Government of **Western Australia**
Department of **Water**

Lake Argyle sedimentation - 2006 survey

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Salinity and land use impacts series

Report no. SLUI 42
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Lake Argyle sedimentation – 2006 survey

By

RNM Dixon, DW Palmer

Water Resource Management Division

Department of Water

Salinity and land use impacts series

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Department of Water
168 St Georges Terrace
Perth Western Australia 6000
Telephone +61 8 6364 7600
Facsimile +61 8 6364 7601
http://www.water.wa.gov.au

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For more information, contact
Renee Dixon, Senior Engineer, Water Resource Management Division

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Summary

Previous and current (2006) sediment surveys have made it possible to estimate the sediment accumulated over the last 35 years in or at the back of the reservoir named Lake Argyle. Currently the sediment occupies 5% of the volume; in one hundred years after construction (2071) 15% of the reservoir may be filled with sediment. The capacity of the reservoir was of concern prior to raising the spillway in 1994, but the increased capacity has lessened this threat. The sedimentation rate into Lake Argyle has been revised by half to 500 Mm^3 per annum or 12 million tonnes per annum. The sedimentation rate has stayed at similar levels from the creation of the lake (1971) to the 1992 and 2006 bathymetric surveys, despite greater flows observed since 1992.

The sedimentation is influenced by the wet years, with nearly 50% of the sediment sourced from only 5 of the 35 years.

The Ord River was dammed to provide water for irrigation for farmlands in the town of Kununurra in the North-West of Western Australia. Nearly all of the sediment flowing into Lake Argyle via the Ord and Bow rivers is trapped in the lake or just upstream of it. The heavier type of sediment consisting of fine to coarse sands settles in and near the Ord and Bow rivers under and near the lake. Most of the silt and clay particles are carried further by the flowing water and spread over most of the lake bed. The 2006 bathymetric survey captured most of the sediment deposited in the river channels. The sediment on the lake bed was estimated by proportioning the volume of sediment captured in the channels. An animation showing the sediment layers in the river channels captured in the 1991/2 and 2006 surveys is presented on an accompanying DVD.

The sediment volume has accumulated to 87 km from the dam wall, which covers most of the delta that is forming and filling the old Ord River channel at the edge of the lake. In the early 1990s, the last 27 km section of the channel was not surveyed and part of the delta's sediment deposition was overestimated since several points on the channel were only available at those times. An assumption was also made that no sediment accumulated between 1987 and 1992 due to low flows and not much change observed in some key cross sections of the Ord River. In 2006, most of this area was surveyed since it was under water. The digital pre-dam surface was improved by adjusting the vertical height of the channel to agree with the 1970 surveys at key cross sections of the Ord River. These factors contributed to a modification of the sediment inflow rate.

The reservoir expands and contracts kilometres and incoming flows are slowed by the still water in the wide channel. This still water can extend as far as 93 km when the lake is full due to the low hydraulic gradients of the rivers near the lake. This has led to more sediments being deposited further upstream in and over the banks than initially thought. Not all of the sediment enters the reservoir as assumed before the construction of the dam; some ends up in and over the upstream channels of the Ord and Bow rivers close to the reservoir.

Fine sediment was last measured in 1987 and takes up 65% of this volume and 46% of the weight. Further work on fine sediment load is recommended to increase accuracy of estimates. The next sediment survey should take place around 2021.

1 Introduction

The Ord River development resulted in irrigated farmlands and the town of Kununurra in the north-west of Western Australia. In 1959, the WA Government planned four stages of the Ord River Irrigation Project. The first stage was the construction of a diversion dam, distribution and drainage systems to service 12 100 ha of irrigated farmland on the Ivanhoe Plain, east of the Ord River. The second stage was the construction of a large dam, 56 km upstream in the Carr Boyd Ranges and the development of 2200 ha of farmland on the Packsaddle Plain, west of the river. The purpose of the dam was to create sufficient storage to supply the Stage 1 farmland and up to a further 60 000 ha of irrigated land. Subsequent stages planned included development of additional irrigation supply areas and the construction of a hydroelectric power station at the main storage dam.

In May 1963 the construction of the Kununurra Diversion Dam was completed. This resulted in the formation of Lake Kununurra. Five farms on the Ivanhoe Plain were initially supplied with irrigation water. The Kununurra Diversion Dam has a capacity of 98 GL at its normal operating level of 41.6 m AHD. Lake Kununurra is currently managed to have as stable a water level as possible so that it provides constant head for the diversion of water down the M1 Supply Area.

The Ord River Dam construction started during the dry season of 1969 and was completed in November 1971. This resulted in the formation of the Lake Argyle Reservoir. Initially the capacity of the reservoir was 5800 GL at full supply level. The spillway is 7 km north-east of the reservoir in Pannikin Bay. The water from the spillway ends up in Lake Kununurra.

After the diversion dam was constructed additional farmlands, drainage and distribution systems were established on Packsaddle Plain. In 1967, the rated land in the Ord Irrigation District reached 9100 ha. Cotton irrigators struggled financially, with pest control being the main problem. Virtually no crops were grown during the 1974/75 season and the irrigated land reduced to 3500 ha. The irrigated area remained below capacity, averaging 41% for the years 1974/75 to 1986/87. Many crops (e.g. rice and sunflower) were trialled over this period but the remoteness of the district made transport and supply costs high. Some farmers grew fodder crops for the cattle industry in the East Kimberley.

The 1990s were more promising for the irrigation area with sugar cane being established. Improvements in the roads and protection of produce during transport made horticultural crops financially viable. Growing and harvesting crops in the growing season opposite to southern Australia has also been profitable. Between the seasons 1996/97 and 2004/05, 10 000–12 200 ha of the Stage 1 areas (15 000 ha) have been irrigated (Department of Water 2006). Crops include sugar cane, sandalwood, cotton, leucaena and horticultural crops such as rockmelons, honeydew melons, bananas, pumpkins and mangoes.

In 1995/96 the Ord River Dam Hydroelectric Power Station was constructed to supply electricity to the Argyle Diamond Mine and towns of Kununurra and Wyndham. A 6-m weir was built across the spillway in December 1994 to provide additional head for the hydroelectric scheme. The full supply level changed from 86.25 to 92.23 m AHD. The new spillway has a floor valve which releases a small flow down Spillway Creek when the lake is below the overflow height.

The capacity of the Lake Argyle Reservoir is now 10 760 gigalitres (GL) at full supply level. The maximum flood storage capacity is 40 616 GL, which represents about 3 times the maximum estimated inflow volume since the dam's construction. Lake Argyle varies in size over the year but is approximately 62 km long and up to 40 km wide. Its surface area is 980 km^2 at full supply level but increased to 1392 km^2 at its peak level (99.25 m AHD) in February 2001.

The Upper Ord River Catchment (UORC) which drains into Lake Argyle is 46 100 km^2 in area and covers the semi-arid tropical region south of Kununurra (Fig. 1). The major tributaries of the Ord River upstream of Lake Argyle are the Wilson/Bow, Behn, Negri, Nicholson, Panton and Elvire rivers.

Large areas of the UORC are prone to erosion due to the low resistance of the materials and sparse vegetation cover combined with intense precipitation. Flood events result from rain from tropical cyclones and deep depressions falling over the catchment during active monsoon conditions. Most of the rain falls during the summer monsoons in January to March.

After European settlement in the 1880s the area was used for cattle grazing due to the abundance of productive pastures and surface waters. Evidence of pasture deterioration was noted in 1905. By the 1930s the increase in grazing pressure from cattle and feral donkeys, combined with the effects of bushfires, had resulted in degraded plains and eroded streambanks. The Nelson, Gordon, Antrim and Elder land systems were particularly vulnerable to erosion (Payne et al. 2004).

Severe erosion in an area including the Ord River and Turner Pastoral stations and parts of the Flora Valley Station was seen as a sedimentation threat to the planned Ord River Dam. In the late 1960s it was estimated that the long-term average annual total sediment load of the Ord River at the dam site would be 24 million tonnes (Kata 1978). To protect the storage capacity of the proposed Lake Argyle, a catchment stabilisation program called 'The Ord River Catchment Regeneration Project' was initiated in 1960 by the Department of Agriculture. The Ord River Regeneration Reserve (ORRR) is 10 230 km^2 in area. The severely eroded area within this reserve is approximately 5200 km^2 and is identified by the shaded zone in Figure 2 (Payne et al. 2004).

A fencing program commenced in the Turner Pastoral station on the Turner Plains (about 170 km^2). Mustering to destock paddocks was undertaken by station lessees. The *Ord River Dam Catchment Area Act* was gazetted in 1967 and amended in 1969. The leases were resumed and contract musterers and Department of Agriculture staff operated and excluded cattle in most years until the mid-1990s. An estimated 143 000 cattle were turned off between 1961 and 1990 (de Salis 1993). The Western Australian and Northern Territory governments undertook regeneration work, such as removal of cattle, eradication of donkeys, contour cultivation and seeding of degraded areas accessible to machinery.

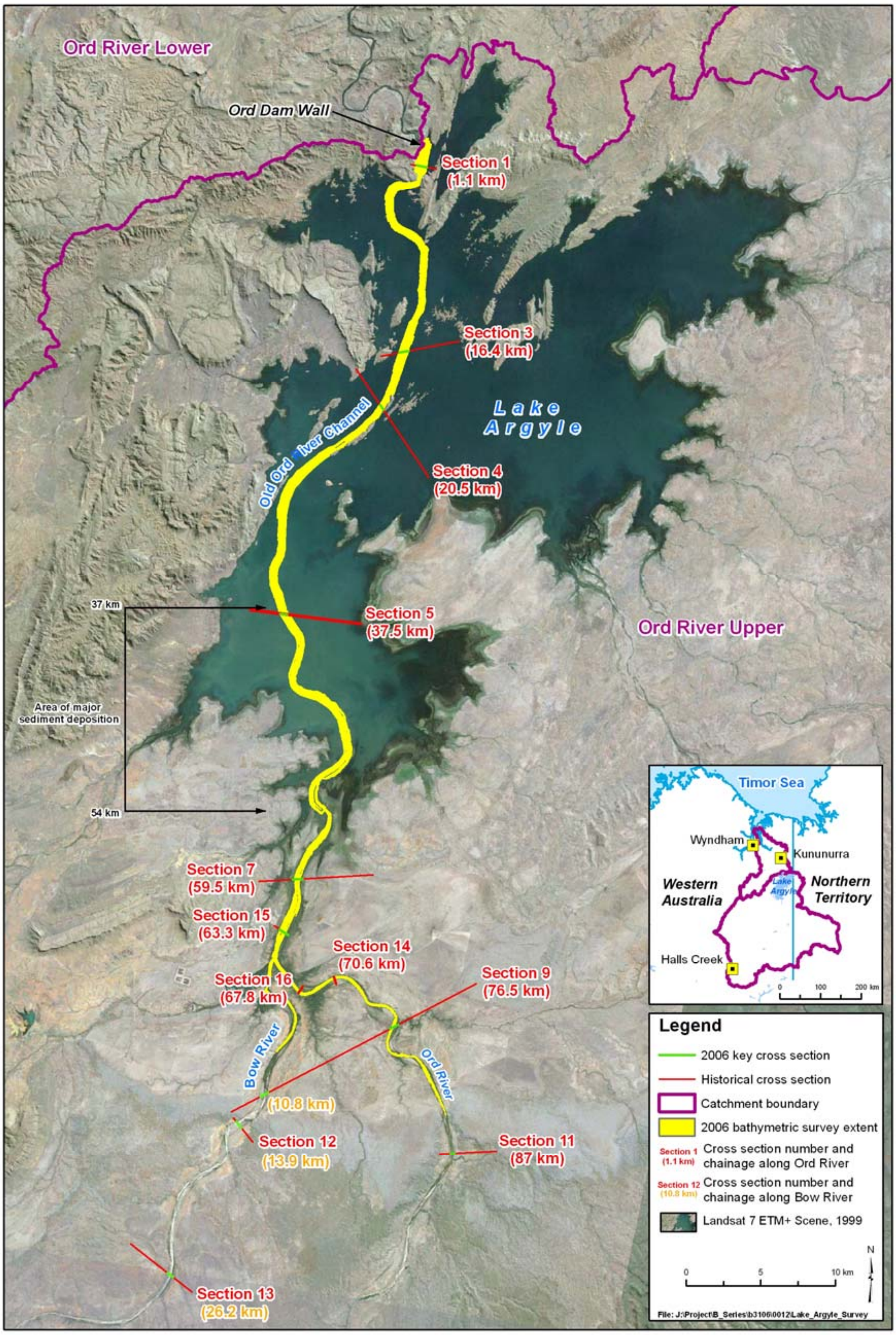


Figure 1 Extent of the October 2006 sediment survey in the Ord River beneath and upstream of Lake Argyle and the upper reaches of the Bow River

By 1974 it was considered that parts of the ORRR had recovered sufficiently to allow research programs in grazing and management trials. These trials concluded in 1995. In 1987 a large part of the area west of the Ord River (which was not badly degraded) was gazetted as the Purnululu (Bungle Bungle) National Park and Conservation Reserve.

