 and Geo2B and decreased at Geo4, as shown in the table below.

Site	Previous % increase in sediment transport capacity	Updated % increase in sediment transport capacity
Geo1	13	39
Geo2B	18	87
Geo4	40	34

The results are illustrated in Figure 6.

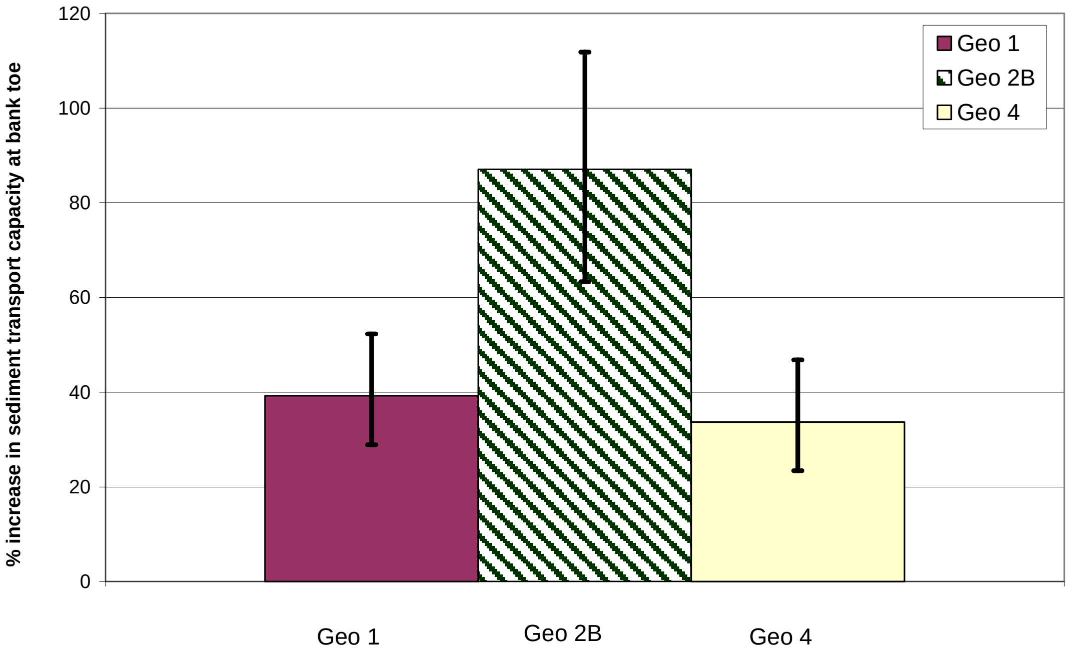

Figure 6; Impact on time averaged sediment transport rate of changing from the present to the Basslink flow regime. The error bars assume a 5 degree temperature change and cumulative +/- 10% uncertainty in other variables. Analysis of results uncertainties is discussed in the previous sediment transport analysis report.

An increase in sediment transport capacity is predicted at all sites. The predicted increase ranges between 25-110% across the three sites, and allowing for uncertainties. This wide variation is to be expected given the variation in water surface slope and cross section area between the three sites.

In general it would be expected that the percentage increase in sediment transport rate would reduce with distance downstream from the power station, as tributary inflows become more significant in the flow regime. The smaller increase at Geo1 compared with Geo2B can be partly attributed to the fact that the water surface slope does not increase with discharge at Geo1 as it does at other sites, due to different water surface control downstream of this site.

The variation between the three sites can be interpreted as an indication of the variation in the increase in sediment transport capacity along the stream generally, depending on local water surface slopes, channel geometry and downstream control. In the long term, adjustments in channel width and depth may also display variation along the stream. The most important feature of the results is that the sediment transport capacity is predicted to increase at all sites, indicating that the potential for bank scour will exist over most of the stream length.

Impact of present flow regime from updated sediment transport analysis

As previously, the impact of the present flow regime on the time-averaged sediment transport capacity of the channel was also determined. This indicated that increase in sediment transport capacity decreased with distance downstream of the power station. Variation between the three sites can again be attributed to differences in channel geometry and water surface slope between the sites.

A decrease in sediment transport capacity under the present regime was predicted at Geo2B and Geo4 as illustrated in Figure 7**Figure** . This outcome should be regarded with caution for several reasons:

1. Firstly, the well documented occurrence of bank scour since introduction of the present flow regime indicates that the sediment transport rate (and probably the capacity) has increased.

2. Secondly, the majority of sediment transport capacity in the natural regime was predicted to have been in large flood events. However, it is likely that sediment supply would have limited the actual sediment transport rate to well below the sediment transport capacity during these events. This would reduce the natural time averaged sediment transport rate relative to that under the present regime. This flood dominance in the natural regime increased with distance downstream due to tributary inflows, and was maximum at Geo4, where the greatest decrease in sediment transport capacity was predicted.
3. Thirdly, the large flows in the natural regime were above the limits of available survey data for all three cross sections. It is likely that these flows would have been dispersed across the floodplain, reducing their sediment transport capacity and the long term average sediment transport capacity relative to the present regime.

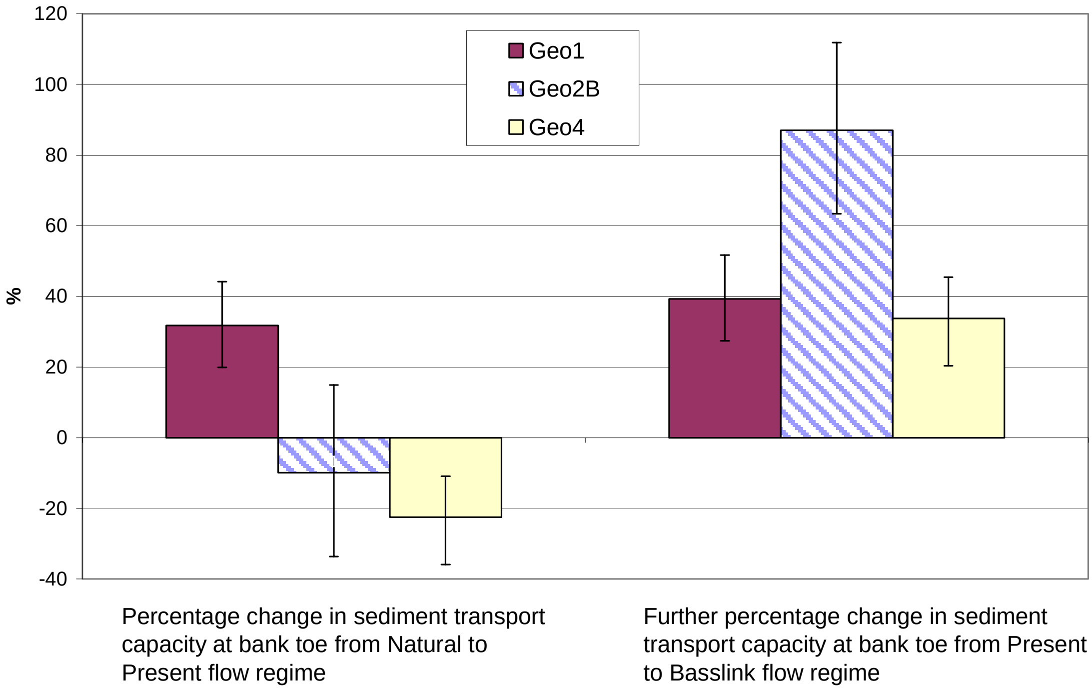

Figure 7; Effect of both changes in flow regime on the sediment transport capacity at bank toe. The right hand three columns show the impact of changing from the present to the Basslink flow regime. The left three columns show the change in sediment transport capacity at the bank toe associated with moving from the Natural to the Present regime. Negative values should be treated with caution. Likely causes of this result are discussed in the text.

The results thus highlight the difficulty in accurately determining sediment transport rates under large natural flows, and the difficulty in comparing sediment transport rates in large natural floods with the more predictable conditions of low to medium flowrates.

Accuracy of changes in sediment transport rate

This analysis was completed using the most accurate hydrologic and hydraulic data available. Sediment transport analysis is intrinsically sensitive to uncertainties in the hydraulic and sediment input variables, however as the results are essentially comparisons of sediment transport under different flow regimes, they are insulated from errors in the sediment transport rates themselves. Errors affecting one flow regime also apply to the other. To quantify the potential errors from uncertainties in input data, a sensitivity analysis was performed. This was done by modifying each input variable in turn by +/-10% and recalculating the change in sediment transport rate between each flow regime. The sensitivity of the results for each site are presented in the following figures.

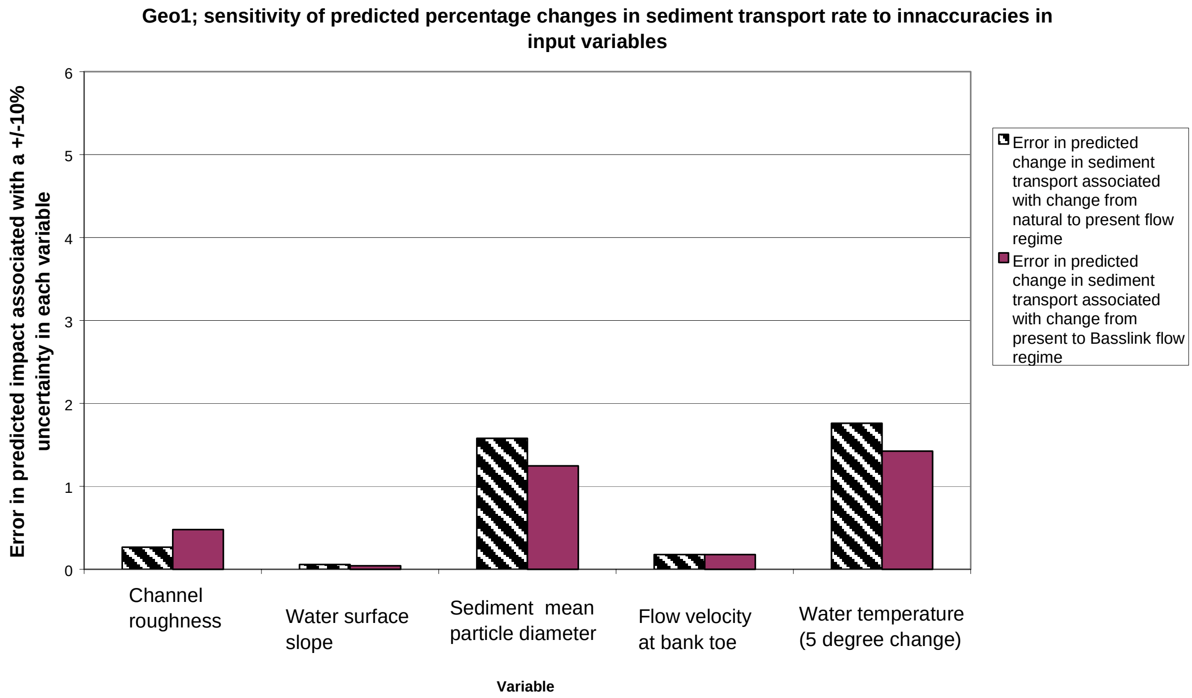

Figure 8; Site Geo1: Maximum error in predicted change in sediment transport associated with a +/-10% uncertainty in each input variable.