Sediments from the floodplains and channels in the upper Ord River catchment are transported downstream by the river system until they reach the Lake Argyle Reservoir, which acts like a sediment trap. Changes in lake level can significantly change the extent of the channel inundated upstream of the lake. Most of the sediment enters the lake via the old Ord River channel that is on average 17 m deep, about 500 m wide and meanders 60 km beneath the lake. The geometry of the channel and the Lake Argyle Reservoir lead to backwater effects in the river and sediment may be deposited up to 28.5 km upstream of the junction of the Ord and Bow rivers (or 93.5 km upstream of the dam wall) when the lake is full (Sandercock 2003).

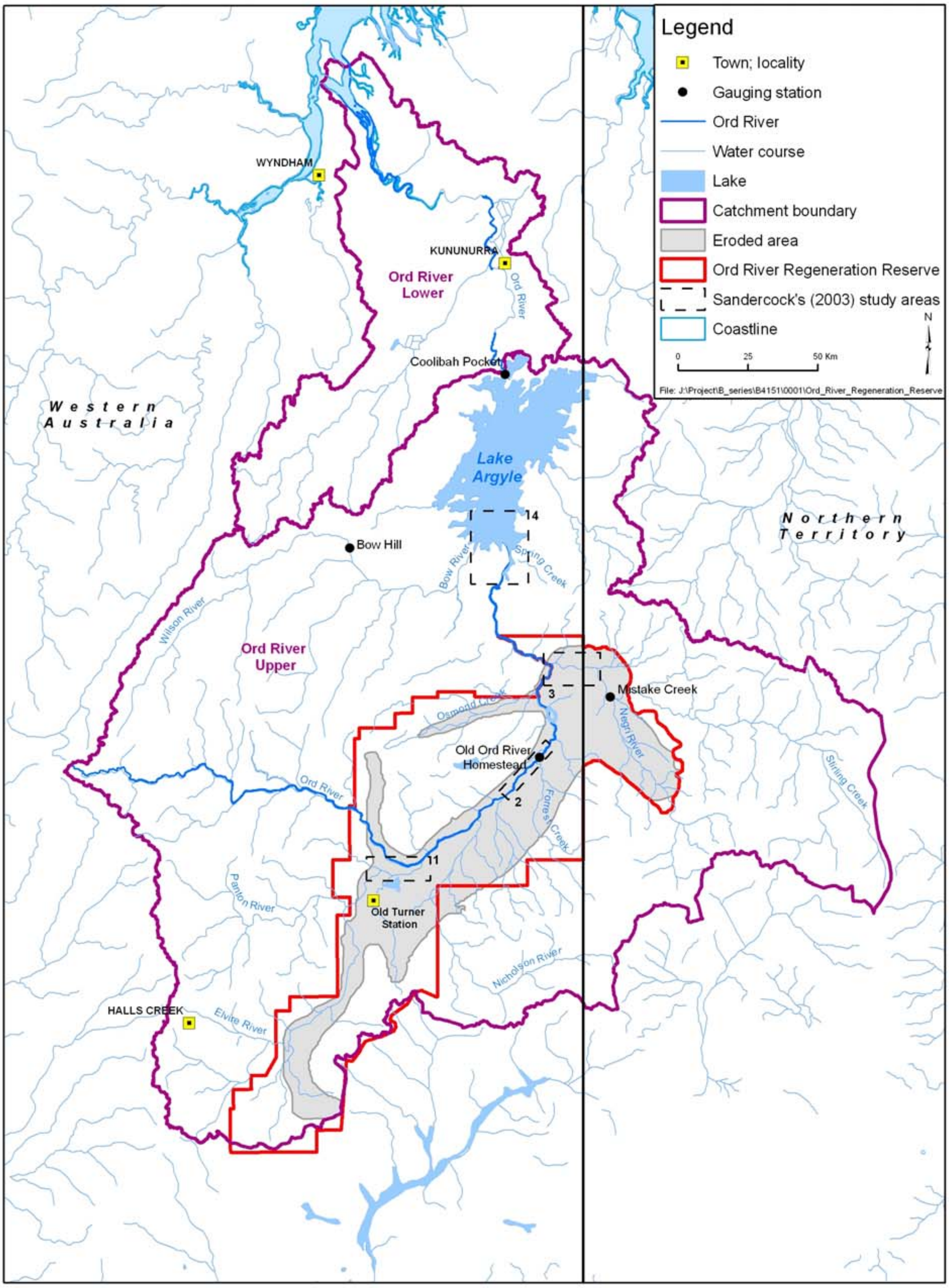


Figure 2 Ord River Regeneration Reserve and the severely eroded area

2 Aims of the 2006 survey

The aim of this study was to estimate the volume of sediments deposited into the old Ord River channel below Lake Argyle since the 1991/92 (known as 1991) bathymetric surveys. The sediment deposition rates from pre-dam to 1991 and 1992 to 2005 flow years could then be compared. The survey results are important to see how the sediment deposition is affecting the storage capacity of the reservoir.

A secondary purpose for surveying the lake again was to see how the higher lake levels (experienced since the construction of the 6-m wall at the spillway in 1994) had affected the location of the sediment deposited.

Since most of the coarse sediments are deposited in the old Ord River channel beneath Lake Argyle a bathymetric survey of this channel was undertaken in 2006. A high lake level (91.25 m AHD in October 2006) was recognised as an advantage to expand the extent of the survey into the upper reaches of the Ord and Bow rivers. It was expected that extending this survey (further) upstream than the 1991 survey would help estimate the volume of sediment deposited in the upper reaches of the lake.

It was also planned to survey again the historical cross sections which were first surveyed before the dam was built. This was considered useful in estimating the rate of sediment deposition since the dam was constructed.

3 Stakeholders

This project has been funded by the Australian Government's National Action Plan for Salinity and Water Quality (NAPSWQ) with funding administered through an agreement between the Rangelands NRM Coordinating Group (RCG) and the Department of Water.

The NAPSWQ was a joint commitment for $1.4 billion over seven years by Australian, state and territory Governments to develop locally relevant solutions to salinity and water quality issues. The NAPSWQ began in 2001 and ended in 2008. It operated in 21 priority regions across Australia including the Ord Catchment.

NAPSWQ funding was distributed according to regional plans which, in the Ord Catchment, was the Strategy for Managing the Natural Resources of Western Australia's Rangelands. The RCG was the organisation established to administer state and commonwealth funds directed towards natural resource management. Priorities for funding were decided by a reference group of local stakeholders, known as the Ord Catchment Reference Group (OCRG).

The OCRG is a partnership of organisations which:

- provides advice and support for natural resource management and related projects to improve land and water management in the Ord River Catchment
- facilitates the development and implementation of strategies and actions which improve land and water resource management and related issues in the Ord Catchment
- advises the RCG of natural resource management priorities in the Ord Catchment including advising on funding allocations through the NAPSWQ
- streamlines communication and engagement relating to natural resource management with the community of the Ord Catchment.

The OCRG comprises organisations with active roles in the management and delivery of natural resource management projects in the Ord Catchment. The current ones are:

- Ord Land and Water
- Department of Agriculture and Food
- Water Corporation
- Shire of Wyndham–East Kimberley
- Miriuwung Gajerrong Corporation
- Department of Water
- Ord Irrigation Cooperative
- East Kimberley Land Conservation Districts Committee
- Kimberley Primary Industries Association
- Department of Environment and Conservation
- Rangelands NRM Coordinating Group

4 Data collection

It was necessary to locate and collate the data from the 1991/92 hydrographic surveys of the old channel beneath Lake Argyle and from the 1970, 1985, 1986, 1991, 1992 and 2000 hydrographic and land surveys of the 'historical cross sections' in order to commence the land and bathymetric surveys (Fig. 1). Digital data of the pre-dam sediment surface was also collected.

4.1 Historical cross sections

The historical cross sections, surveyed across the lake area and Ord and Bow River channels before and after the dam was built, are useful because they have been surveyed more frequently than the old Ord River channel beneath the lake and allow calculation of rough estimates of sediment deposition rates. These cross sections are known by their numbers. The survey years of each section are given in Table 1 and some are shown on Figure 1.

Table 1 Historical cross sections — years surveyed

Cross section	Location (km)	River	Years surveyed				
Section 2	1.1 [b]	Ord	1970	1986	1992		2006
Section 3	16.4 [b]	Ord	1970	1986	1992		2006
Section 4	20.5 [b]	Ord	1970	1986	1992		2006
Section 5	37.5 [b]	Ord	1970	1986	1992		2006
Section 7	59.5 [b]	Ord	1970	1985	1992	2000	2006
Section 15	63.3 [b]	Ord				2000	2006
Section 16	67.8 [b]	Ord				2000	2006
Section 14	70.6 [b]	Ord				2000	2006
Section 9 Ord River	76.5 [b]	Ord	1970	1986	1991	2000	2006
Section 11	87.0 [b]	Ord	1970			2000	2006 [a]
Section 9 Bow River	10.8 [c]	Bow	1970	1986	1991		2006 [a]
Section 12	13.9 [c]	Bow	1970	1986	1991		2006 [a]
Section 13	26.2 [c]	Bow	1970		1991		2006

a The survey boat could not reach these cross sections. Only the portions of the sections above water were captured.

b Upstream of the dam

c Upstream of the confluence of the Ord and Bow rivers (65 km from the dam wall)

It was decided that only portions of the historical cross sections near the old Ord, current Ord and Bow River channels should be surveyed in 2006 and the parts surveyed are named the 2006 Key cross sections in Figure 1.

4.2 Channel bed elevation surfaces

To calculate the volumes of sediment deposited since the dam was built, an original pre-dam surface in the channel bed was needed. In previous sedimentation studies of Lake Argyle, this base elevation surface was for the years 1955 and 1961 and was generated from aerial stereo-paired photography of the Ord and Bow rivers. This pre-dam surface had to be extended since the surveyed channels in 2005 went further upstream than the 1991 survey. The 1991 survey and the existing pre-dam elevation surface stopped at a distance 59.4 km upstream of the old Ord River channel from the dam wall. The 2006 survey stopped 84.4 km from the dam wall along the upper reaches of the Ord River and also extended 8 km upstream along the Bow River. The pre-dam surface was extended by joining an elevation surface in the south derived from 1968 aerial stereo-paired photography. This elevation surface, derived in 2006 by Landgate, was of better quality than the 1955/61 elevation surface used in the north. It also extended a large distance from the channels and would be useful for future surveys when the channels could overflow with sediment.