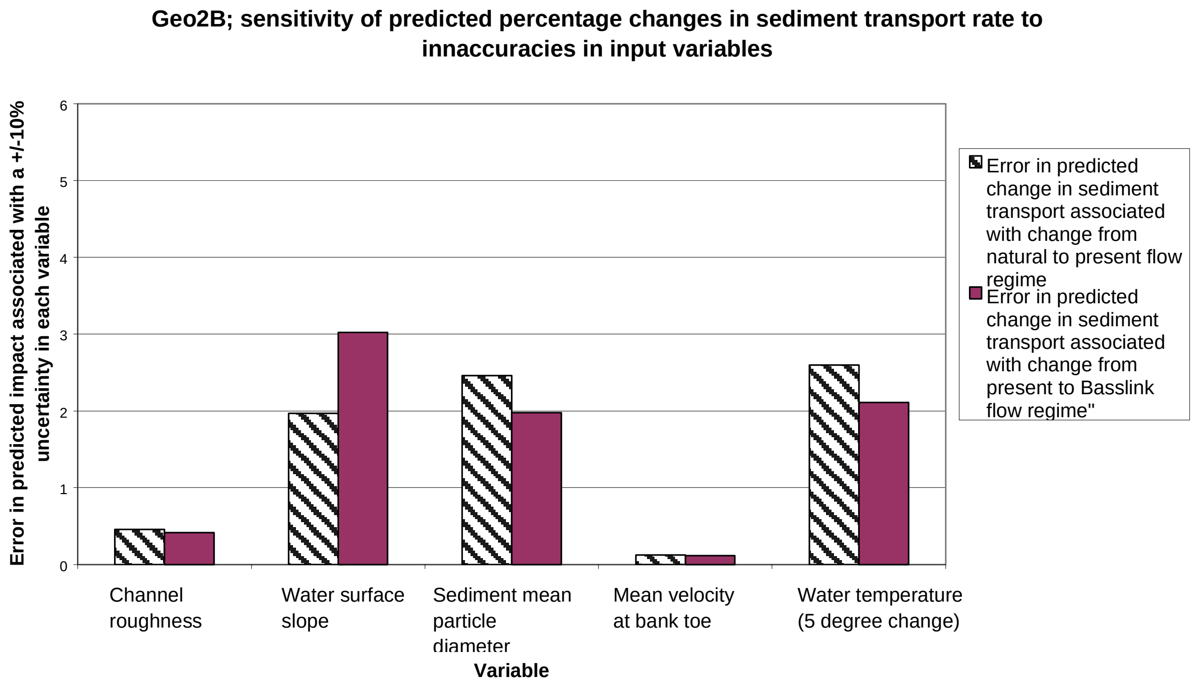

Figure 9; Site Geo2B: Maximum error in predicted change in sediment transport associated with a +/-10% uncertainty in each input variable.

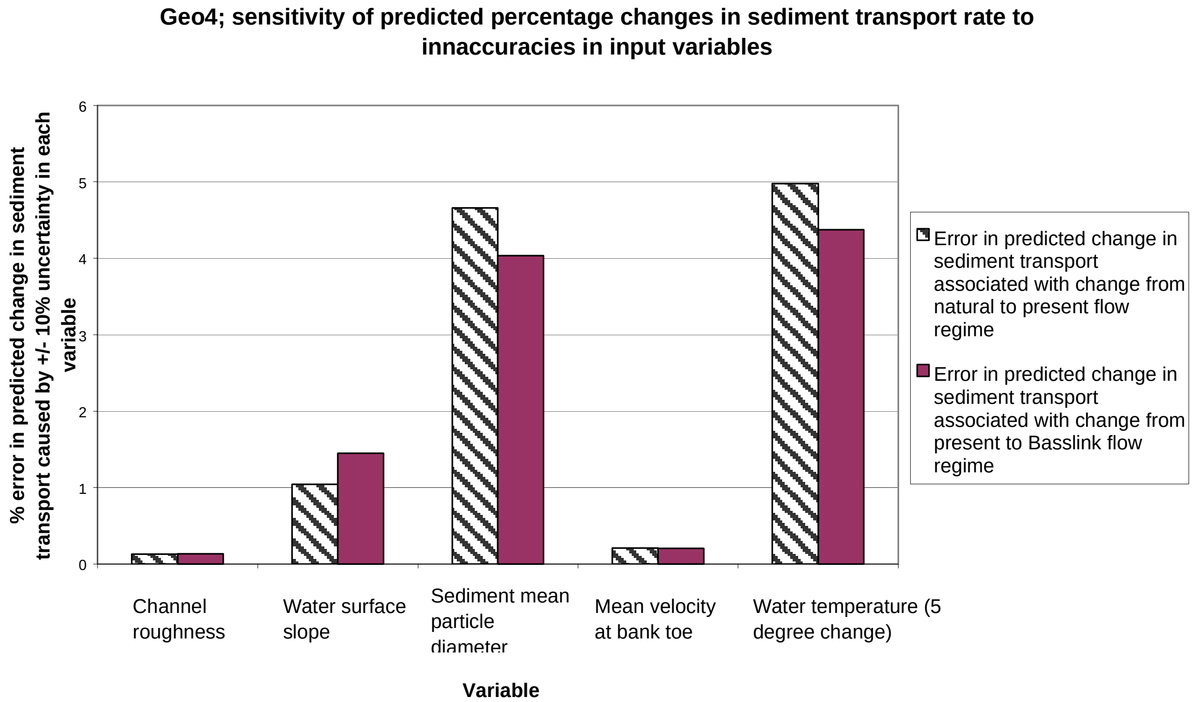

Figure 10; Site Geo4: Maximum error in predicted change in sediment transport associated with a +/-10% uncertainty in each input variable.

The sensitivity to variations in input parameters was greatest at Geo4, probably due to the higher sediment transport rates computed at this site, as indicated by the sediment rating curves in Figure 5. The results were most sensitive to sediment mean particle diameter, water surface slope and water temperature. At sites Geo2B and Geo4, different values of water surface slope were used at high and low flow. It was found that the error was greatest when a +10% change in the slope at high flow was combined with a –10% change at low flow and this worst case is presented above. The result at Geo1 is less sensitive to water surface slope since the same value was used at both high and low slope. The results were sensitive to water temperature due to its effect on viscosity. The sensitivity of the results to uncertainty in the coefficient α in the rough turbulent formula was also tested and found to be negligible.