A review of the vertical accuracy of the pre-dam surfaces was performed after the first analysis of sediment volumes and 1 km cross sections. A comprehensive survey of the elevations near the historical cross sections 2, 3, 4, 5, 7, 9, 11 and 12 was undertaken in 1970 before the area was flooded. Plans from the Public Works Department of Western Australia (36537-35-1 to 36537-35-22) were checked against elevations of the digital pre-dam surfaces (1955/1961 and 1968) at each historical cross section. The plans usually showed three survey lines crossed by chainage lines at 1000 ft intervals, overlaid on contours derived from aerial photography taken on 2/6/1970 for each historical cross section. The effect of the corrections on the 1955/61 surface is seen in Figure 3 which was generated from a line approximately along the centre of the Ord River channel from the dam to 6 km south of Section 7. The 1955/1961 and 1968 pre-dam surfaces were adjusted separately by adding a grid of elevation changes. Adjustments of up to -2.4 m at Section 4 and +0.9 m at Section 11 were applied. The changes required at points were used to generate a grid of elevation changes using the kriging method. The grid of elevation changes was added to the original elevation surfaces to adjust them. Later they were combined. A revised combined pre-dam surface along the Ord River channel was used to re-calculate sediment deposition and volumes.

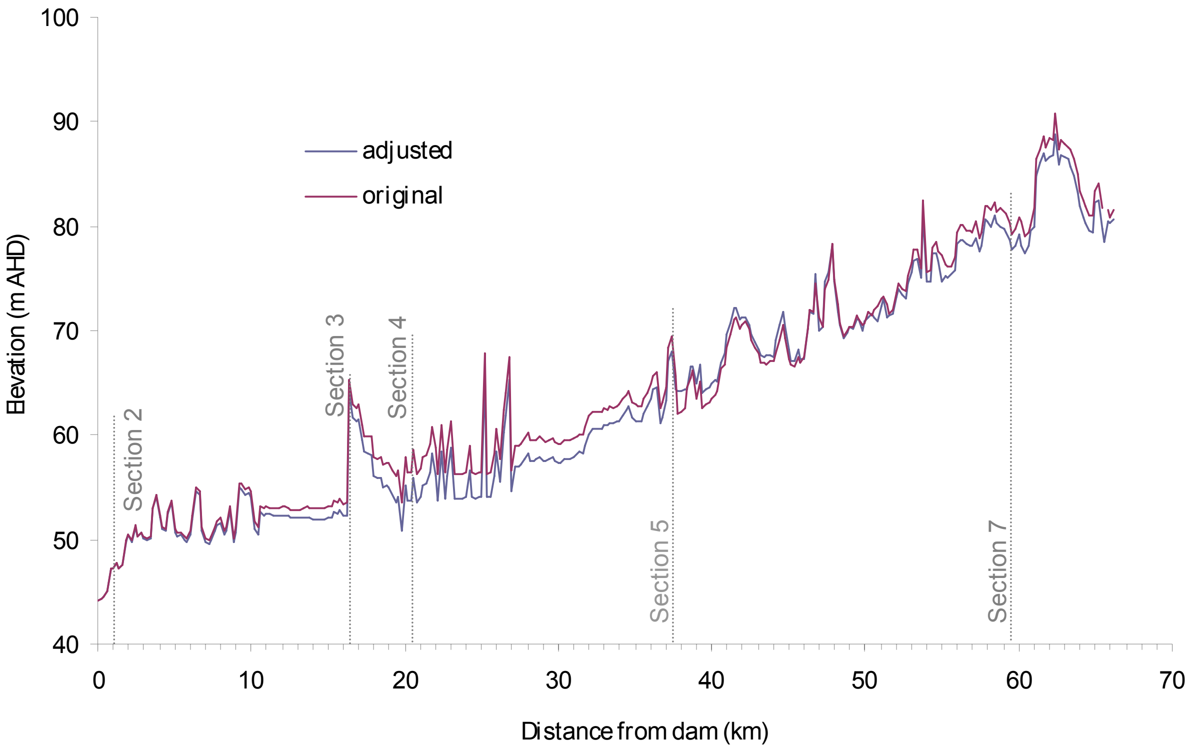


Figure 3 Adjustments made to the 1955/1961 pre-dam surface

Surveyed sediment information from 1991 and 1992 was captured at 200 m cross sections along the channel bed and also along the centre of the channel for the 1992 survey. Contours of the channel banks and the above were used to generate a continuous surface of the channel bed generated by interpolation between cross sections. Results of both surveys were joined into one elevation surface named after the flow year 1991 since the earlier survey extended further south.

The results of the 2006 survey were supplied as an elevation surface by the surveyor since the whole of the channel bed was captured. It was named the 2005 surface to align with the 2005 water year (October 2005 to September 2006). More details of the channel bed elevation surfaces are in Appendix C.2.

5 Previous sediment studies

5.1 Previous sediment inflow rates

Previous estimates of the sediment inflow rate are shown in Table 2 and explained in more detail in Sections 5.2–5.4.

Table 2 Previous estimates of sediment inflow rates

Data captured in flow year	Method	Source	Flow years for sediment rate calculation	Average inflow (GL)	Sediment inflow rate (Mtpa)
1955–67	Rating curve	Kata (1978)	1905–67	4030[a]	24.0
1986 (soft sediment on lake bed) 1985–86 (coarse sediment in Ord channel)	Cross sections & core sampling of lake bed	Wark (1987)	1971–87	4060[a]	23.5 [b]
1991	Hydrographic survey	Mauger & Hawkins (1994)	1971–91	3775	20.1 [c]

a Estimated by R Dixon from Water Authority estimates received in 2008

b Overestimated. See Sections 5.3 and 7.5

c Since revised to 12.5 Mtpa (Table 12)

5.2 Rating curve method

Prior to the construction of the Ord Dam, sediment sampling was the best way of estimating the sources and amount of sediment that could be trapped in the reservoir and of locating its major sources. Sediment samples were taken from the Ord River at the Coolibah Pocket gauging station, which is currently underwater near the location of the current Ord Dam (Fig. 2). Samples were also taken at other major sites, such as on the Negri River at the Mistake Creek gauging station (catchment area 7770 km^2), on the Wilson River at the Bow Hill gauging station (catchment area 6600 km^2) and the Ord River at Ord River Homestead (catchment area of 19 600 km^2) (Table 6; Fig. 2). Non-continuous samples were taken over the period 1955–68 at the Coolibah Pocket gauging station.

Sediment sampling began at the Coolibah Pocket gauging station in November 1955. In the early years, sampling was crude and relied on scoop samples near the bank. After 1962, sampling methods improved, with the use of a D49 sampler operated from a manned cableway. Samples were either at the surface or depth integrated. The concentration of sediment was assessed on a dry-weight basis. Fair results were obtained at low and medium flows but at higher flows they were limited by the time taken to fill a 1-pint sample bottle. Between 1966 and 1969 an intensive sampling program was conducted using a Turbidisonde sampler (Kata 1978). It was an effective sampler for large rivers, being quite steady at high flow velocities. The sampler was suspended by a hollow cable connected through a suspension winch to a cylinder of compressed air. The air supply could be opened and closed to open and close the sampling chamber. It was possible to take integrated depth samples by taking the water sample as it was raised at a steady rate. In addition, multiple point samples were taken to establish a relationship between point and integrated samples. At high flows, point samples were taken, then the relationship used to adjust the point samples to integrated samples.

The Ord River bedload was computed for a variety of flows and seasons by applying the modified Eistein Equation developed by Colby in 1957 (Vanoni 2006). The computed bedload showed marked differences which Kata explained in terms of quantity and distribution of rainfall, nature of the catchment surface, time of season, the availability and particle size distribution of sediment and whether it was a rising or receding stage. The total sediment load was estimated by assuming the bedload was 23% of the suspended load.

A scatter diagram was plotted of equivalent integrated sediment concentration versus instantaneous flow rate for observations over the period 1962–69. It contained 353 measurements and showed a large scatter because the sediment concentration depends not only on river flow but also on the availability of sediment and the location of storm centres. A mean curve was fitted to the observations.

The total annual sediment was estimated for each of the 12 years of flow record by applying the concentration curve to flow-duration figures for the year. A strong relationship was found with a coefficient of determination (R^2) of 0.99 (Fig. 4).

The average sediment inflow at the Coolibah Pocket gauging station was 29.25 million tonnes per annum (Mtpa) for the flow years 1955–67 (Kata 1978). The average flow for the same period was 5542 GL. The estimated annual yield from the Ord River Homestead was 17.07 Mtpa and from the Negri River 1.07 Mtpa. Though the Wilson River was gauged, the sediment data had not been processed at the time of the Kata study. Assuming the Wilson River had the same sediment yield as the Negri River, Kata assumed that 11.1 Mtpa of sediment was produced between the Homestead gauging station and the main dam.

To estimate the long-term average suspended sediment discharge, the annual sediment versus flow curve was applied to 62 years of flows estimated from rainfall records. Kata (1978) estimated that the long-term average sediment load of the Ord River before the dam was built was 24 Mtpa. This included 20 Mtpa of suspended sediment load, derived from stream sediment sampling at the Coolibah Pocket gauging station, and an estimated bedload of 4 Mtpa. Sadler (1970) reported the same data from the Coolibah Pocket. The sediment density assumed was 1.2 tonnes per cubic metre (t/m^3).The bedload assumed was 20% of the suspended sediment load. The standard error of the simulated annual mean gives a result of 24.00 ± 11.75 Mtpa (Department of Agriculture 1994).

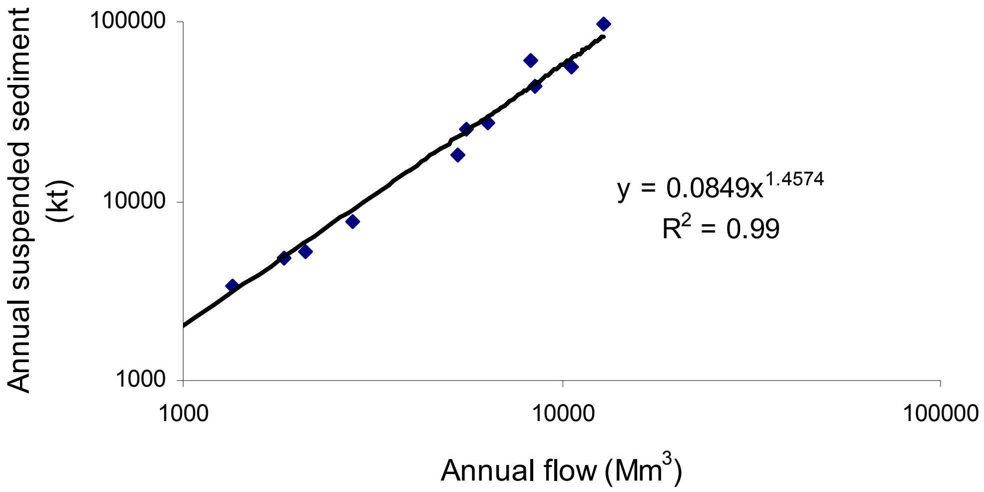


Figure 4 Annual flow vs suspended sediment discharge at Coolibah Creek (1955/56 to 1967/68)

Adapted from Kata (1978*)*

5.3 Surveyed cross sections and lake bed in 1985–87

In mid-1987, sediments were sampled over Lake Argyle floor bed and in or close to the old river channel (Maesapp 1988). In 1991, more coarse samples were taken from the beds of the Ord and Bow rivers. Two types of sediments were encountered. The first was a finer colloidal sediment (soft sediment) widely distributed throughout the reservoir bed. It generally consisted of silty clay overlying the in-situ clayey topsoil material. The second type of sediment found was fine–coarse sand (coarse sediment) and was in or near the river beds.

Most of the lake bed cores were obtained by using a 53 mm-diameter piston Tonka corer. Five thin walled in-situ density samples of sediment were taken near the banks of the Ord River. A sand replacement test was also performed near the river bank on coarse sediments. Wark (1988) used 22 of the soft sediment samples to get an average depth and dry density of 213 mm and 0.567 t/m^3 respectively. The surface area of the lake bed was assumed to be around 750 km^2 at the time. The coarse sediments in or near river beds consisted of fine, medium and coarse sand and had a dry density of 1.2–1.35 t/m^3. Wark selected 9 of the appropriate coarse samples obtained from the Tonka corer and the in-situ samples near the river bed to obtain a dry density of 1.27 t/m^3.

To facilitate future measurements, a number of cross sections were surveyed in 1970. Over the period 1985–87 the historical cross sections 2–12 (Wark 1987) were surveyed to estimate the volume of sediment deposited in Lake Argyle. The volume of coarse and soft sediments deposited in the 16 years after the dam was 380 Mm^3. The storage volume of the reservoir was then estimated to have reduced by 6%. This study estimated a sediment transport rate of 24 Mtpa (Table 3). Following more comprehensive surveys, the coarse sediment volume was found to be overestimated (Section 7.5).

Table 3 Sedimentation rate using 1985–87 surveyed cross sections and sediment samples

Sediment type	Density (t/m^3)	Volume (Mm^3)	Weight (Mt)	Years of deposition	Volume rate (Mm^3/a)	Sediment inflow rate (Mt/a)
Coarse in channel	1.27	210	267	15	14	17.8
Soft in lake	0.57	160	91.2	16	10	5.7
Total		380	376	16	24	23.5

Source: Wark (1987)

It is worth expanding on how the coarse sediment volume (210 Mm^3) in the old Ord River channel was estimated since it is so much higher than subsequent surveys in 1991 and 2005 (Figs 6 & 13). Wark's estimate of the coarse sediment was appropriate for the time, with such limited information available.

The historical cross sections were surveyed in 1970 before the dam was built and again in 1985/1986. The profiles drawn from the surveys are on drawings PWD WA 36537–35–27 to 53. Cross sectional areas were calculated from these cross sections. These were used with the distance along the channel to estimate volumes as in Table 4. Section 11 was not surveyed in 1986.

Table 4 Coarse sediment (1971–86) in channel estimated by Wark

Section	Chainage (km)	Distance (km)	Area (m^2)		Coarse sediment volume (m^3)		Cumulative coarse sediment volume (Mm^3)
Ord R			> 88 m AHD	< 88 m AHD	> 88 m AHD	< 88 m AHD	
2	0	7.5		530		3975	3.975
3	15	10.5		2435		25 568	29.543
4	18	9.5		2540		24 130	53.673
5	35	19		2790		53 010	106.683
7	55	20	144.5	2595	2890	51 900	161.473
9	73	20.5 [a]	800	1505	16 400	30 853	208. 726
11	87		N/A	N/A			
Bow R							
9			82				
12		15	107		1425		210.151

a Section 11 was not surveyed in 1986, so the Section 9 cross section was used for the volume estimate from chainage 66.5 to 87 km (Section 11)

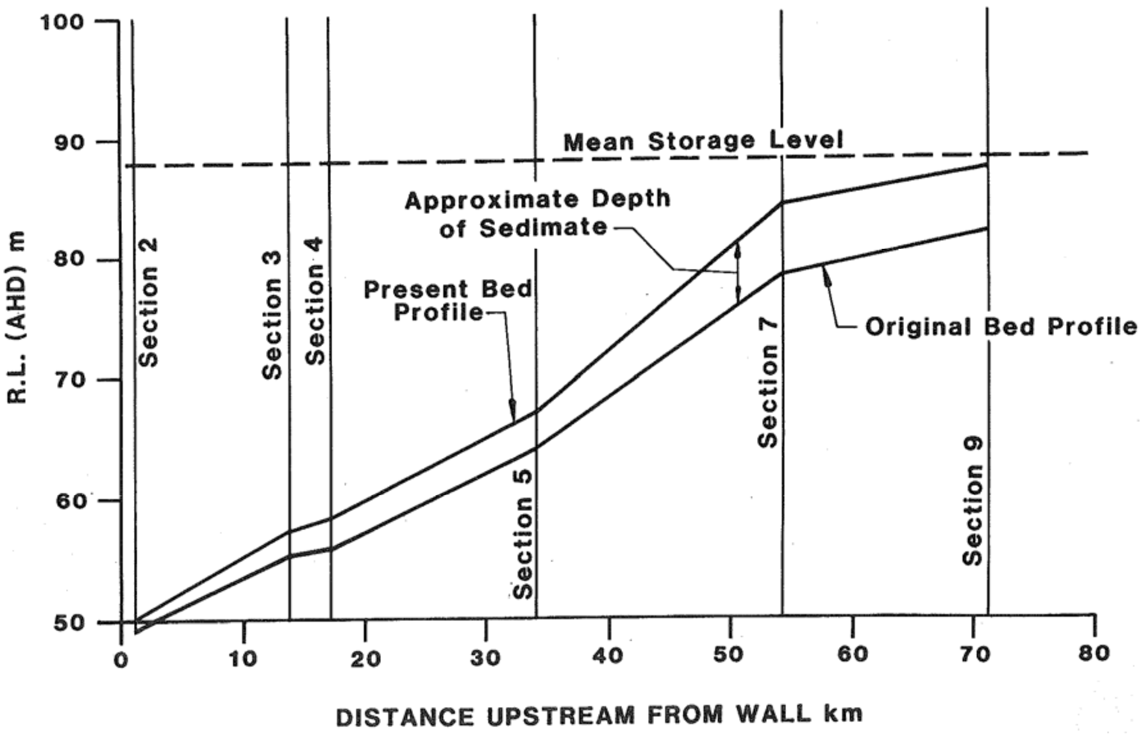
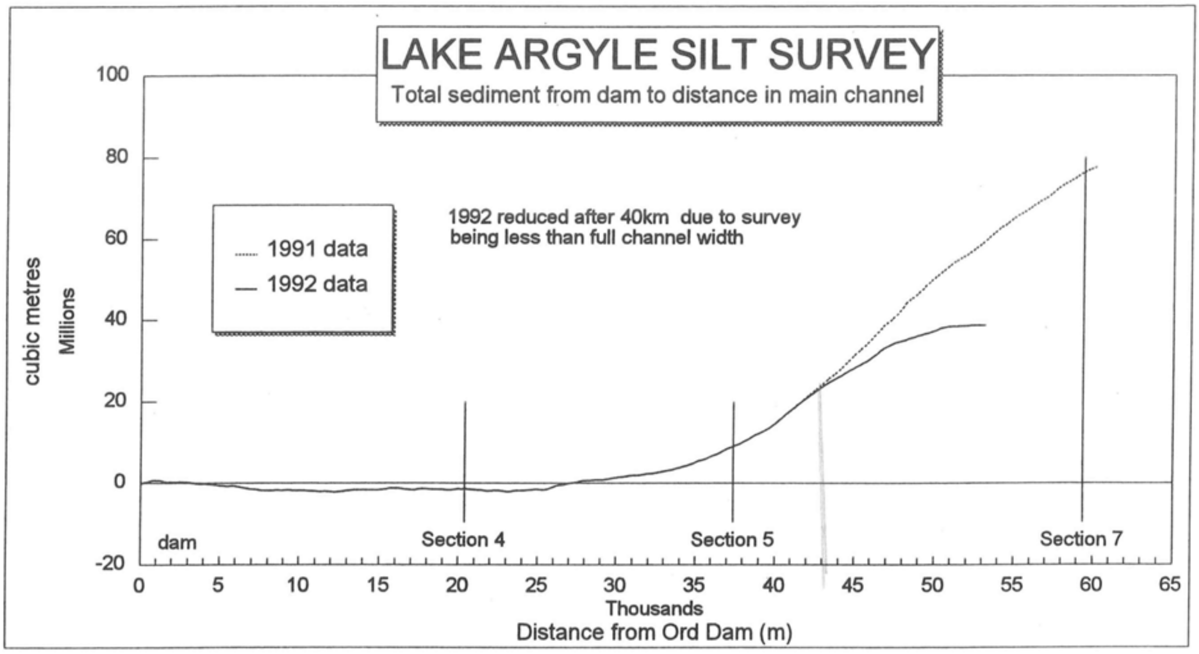


Figure 5 Depths of sediment deposition in Lake Argyle from the 1985/1986 surveys

Source: Wark (1987)

5.4 Echo-sounding survey in 1991

A complete hydrographic survey of the channels was planned for 1992 to estimate the sediment deposition in the channels. This was preceded by a trial survey in October 1991 on part of the old channel at the southern end of the lake. This trial was successful so the complete survey of the channels starting from the dam wall was done in September 1992. Both surveys used an echo-sounder and a differential GPS facility mounted on a 7.2-m aluminium boat. The 1991 survey proved useful since the lake level was higher in 1991 than in 1992 and the lake extended further along the channel. This hydrographic data was used instead of the 1992 data from a distance of 42 km upstream of the dam wall.



	Section 4		Section 5		Section 7
Distance from dam (m)	20,400		37,400		59,400
Volume from dam to Section (cu.m)	-1361758		9,115,723		76,559,417
Volume between Sections (cu.m)		10,477,480		67,443,694	

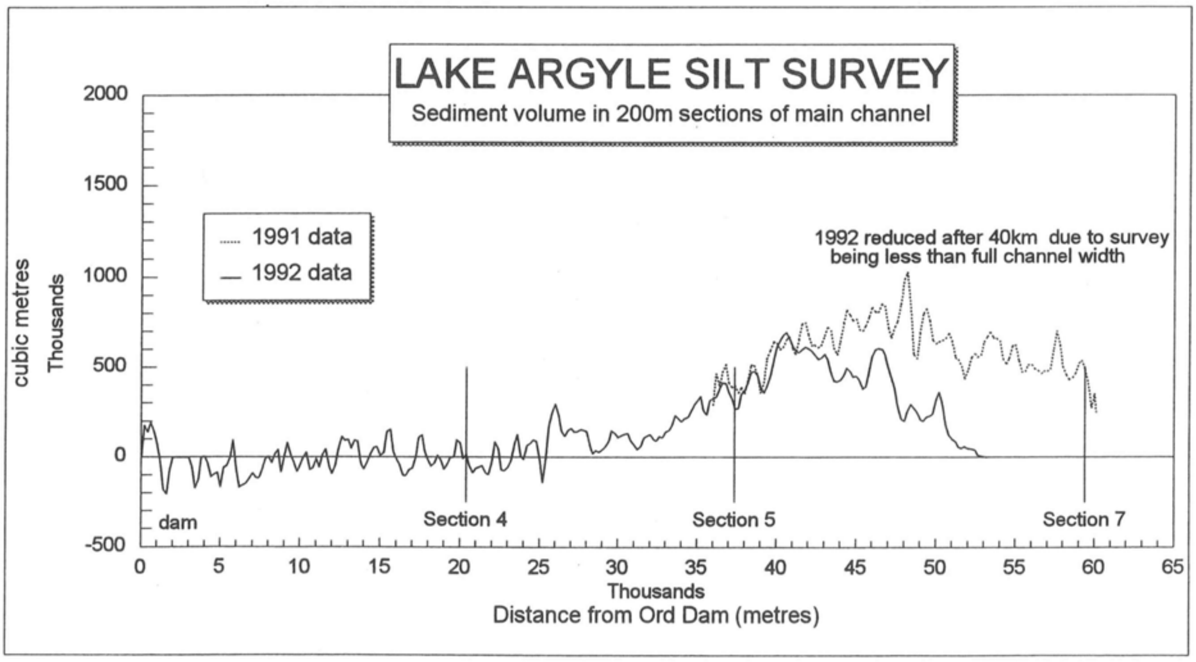


Figure 6 Sediment volumes in main channel for 1991/1992 (Source: Mauger & Hawkins 1994)

From the dam wall to 26 km up the old Ord River channel, sediment deposition was minimal. Most was deposited between 32 km from the wall to where the 1991 survey finished, near Section 7 (Fig. 6).