The uncertainty in the percentage changes in sediment transport rate was also determined assuming a 10% uncertainty in all input variables. This was done by addition of the uncertainties associated with individual variables. The appropriateness of this method was checked and found to be accurate. The range of the resulting uncertainty is illustrated by the error bars in Figures 6 and 7. From these figures it can be estimated that the uncertainty in the change in sediment transport rate would begin to approach zero if every variable contained greater than +/-20% uncertainty. That is the error bars would extend twice as far from the calculated value. From discussions with the data suppliers it is believed that the data uncertainty is less than 20%.

The error in the results caused by representing the sediment by the d_{50} rather than the full size distributions shown Figure 1 was also determined using a method developed by White [White, 1982]. Combined with the Ackers-White equation, this method has been found to be accurate when compared with measurements of sediment transport at several sites including the lower Fraser River in Canada [McLean, 1999]. Application to the present analysis showed that replacing the d_{50} with a full representation of the particle size distribution had a significant effect on calculated sediment transport rates (up to 80%). However, the predicted changes in sediment transport rate between different flow regimes were almost unaffected, with <1.5% variation. This small error was included into the error bars shown in Figures 6 and 7. The small size of the error indicates that the results in this report are insensitive to the details of the sediment transport analysis.

In summary, a detailed sensitivity analysis was conducted to determine the accuracy of the predicted changes to the sediment transport rates shown in Figures 6 and 7. This analysis supported the finding that a significant increase in sediment transport capacity at the bank toe would be associated with changing from the present flow regime to the Basslink flow regime.

Conclusions

This sediment transport analysis provides an indication of the potential of the Gordon River to scour the bank toe and also to transport sediment mobilised by dynamic flow effects such as bank de-watering and slumping.

It is concluded that the proposed Basslink flow regime will result in an increase in the sediment transport capacity within the Gordon River. This increase will be additional to the observed sediment transport impact of the present regulation. The magnitude of the increase will vary along the stream depending on local hydraulic conditions.

This analysis again highlighted the difficulties in comparing sediment transport rates between a natural, flood dominated regime and a constant, regulated regime, due to sediment supply constraints and floodplain flow in natural floods.

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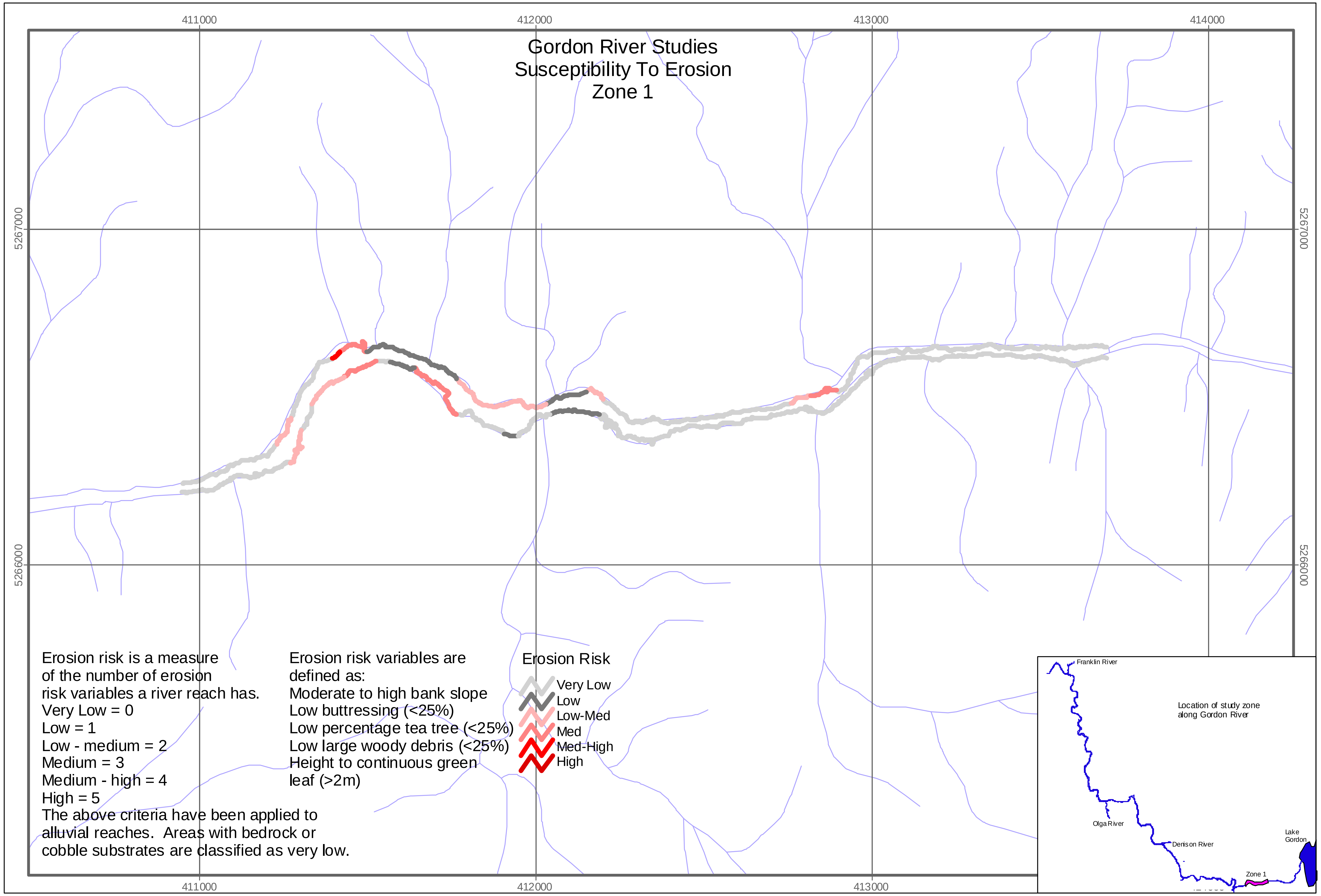
ATTACHMENT 10

EROSION SUSCEPTIBILITY MAPS



BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT

HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION

Hydro Tasmania

Environmental Services

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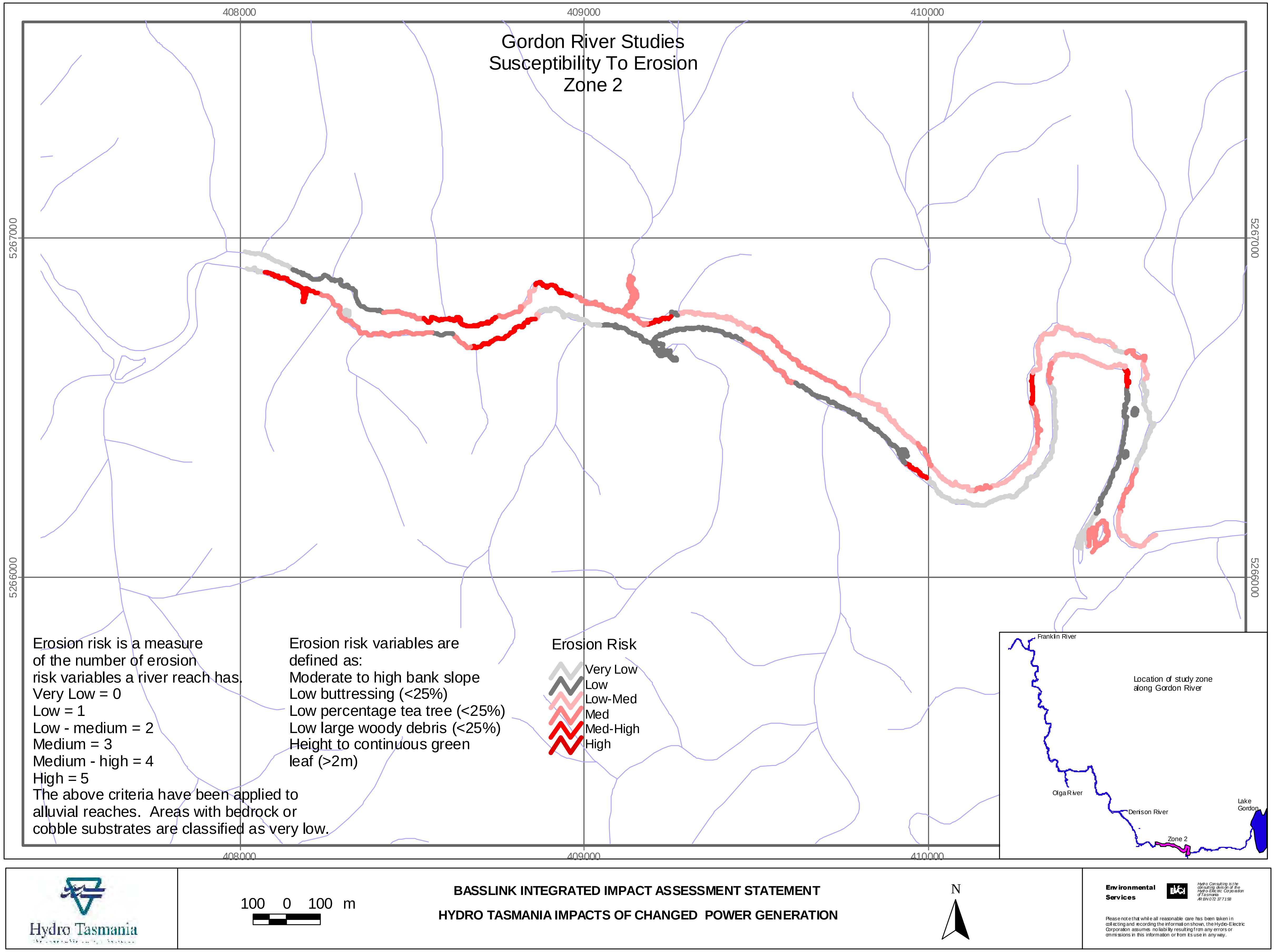
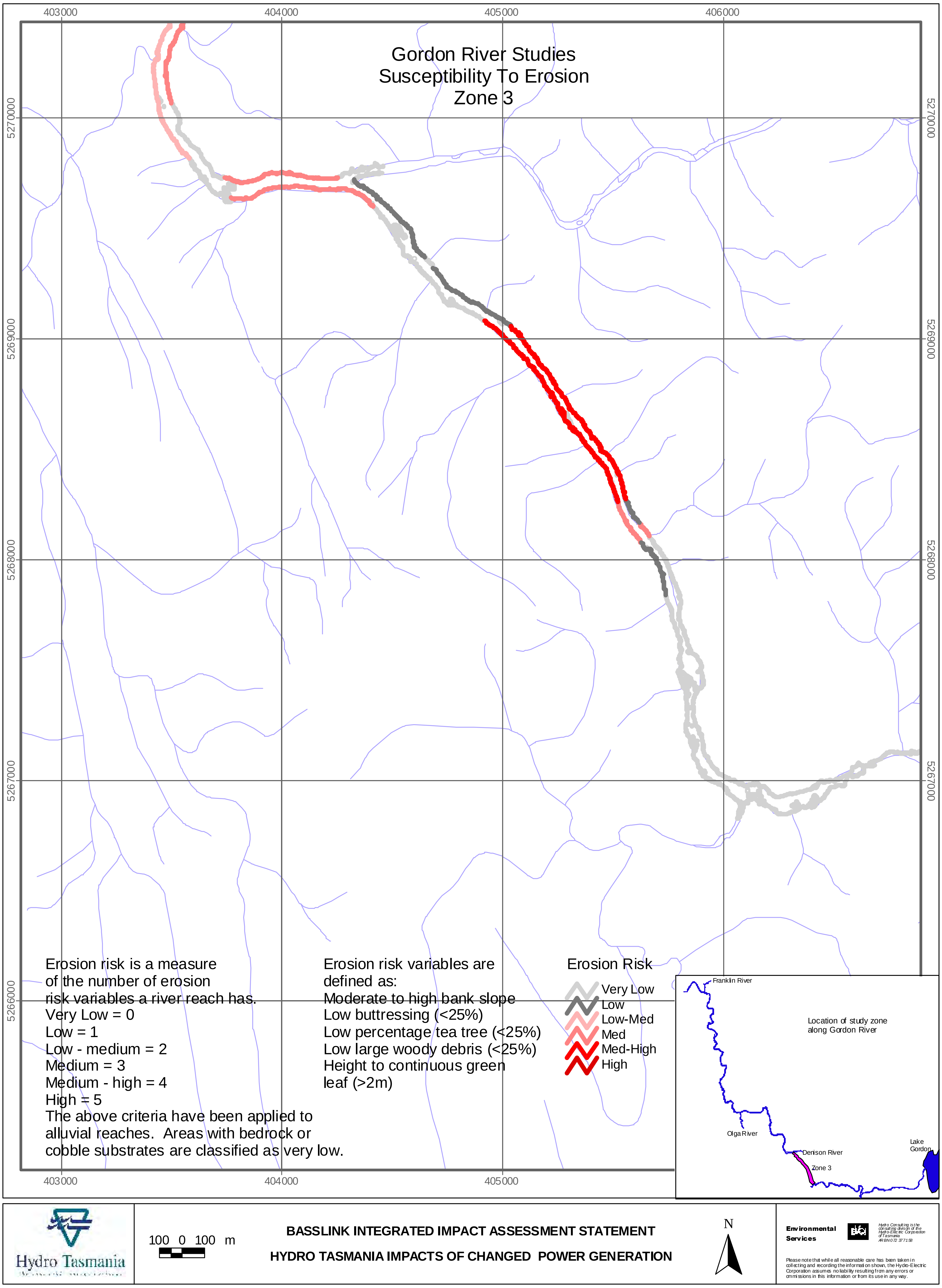