The estimate of average sediment inflow rate was reported as 19.7 Mm^3/a or 20.1 Mtpa in Mauger & Hawkins (1994). The sediment inflow rate should have been reported as 18.1 Mtpa (Mauger pers. comm. 2007) (Table 5).

Table 5 Sedimentation rate using the 1991 survey

Sediment type	Density (t/m^3)	Volume (Mm^3)	Weight (Mt)	Years of deposition	Volume rate (Mm^3/a)	Sediment inflow rate (Mtpa)
Coarse in channel	1.27	146	185.4	15	9.7	12.4
Soft in lake	0.57	150	85.5	15	10.0	5.7
Total to Section 9		296	271	15	19.7	18.1 (20.1[a])

a Reported as 20.1 in Mauger & Hawkins (1994) but should have been 18.1 (Mauger, pers. comm. 2007)

Mauger and Hawkins used the following assumptions to derive the figures in Table 5. Some of these assumptions have been revised in Section 7.5 using information available since the 2006 survey. Subsequently the sediment inflow rate has been revised to 12.5 Mtpa (Table ***12***).

- The stretch of channels for the Ord River between Sections 7 and 11 and for the Bow River between the confluence and Section 12 was not surveyed for sediments as the low lake level prevented access by boat. The total volume of sediments for these stretches was estimated using Wark's historical cross sections and the distances along the channel. Mauger recalculated the chainage of the historical cross sections, which reduced the total coarse sediment volume from the dam wall to Section 7 from 161 (Table 4) to 141 Mm^3. The coarse sediment volume for the missing channel reaches was estimated to be the total coarse sediment to Sections 11 and 12: 210 Mm^3 (Table 4) minus the coarse sediment volume to Section 7 (141 Mm^3). This equated to 69 Mm^3. This did not take into account the new survey in May 1991 for Section 11.
- The volume of coarse sediment in the channel for the stretch from the dam wall to Section 7 was surveyed in 1991/92 to be 76.6 Mm^3 (Fig. 6) and was assumed to have accumulated between the flow years 1971–85.
- The soft sediments in the lake have the same rates of deposition between 1971–87 and 1988–91.
- The number of years used for Mauger and Hawkins' rate calculations was 15 (Oct. 1971 – Sept. 1987), even though the volume was accumulated over 21 years (Oct. 1971 – Sept. 1992). Mauger and Hawkins reasoned this because historical cross sections 4 and 7 (Fig. 8 in Mauger & Hawkins 1994) indicated there was no significant sediment accumulation between the flow years 1986 and 1991. Section 5 was seen as unreliable since variations in bank slopes suggested that the various surveys were on slightly different alignments. Also, the volume of coarse sediments between Sections 5 and 7 from the 1991/92 echo-sounding was close to Wark's estimate.

5.5 Sources of the sediment in the catchment

The soils and landforms of the Lake Argyle catchment correlate closely with the major rock groups (Fig. 7). Most of the sediment is sourced east of the Halls Creek fault from the Cambrian sediments on the Hardman, Rosewood and Argyle Synclines. The landforms on these synclines are undulating plains, cuestas and strike ridges. The soils are calcareous loams on slopes with deep loams and clays on lower slopes and plains. The rocks are Cambrian limestone, siltstone, sandstone and mudstone. Some of the Argyle Synclines are submerged by the lake. The upper reaches of the Bow and Ord rivers pass through the Rosewood Syncline.

Stream gravel rock types were examined and isotopes of strontium (Sr) and neodymium (Nr) were used to trace the source of sediments in the Upper Ord catchment. The Sr isotopes were of limited value. Mineral particle magnetic tracing was used to estimate the tributary channel contributions to the Ord River. The uranium (U) and thorium (Th) decay chain traces were used to try and estimate the tributary contributions, but were found to be of limited use in this study.

Wasson et al. (1994) estimated the sediment yields for the Ord River and its major tributaries (Table 6). They assumed Wark's (1987) estimated value of reservoir sediment of 23.5 Mtpa when they calculated the mean annual sediment yields for the Ord River. They also used Kata's (1978) measured suspended and calculated bed load for some of the rivers. The standard deviation of estimates was high but gave a picture of the sources of sediment to Lake Argyle. The data from the Lake Argyle catchment shows an increasing rate of sediment yield with catchment area. Wasson et al. (1994) speculated that the tendency for specific yield to increase is probably a result of the presence, in the larger subcatchments of an area, of Cambrian Sediments in their downstream parts. These soils and rocks increase the sediment load of the streams at a rate which is greater than the rate of storage of sediment in floodplains.

Wasson et al. made the following conclusions from their and other studies:

- The Bow, Negri, Panton rivers and Osmond and Spring creeks make the largest relative sediment contributions to the Ord River.
- ~60% of the sediment in Lake Argyle comes from the Hardman Syncline, and most of this fraction comes from the Cambrian Sediments rather than the Antrim Volcanics.
- About 34% of the sediment in the lake comes from the area between the Negri River and the lake.
- 6% of the sediment in the lake comes from the Precambrian rocks, most of which lie west of the Halls Creek Fault.
- 90% of the all the sediment comes from subsurface soils, and most of this fraction comes from channel and gully erosion. A smaller proportion of this would come from erosion of big channels like the Ord River.
- 10% of the sediment comes from sheet erosion of the surface soils.

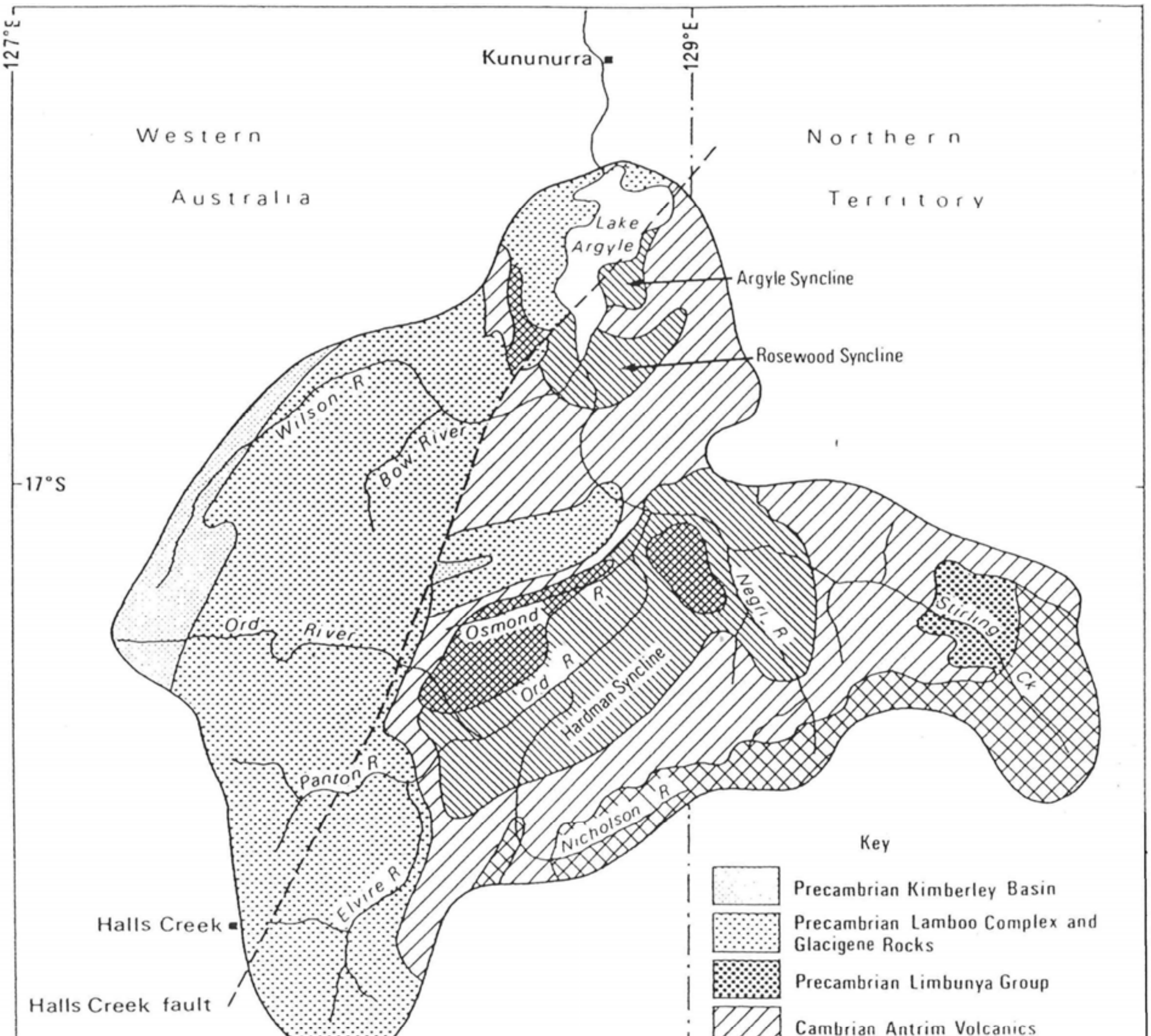


Figure 7 Major rock groups in the Lake Argyle catchment

Source: Wasson et al. (1994)

Table 6 Measured and calculated mean annual sediments yields for the Ord River and major tributaries

Location on Ord	Catchment area on Ord (km^2)	Tributary catchment area (km^2)	Sediment yield in Ord River (Mtpa)	Annual Ord catchment erosion rate (t/km^2)	Tributary load at junction (Mtpa)	Annual tributary erosion rate (t/km^2)
Panton junction	9000		0.9 [c]	100 [c]		
Nicholson junction	17 542	2461	4.5 [c]	256 [c]	0.32[e] ± 0.95	130 [e] ± 386
Old Homestead	19 600		10.69 ± 3.57[b]	545 [b]		
Osmond junction	22 200	1400	13.8 [c]	622 [c]	8.56 [e] ± 9.4	1214 [e] ± 6114
Negri junction	32 100	7775	15.5 [c]	483 [c]	0.71[b] ± 0.29 or 3.1 [e] ± 0.8	91[b] ± 37 or 399 [e] ± 103
Spring Creek junction	33 000	250	17.0 [c]	515 [c]	3.06[e] ± 1.36	12 240[e] ± 5540
Wilson-Bow junction	40 784	6300	23.0 [c]	564 [c]	≤0.90 [d] ± 0.17 or ≤4.6[e]	≤143 [d] ± 111 or ≤730[e]
Lake Argyle	46 100	1818	23.49 ± 4.70 [a]	510 [a]		

a calculated from Wark (1987)

b measured suspended load and calculated bedload before dam construction from Kata (1978)

c calculated by Wasson et al (1994) assuming Wark's estimate of sediment to Lake Argyle is correct

d survey by WAWA and Wasson et al. (1994)

e estimated from magnetic tracers

5.6 Controls on gully erosion in the upper Ord River catchment

Callow (2000) identified the controls on gully erosion defined by the geomorphological and hydroclimatological setting of the upper Ord River catchment. Eight gully network study sites were selected on the floodplain around the Old Ord River Homestead (Fig. 2). Processes responsible for initiating and expanding gully networks and behaviour of materials were investigated. Field investigations of the gully networks were also performed during June and July 2000. Stratigraphic logs, material size distributions, geotechnical properties of materials, infiltration rates, water repellence of microbiotic crusts, precipitation and runoff were taken and investigated. A piezometer network was also used at Hackers Gully to help understand the processes of subsurface flow on erosion in the gullies. Four island study sites were selected within the Ord/Panton Island area.