Gordon River Studies
Susceptibility To Erosion
Zone 2
408000
409000
410000
5267000
5266000
Erosion risk is a measure of the number of erosion risk variables a river reach has.
Very Low = 0
Low = 1
Low - medium = 2
Medium = 3
Medium - high = 4
High = 5
The above criteria have been applied to alluvial reaches. Areas with bedrock or cobble substrates are classified as very low.
Erosion risk variables are defined as:
Moderate to high bank slope
Low buttressing (<25%)
Low percentage tea tree (<25%)
Low large woody debris (<25%)
Height to continuous green leaf (>2m)
Erosion Risk
Very Low
Low
Low-Med
Med
Med-High
High
Location of study zone along Gordon River
Franklin River
Olga River
Denison River
Zone 2
Lake Gordon
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
Environmental Services


Gordon River Studies
Susceptibility To Erosion
Zone 3
403000
404000
405000
406000
5270000
5269000
5268000
5267000
5266000
Erosion risk is a measure of the number of erosion risk variables a river reach has.
Very Low = 0
Low = 1
Low - medium = 2
Medium = 3
Medium - high = 4
High = 5
The above criteria have been applied to alluvial reaches. Areas with bedrock or cobble substrates are classified as very low.
Erosion risk variables are defined as:
Moderate to high bank slope
Low buttressing (<25%)
Low percentage tea tree (<25%)
Low large woody debris (<25%)
Height to continuous green leaf (>2m)
Erosion Risk
Very Low
Low
Low-Med
Med
Med-High
High
Franklin River
Location of study zone along Gordon River
Olga River
Denison River
Zone 3
Lake Gordon
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
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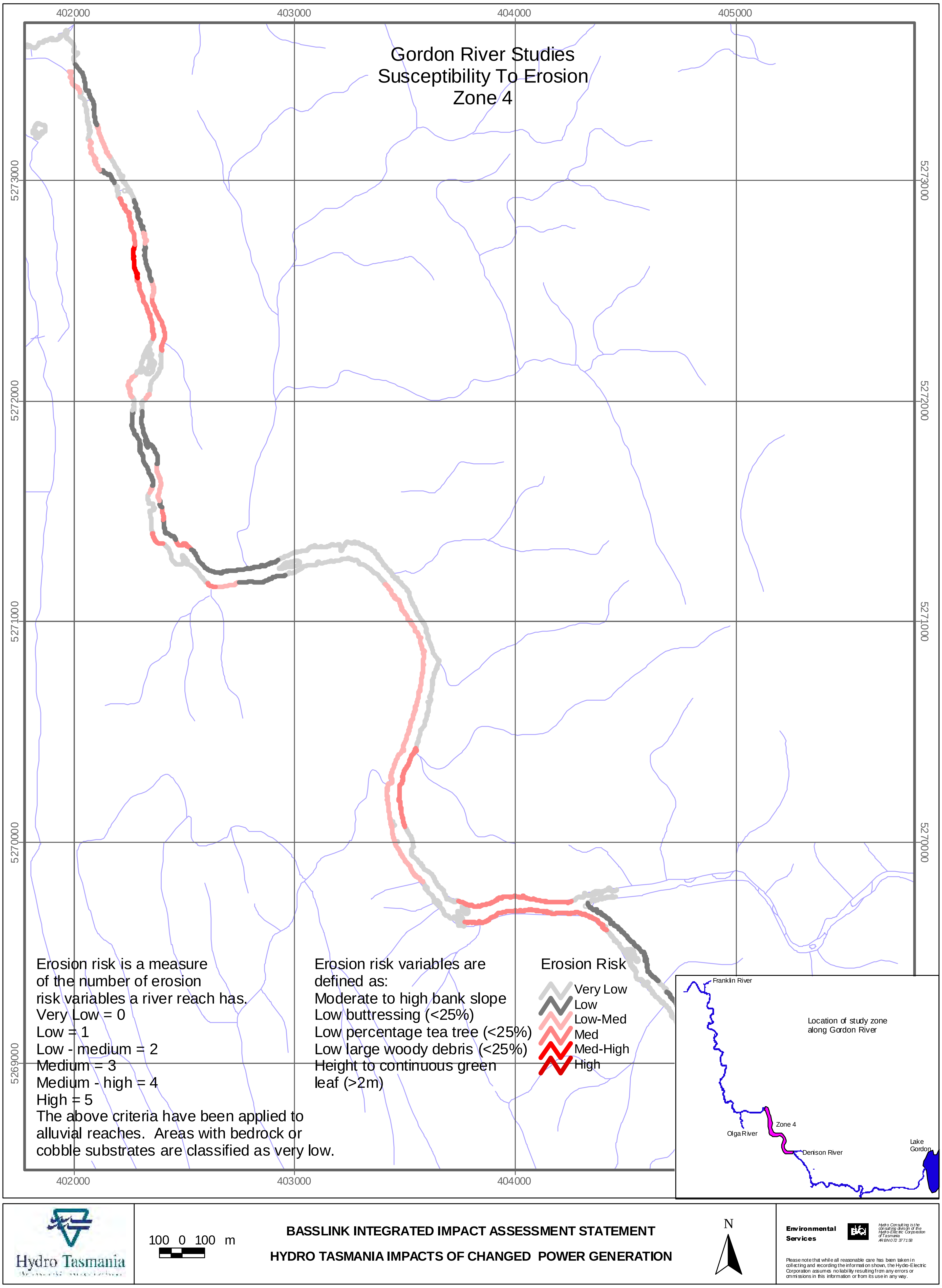
Environmental Services


Gordon River Studies
Susceptibility To Erosion
Zone 4
402000
403000
404000
405000
5273000
5272000
5271000
5270000
5269000
Erosion risk is a measure of the number of erosion risk variables a river reach has.
Very Low = 0
Low = 1
Low - medium = 2
Medium = 3
Medium - high = 4
High = 5
The above criteria have been applied to alluvial reaches. Areas with bedrock or cobble substrates are classified as very low.
Erosion risk variables are defined as:
Moderate to high bank slope
Low buttressing (<25%)
Low percentage tea tree (<25%)
Low large woody debris (<25%)
Height to continuous green leaf (>2m)
Erosion Risk
Very Low
Low
Low-Med
Med
Med-High
High
Franklin River
Location of study zone along Gordon River
Olga River
Zone 4
Denison River
Lake Gordon
Hydro Tasmania
100 0 100 m
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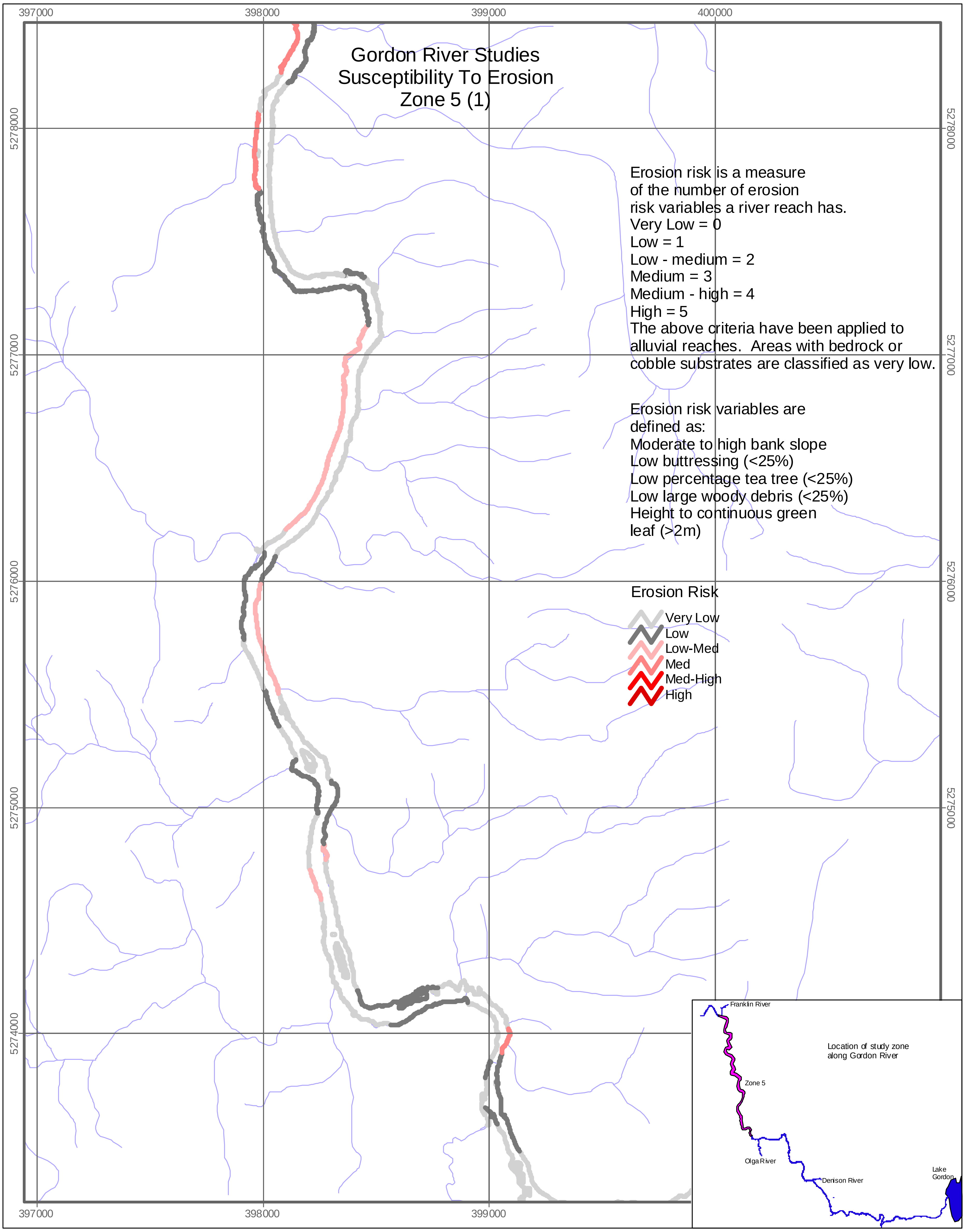