Some of Callow's conclusions are:

- The processes of gully erosion are linked to material strength and behaviour. On the stronger limestone and unweathered shale materials, overland flow is the sole process of erosion. Upon wetting, the weaker alluvial and weathered shale units experience a loss in strength, leaving them prone to erosion by overland flow, subsurface flow and mass failure. Vegetation and microbiotic crusts help provide strength when wet, helping to reduce the high erosion rates.
- The hydroclimatology exerts a control on erosion. Long duration rainfall at intensities greater than the infiltration capacity of the soil generates a large erosive potential. Drought periods and fire remove the vegetation cover. If these periods are followed by intense rainfall, it provides a mechanism for high natural erosion rates in the catchment.
- The geomorphological setting is conductive to high runoff and erosion. Remnant limestone ridges and the underlying shale materials generate high runoff coefficients. This water runs to the plains that have low slope angles. This landscape is susceptible to erosion with evidence from the wide intermontane outwash plains that developed from weathered silty shale material.
- Gully erosion in the catchment is a natural phenomenon. There is historical, stratigraphic and erosive evidence to support this. A significant part of many present gully networks is pre-European.
- There is evidence that there was a period of accelerated erosion since grazing occurred in the catchment. A reduction in vegetation resulted from overgrazing and the natural variability of the hydroclimatology regime. Revegetation in the Ord River Regeneration Reserve is a minimisation policy to try and limit the erosion to natural levels.

5.7 Causes and nature of river channel changes

It is worth summarising the Sandercock (2003) findings since he was investigating the causes and nature of river channel changes in the Upper Ord River catchment. He investigated the effects of land use changes and reservoir construction on the sediment transport regime of the Ord River. He did this by surveying sections along the channel in study regions and analysing the sediment composition at exposed points along the cross section. He also mapped the channel morphology and looked at a sequence of aerial photographs from the past.

Four study regions located in the Upper Ord River catchment were selected (Fig. 2). Study area 1, just downstream of the confluence of the Panton and Ord rivers, is in the ORRR, near Old Turner Station. Study area 2 is located centrally in the severely degraded area in the ORRR and contains the junction of Forest Creek and the Ord River and Old Ord River Homestead. Study area 3 is in the northern section of the ORRR, near where the Negri River meets the Ord River. Study area 4 includes the Ord River channel reaches immediately upstream of Lake Argyle.

Study area 1

- Most of the gravel sediments are sourced from the Panton River.
- In the upper parts of the catchment, there is a high rate of sediment supply to the channel reaches.
- The Ord/Panton reaches tend to be more sensitive to changes in runoff/stream power than other parts of the river system.
- The higher rate of runoff in the last 50 years and the increased stream power of flood events have resulted in the reworking of in-channel sediment storages and a reduced potential for the sediments to be stored in the channel.
- Considerable losses in riparian vegetation and channel morphological changes had already occurred in the Panton and Ord River reaches downstream of the confluence by 1928.

Study areas 2 & 3

- The dimensions of the terraces and barforms in the studied reaches have not changed significantly in the last 50 years.
- There is a lack of bedload sediments downstream of the junction of the Panton and Ord rivers.
- Gravel and sand bedload sediment is stored in large gravel barforms with gravel pavement/armour layers. These barforms are insensitive to any increased runoff that may have occurred in the last 120 years.
- A close succession of a series of flood events is needed to disrupt the structure of the gravel pavement/armour layers. Once the structure has been disturbed, subsequent flow can rework sediments stored in these bars.
- Some gullies found in the severely degraded region in the plains have dissected into underlying bedrock and pedocalcic profiles. A long history of erosion is required for this to occur. Sandercock argued that gullies in this region were already present prior to European settlement and cattle grazing.
- The Ord River floodplain was exposed in a bank of Forest Creek. Charcoal material sampled towards the base of the section (10.5 m below the floodplain surface) had a date of 827 +/- 48 years (Fig. 4.28, Sandercock 2003). The charcoal was embedded in horizontal fine sand and silt beds. If the assumption is made that overbank deposition rates are coupled with rates of erosion, then this provides evidence that high rates of erosion appear to have been the characteristic of the upper Ord River catchment over the past 800 years.
- Sandercock anticipated that, even under natural conditions, the occurrence of drought periods and subsequent reductions in vegetation cover followed by intense rainfall events would have been sufficient to maintain high erosion rates in the plains and floodplains of the upper Ord River catchment.

Study area 4 (upper reaches of Lake Argyle)

- The construction of the dam has caused sand and silt/clay sediments to aggrade in the channel and over the large barforms and lower inset terraces present before the dam's construction.
- The floodplains and large barforms in the Upper Ord catchment are the source of eroded and mobilised sediments.
- The rapidly fluctuating base level of the lake is influencing the deposition of sediment in the upper reaches. Higher lake levels cause the sediment to be deposited further upstream than if the lake had been at a lower level prior to the flood.
- Recently deposited sediments at the channel margins may be reworked through processes of flood scour or gullying. In the latter case, as the water levels fall, shear failure may occur at the channel margins. Gully headcuts may advance through the subsurface flow leading to further erosion of sediments stored on the terraces.
- The establishment of riparian vegetation at the channel margins and encroachment of vegetation over the barforms has enhanced in-channel and storage deposition.
- The continued high rates of deposition in the channel reaches upstream of Lake Argyle indicate there has not been a reduction in rates of fine suspended sediments from the Upper Ord in the past 30 years.
- The progressive filling with sediments reduces channel capacity. In the future, dynamic interactions are anticipated between fluctuating water levels, vegetation growth and stabilisation of sediment storages and later reworking by higher magnitude floods in the channel reaches.

5.8 Field inspection of the Ord River Regeneration Reserve

In August 2002 the Department of Agriculture did a field inspection of 32 sites of the Ord River Regeneration Reserve (Fig. 2) and found dense ground cover of introduced and native perennial grasses over large portions of the Reserve (Payne et al. 2004). Active soil erosion was rarely seen during the inspection but occasionally occurred on areas up to a few hundred metres in extent. Five sites were assessed as having slight or minor erosion. Twenty-seven sites had stable soil surfaces. The increased rainfall in the last decade has contributed to the dominance of long-lived perennial species. A return to average rainfall patterns is not likely to reverse the condition of the soils and vegetation in the Reserve (Payne et al. 2004). An example of a gully network is shown in Figure 8.

Figure 8 Gully network on the floodplains of the Upper Ord River catchment at the time of the 1991 survey

Photo: Geoff Mauger

6 Bathymetric and land surveys of 2006

The major component of this project was the completion of a bathymetric survey of the old Ord River channel beneath Lake Argyle and in the upper reaches of the Ord and Bow rivers. This type of surveying is a specialised service with a limited number of operators Australia-wide. The remoteness of Lake Argyle and the lack of services in the area increased the difficultly in finding contractors willing to undertake the project.

The successful tenderer was Whelans in partnership with 3D-Marine Mapping. Whelans conducted the land surveying component and 3D-Marine Mapping undertook the bathymetric survey.

The decision to select the Whelans and 3D-Marine Mapping partnership was influenced by 3D- Marine Mapping's ability to use a GeoSwath 32 system. Whelans' location, local knowledge and experience in the area were also seen as an advantage. The GeoSwath System provided complete coverage of the channel floor over an area up to 12 times the depth of water. This resulted in a complete coverage of the entire length of the Ord channel. This was a great improvement on the 1991 survey where single lines were surveyed across the channel at 200-m spacing (Mauger & Hawkins 1994) and the gap between the cross sections interpolated. This method, the best available at the time, is suitable in areas where there is a gradual change in the bed floor elevation but may lose details in areas with sharp elevation changes on the bed floor or isolated features.

Whelans and 3D-Marine Mapping commenced work at Lake Argyle on 25 October 2006 and finished the survey on 31 October 2006 (Fig. 9). 3D-Marine Mapping used a local 8-m aluminium commercial fishing vessel to which they mounted a variety of instruments (GeoAcoustics GeoSwath Plus sounding system, TSS DMS 02 motion sensor, SG Brown Meridian gyrocompass, Trimble Ag332 differential GPS receiver, Trimble HydroPro navigation system).

Run lines were based on the centre lines of the old Ord channel, with each run line spaced at 50 to 80 m (depending on water depth) to provide 100% total bottom coverage of the old river beds. Run lines continued up the Ord and Bow rivers as far as water depth allowed.

Whelans were required to establish a control network and conduct cross-section surveys at the banks of nine key locations on the Ord and Bow rivers at the southern end of the lake (Sections 7, 15, 16, 14, 9 Ord River, 9 Bow River, 11, 12 and 13 on Fig. 1). The surveyors employed a local tour boat operator to transport them to and from the survey areas.

Full reports on surveyor methods, equipment and specifications are in the survey reports: Albers (2006) in Appendix A and Lange (2007) in Appendix B.

Figure 9 (a) Survey boat with hydrographic survey equipment (b) Land survey of historical cross section 7, facing north, taken on 26 October 2006

6.1 Lake level anomaly

The 2006 survey had two tide recorders 60 km apart to measure the water levels in Lake Argyle. These levels were measured to work out the elevations of the sounded depths which were referenced from the surface of the lake (Fig. 10). There was a water level anomaly of 300 mm between the two recorders. Whelans' GPS baselines and data were rechecked and reprocessed and produced identical results and miscloses the second time (Appendix A).

There was a further check on 16 November 2007 when Duncan Palmer of the Department of Water asked the Water Corporation to read the boat ramp gauge board, water level = 91.02 m. At about the same time on the same day Whelans took a spirit level reading from Knoll, a primary control point, to the nearby water level 100 m away. The water level measured was 90.805 m, a difference of 215 mm. Knoll (previously a coordinated photo control point at Flying Fox Knoll) was situated about 40 km upstream of the dam wall and about 20 km from the Ord/Bow rivers junction. This 215 mm difference over 40 km is the same proportion as the 321 mm over about 60 km at the Ord gauge board.

It is recommended that the lake level anomaly be investigated before any future bathymetric surveys of Lake Argyle. The geodetic network should be investigated to see if it has been adjusted to take account of any possible seismic movements. The area surveyed spans a couple of seismic zones, the southern part of which is believed to be moving.

Figure 10 Lake Argyle near the Ord Dam, 26 October 2006

3D-Marine Mapping's processing program could not interpolate the lake level between tide/level gauge positions. It used whatever tide gauge was nearest. To take account of the different lake level at the tide gauges, a further three interpolated 'pretend' gauges, at equispaced distances, were adopted to reduce potential steps in the processed depths to less than 0.1 m.