Hydro Tasmania

100 0 100 m

BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT

HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION

N

Environmental Services

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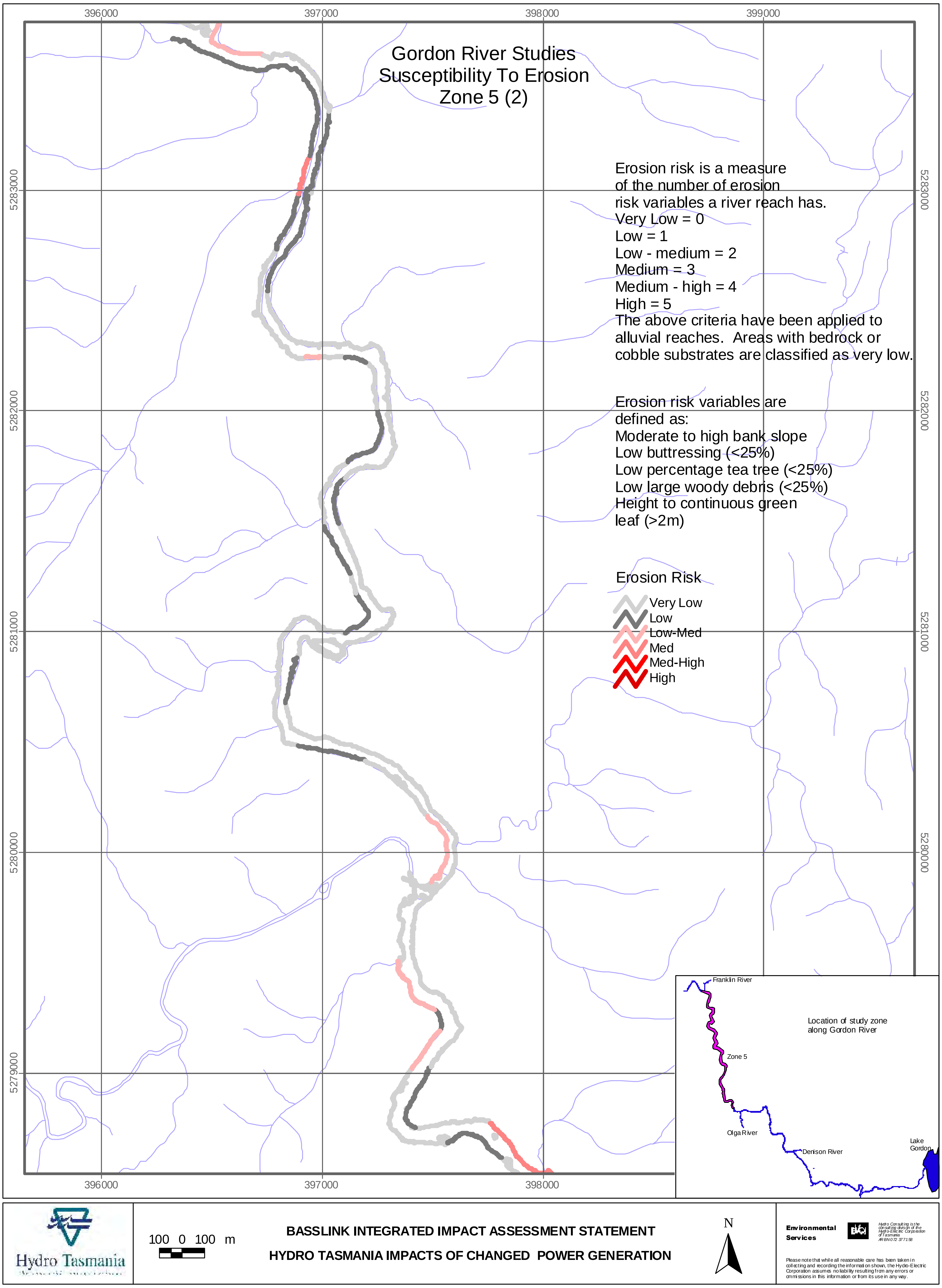
Gordon River Studies
Susceptibility To Erosion
Zone 5 (2)
Erosion risk is a measure of the number of erosion risk variables a river reach has.
Very Low = 0
Low = 1
Low - medium = 2
Medium = 3
Medium - high = 4
High = 5
The above criteria have been applied to alluvial reaches. Areas with bedrock or cobble substrates are classified as very low.
Erosion risk variables are defined as:
Moderate to high bank slope
Low buttressing (<25%)
Low percentage tea tree (<25%)
Low large woody debris (<25%)
Height to continuous green leaf (>2m)
Erosion Risk
Very Low
Low
Low-Med
Med
Med-High
High
396000
397000
398000
399000
5283000
5282000
5281000
5280000
5279000
Franklin River
Location of study zone along Gordon River
Zone 5
Olga River
Denison River
Lake Gordon
Hydro Tasmania
100 0 100 m
BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT
HYDRO TASMANIA IMPACTS OF CHANGED POWER GENERATION
N
Environmental Services