6.2 2005 sediment surface

A Digital Elevation Model (DEM) of the 2005 sediment surface derived from the October 2006 hydrographic survey data was supplied by 3D-Marine Mapping. The date 2005 is used for the surface because it is close to the end of the 2005/06 flow year (October 2005–September 2006). This DEM was used to create 3D images of the 2005 sediment surface and provided the information for subsequent volume calculations.

The 2005 DEM extends from the Ord Dam wall in the north to beyond the southern shore of Lake Argyle. It includes 19 km of the current Ord River upstream of the confluence of the Ord and Bow rivers (Fig. 1). Combined with the old Ord River channel beneath the lake, a total of 84 km of the Ord River was captured. The DEM also covered 8 km of the Bow River upstream of the confluence.

The raw survey data was processed using GeoAcoustics swath processing software which converted the depth datum to water level and compensated for both the motion of the vessel/tranducers and variations in the speed of sound over the water column. Various filters were used to remove noise from the raw data and the filtered set was gridded using mean depths based on 5-m cells.

The sounding system used during the survey had a frequency of 250 kHz, which meant the depth to sediment was measured to the top of the soft sediment layer. Elevations were reduced from water levels logged at the 'Boat Ramp' and 'Ord' water-level boards. Elevation accuracy depends on the depth of water above the bed of the channel — the deeper the water in the lake, the less accurate the sediment elevation (Table 7). The distance measurements start from the dam wall and continue south along the Ord River channel.

Table 7 Accuracy of elevation of the 2005 sediment surface

Distance along channel surveyed (km)	Elevation of top of sediment (m AHD)	Accuracy (m)
< 34	< 67	± 0.3
34–44	67–80	± 0.2
> 44	>80	± 0.1

7 Current sediment analysis

7.1 Sediment depth and volume data in 2005

An average depth and volume of sediment in the Ord River channel for each kilometre section from the dam to 85 km was calculated using Terramodel software by 3D-Marine Mapping. Details of this process can be found in Appendix C.3.

The 1991 survey finished at distance 59.4 km, near Section 7. The October 2006 (near the end of the flow year 2005) survey went further — to 85 km along the Ord channel and 8 km along the Bow channel. Sediment deposition and volumes were averaged for 1 km sections and then summed for larger distances (Tables 8 & 9). Some of the sediment was estimated upstream of the survey by using information from Sections 12 and 13.

The Ord River channel and its sediment deposition averaged over 1 km sections are shown in Figure 11. Since the average sediment depth is averaged across the channel and along 1 km sections it is substantially less than the channel centre depth at each 1 km section.

Note the full supply levels of the reservoir before and after the spillway was raised (Fig. 11). Most of the sediment is deposited in the vicinity of where these levels meet the top of the channel. A delta is forming underwater in this vicinity. Some more sediment is being deposited upstream of Section 9, past the peak flood level of 99.25 m AHD recorded in February 2001. See Section 7.2 for an explanation of why sediment is accumulating past Section 9. It is due to the backwater effects of the reservoir.

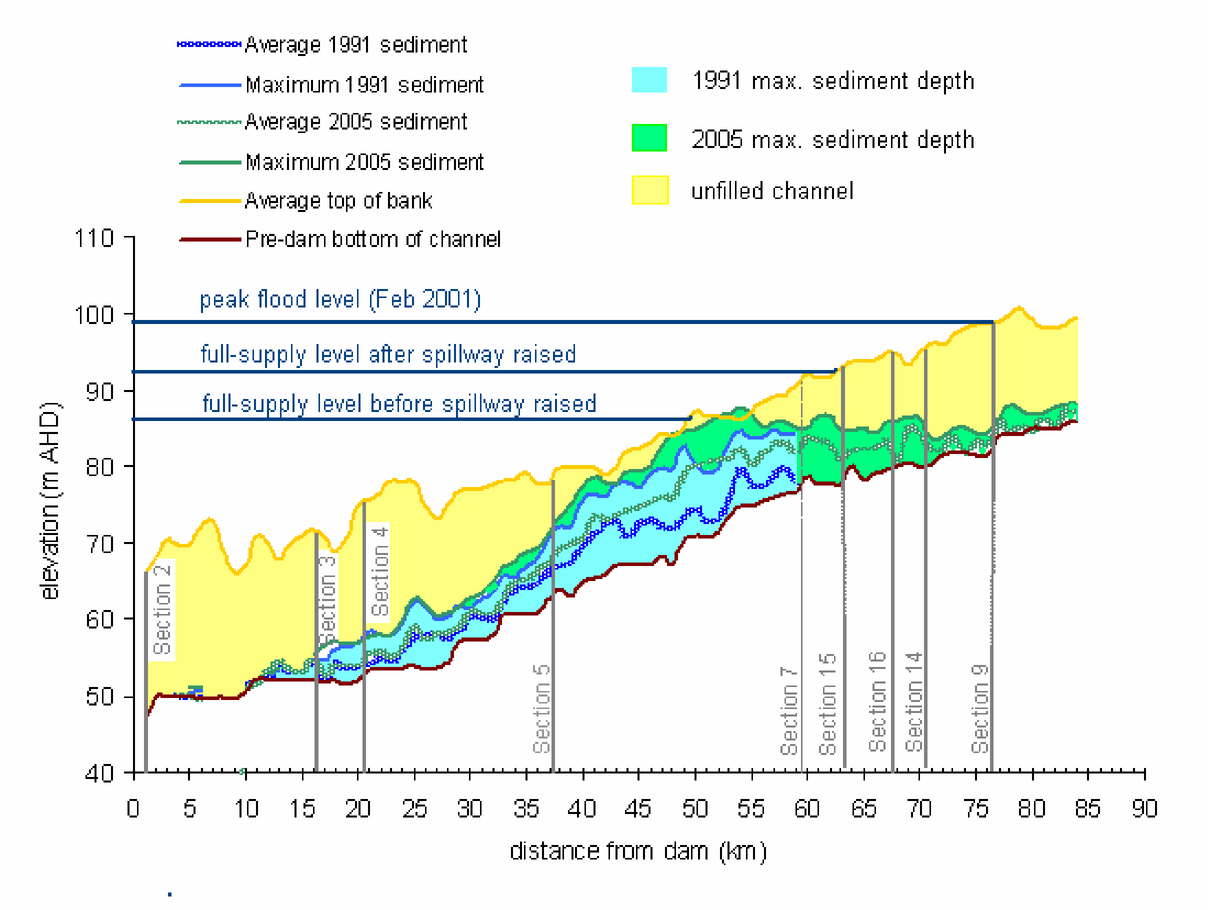


Figure 11 Sediment deposition along the Ord River channel

The channel is nearly full of sediment between 46 and 55 km from the dam wall. At 48 km from the dam the deposition in the thalweg was 18.1 m in 2005 but across the whole channel the average deposition was 8.2 m.

Most of the sediment is located between distances 37–53 km (Fig. 11; Tables 8, 9 & 10) where the average sediment depth across the channel averages 8.1 m, with 3.7 m deposited since 1991. At distance 49 km, the average depth of the channel was largest at 10.2 m, with an average depth of 4.5 m in 1991. Another region with deep deposits was between distances 53–59 km where the average sediment depth across the whole channel is 6.8 m, with 3.1 m deposited since 1991.

Table 8 Sediment deposited in the Ord River channel up to 1991

Section of channel (km from dam wall)	Volume deposited (Mm^3)	Weight of sediment (Mt)	Av. deposition height (m)
10–20 (near Section 4)	7.9	10.0	1.5
20–37 (near Section 5)	27.5	35.0	3.2
37–53	42.9	54.5	4.4
53–59 (near Section 7)	12.5	15.9	3.1
Up to Section 7	90.9	115.4	3.3

Average ‘deposition’ values, particularly in the first 10–12 km of the river from the dam fluctuated around zero. It was assumed that there was next to no real deposition or erosion in this section of the channel as the volumes either way generated were due to mostly poor positioning of the 1968 and 1991/1992 DEMs compared to the 2005 DEM. This combined with steeper slopes can result in large volume differences either way but generally cancel out when calculated as an average deposition. After about the 12 km mark, the vertical accumulations were much more in line with the realities of sedimentation. Comparison of the cross sections confirmed this. More details of the errors in this section of channel are detailed in Appendix C.3. Consequently, the average depth of sediment, volume and accumulated volume were not reported for the distances 0–10 km from the dam wall.

Table 9 Sediment deposited in the Ord and Bow rivers up to 2005

Section of Ord River (km from dam wall)	Volume deposited (Mm^3)	Weight of sediment (Mt)	Av. deposition height (m)
10–20 (near Section 4)	9.0	11.4	1.7
20–37 (near Section 5)	34.4	43.7	4.0
37–53	75.5	95.9	8.1
53–59 (near Section 7)	22.5	28.6	6.8
59–68 (near Section 16)	17.1	21.7	3.8
68-77 (near Section 9)	7.9	10.0	2.7
77–87	3.1 [a]	3.9 [a]	1.3[a]
0–Section 7	141.4	179.6	5.3
0–Section 9	166.4	211.3	4.9
Section 7 to Section 11	28.0	35.6	2.9
0–Section 11 Ord River	169.6 [a]	215.4 [a]	4.7 [a]
Section of Bow River (km from Ord and Bow rivers confluence)			
0–8	5.4	6.9	2.7
8–14 (near Section 12)	2.1 [b]	2.6 [b]	1.5 [b]
Up to Section 12 Bow River	7.5 [b]	9.5 [b]	2.2 [b]
Total Ord and Bow rivers	177.0 [ab]	224.8 [ab]	4.5 [ab]

a Sediment upstream of 84.4 km along the Ord River was estimated

b Sediment upstream of 7.9 km along the Bow River was estimated

The errors in bank alignment improved after 10 km but the alignment of the banks could still be out by 30 m in the horizontal. However, the channel width varied from 300 to 500 m. Often a cut on one side was balanced by a fill on the other and the errors could be reduced by this balancing effect. An upset in balance could be caused if the height of the channels on each side varied significantly. After distance 38 km, a better quality 1968 elevation surface was used for the pre-dam surface and the accuracy improved.

Table 10 Sediment deposited in the Ord River channel between 1991 and 2005

Section of channel (km from dam wall)	Volume deposited (Mm^3)	Weight of sediment (Mt)	Av. deposition height (m)
10–20 (near Section 4)	1.1	1.4	0.2
20–37 (near Section 5)	6.9	8.7	0.8
37–53	32.6	41.4	3.7
53–59 (near Section 7)	10.0	12.7	3.7
Up to Section 7	50.6	64.6	2.0

The sediment deposition for the flow year 2005 was summed to Section 11 in the Ord River and to Section 12 in the Bow River. The edge of the reservoir reached Section 9 during a flood in 2001 (Fig. 11). Sediment accumulated past Section 9 does not affect most of the storage capacity of the lake but might affect how the water enters the lake in the future. The sediment volumes accumulated since the dam's construction for each period up to 1991 and 2005 were also calculated (Fig. 12; Tables 7 & 9).

The sediment upstream of 84.4 km along the Ord River and 7.9 km along the Bow River was estimated using the key section details (Table 11) and the length of the channel.

The accumulated sediment in the Ord River is shown in Figure 13. Most of the net accumulation levels out near Section 9.

Only the parts of the channel accessible by boat were surveyed. Portions of the channel missed were near distances 52, 55–57, 60 , 63–67 km. To reduce the errors when calculating volumes, the 2005 sediment surface was extended to the edges of the channel bank.

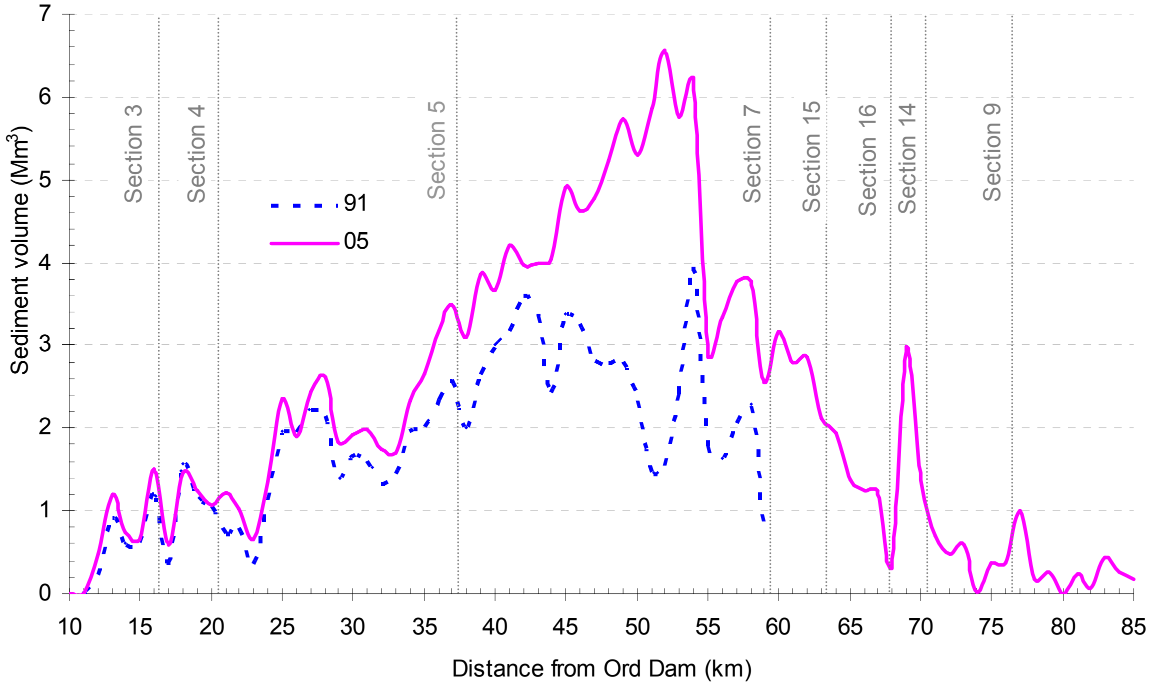


Figure 12 Sediment volume in 1 km sections along the Ord River channel

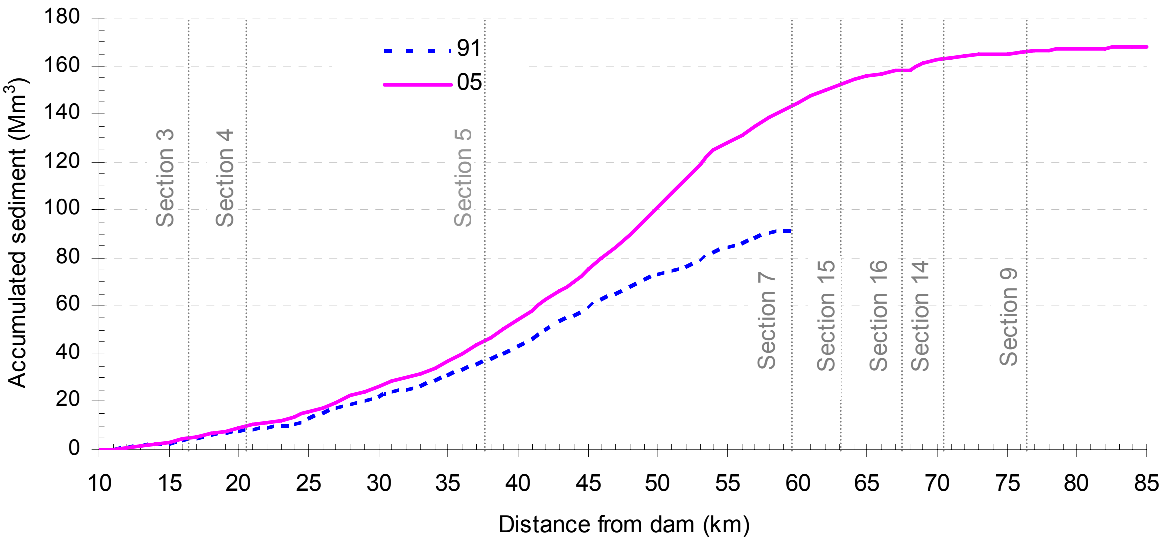


Figure 13 Accumulated sediment volume along the Ord River channel

Figure 14 Sediment at Bow River, 8 km from the confluence of the Bow and Ord rivers

Section 9 intersects the Bow River at 10.8 km from the confluence of the Bow and Ord rivers. Some sediment was not captured for the final 2.8 km of the Bow River. The boat could only reach to 8 km from the confluence at the time of the 2005 hydrographic survey (Fig. 14). The flood waters that enter the lake must be very high and turbulent. See the evidence in Figure 15. Note the flood debris 6 m high in the trees and the fallen tree in the photograph taken on 26 October 2006.

Figure 15 Evidence of the power of the approximate 6-m flood waters in the Bow River 8 km from the confluence of the Ord and Bow rivers

7.2 Backwater effects of the reservoir

The construction of the Ord River Dam has led to significant morphological changes in the channel reaches upstream of the lake. These reaches are affected by backwater inundation from the lake and accumulating sediments consisting of fine to coarse sand. When flood waters enter these reaches filled with water from the backwater effects of the lake, the water velocity drops. Some sediment is deposited over large barforms and inset terraces that existed before the dam was constructed. Riparian vegetation growing on these sediment bars and terraces has helped this process (Sandercock 2003).

The lake level, which determines how far upstream the channel reaches of the Ord and Bow rivers are inundated, fluctuates markedly over time and leads to the retraction and extension of water in the channels. For example, a decrease in the lake level from 88 to 84 m AHD will cause water upstream to recede about 28 km (from Section 11 to Section 7).

Since the spillway was raised in 1996, the average lake level has risen to 92.2 m AHD (for the period October 1999 to September 2006). The average lake level before the spillway was raised was 88.34 m AHD (Sandercock 2003). The lake levels for the years 1999–2005 are shown in Figure 16.

Low gradients and the large hydraulic capacity of the channel permit the backwater effects of Lake Argyle to extend as far back as around 28.5 km upstream of the junction of the Ord and Bow rivers, or 93.5 km from the dam wall when the lake is full, at a level of 92.23 m AHD (Sandercock 2003).

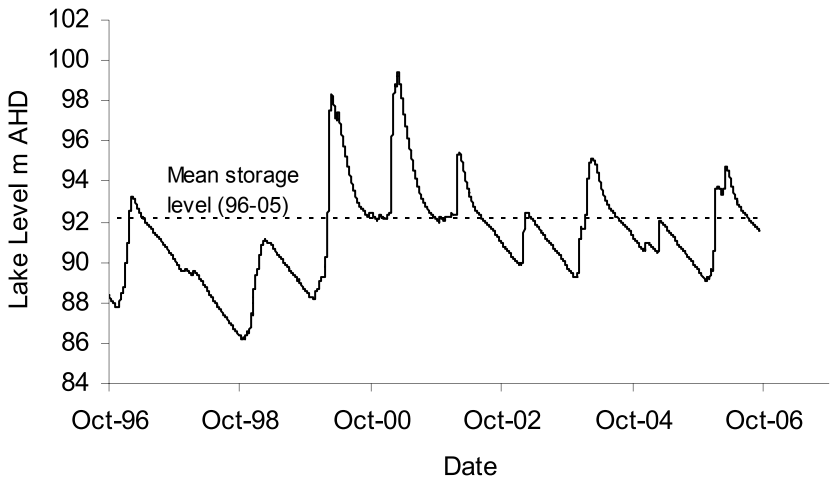


Figure 16 Fluctuations in the Lake Argyle water level

7.3 Historical cross sections

The current and previous surveys of most of the historical cross sections near the channel are shown in Figures 21–26 and 28–32 (Appendix E.1). Sediment areas and average depths across the channel were calculated between the area limits shown in each diagram of the cross sections (Table 11). Section 13 Bow River (Fig. 32) must have had different alignments for each year surveyed, so areas of sedimentation could not be calculated for this section.

Table 11 Sediment areas, average depth deposited and simple volume change for each cross section

Historical cross section	Distance (km)	Channel width (m)	1986		1991		2001		2006	
			A (m^2)	S (m)	A (m^2)	S (m)	A (m^2)	S (m)	A (m^2)	S (m)
2	1.1 [a]	366	296	0.8	665	1.8			731	2.0
3	16.4 [a]	582	718	1.2	914	1.6			1328	2.3
4	20.5 [a]	300	772	2.6	1070	3.6			1264	4.2
5	37.5 [a]	385	977	2.5	2387	6.2			2995	7.8
7	59.5 [a]	550	2674	4.9	2301	4.2			3310	6.0
15	63.3 [a]	620	_	_	_	_	3313	5.3	2293	3.7
16	67.8 [a]	512	_	_	_	_	1557	3.0	822	1.6
14	70.6 [a]	447	_	_	_	_	2279	5.1	1637	3.7
9 (Ord R)	76.5 [a]	633	2132	3.4	2167	3.4	2554	4.0	2753	4.3
11 (Ord R)	87.0 [a]	346	–	–	248	0.7	468	1.4	–	1.6 [c]
9 (Bow R)	10.8 [b]	285	154	0.8	202	1.1	–	–	300 [d]	1.5 [d]
12 (Bow R)	13.9 [b]	170	57	0.3	78	0.5	–	–	186	1.1

A is the cross sectional area
S is the average depth of sediment across the whole channel
a Distance from the dam wall along the Ord River
b Distance from the confluence of the Bow and Ord rivers along the Bow River
c Estimated by adding 20% to the 2001 depth
d Estimated by closest 1 km cross section (8 km)

This average depth data was superimposed on the estimated average depth for 1 km sections calculated by 3D-Marine Mapping in Figure 17. The sediment depths at the historical cross sections did not match the average sediment depths calculated from the 1991 and 2005 survey DEMs. This is expected since the survey average depths were calculated over 1 km sections of channel. The channel width also varies over the length of the river and the depth of sediment would be influenced by the width of the channel, as well as other factors. The 1986 survey at historical cross section 5 (37.5 km from the dam wall) was most likely on a different alignment to the other surveys (Fig. 22).

The 1991 survey finished near Section 7 so the sediment volume was not captured between Sections 7 and 11 that year. The average depths of sediment across the channel at cross section 7 were 4.2 m in 1991 and 6.0 m in 2006 respectively. For cross section 9 the average depths of sediment were 3.4 m in 1991 and 4.3 m in 2006.

Using the depths measured at historical cross sections 7 and 9 in 1991 and 2006, the missing volume of sediment deposited between these sections during 1970–91 is assumed to be proportional to the areas or depths at the cross sections. The depth and area difference ratios (1970–91/1970–2006) work out to 73% and 74% respectively. It can be assumed the missing volume accumulated between Sections 7 and 11 in the Ord River and up to Section 12 in the Bow River is 73% of the 2005 volume (28.0 Mm^3 + 7.5 Mm^3) or 26 Mm^3. The estimated volume of coarse sediment deposited in the Ord River channel from the dam wall to Section 11 during 1970–91 is estimated as 91 Mm^3 (Table 8) plus 26 Mm^3 or 117 Mm^3.

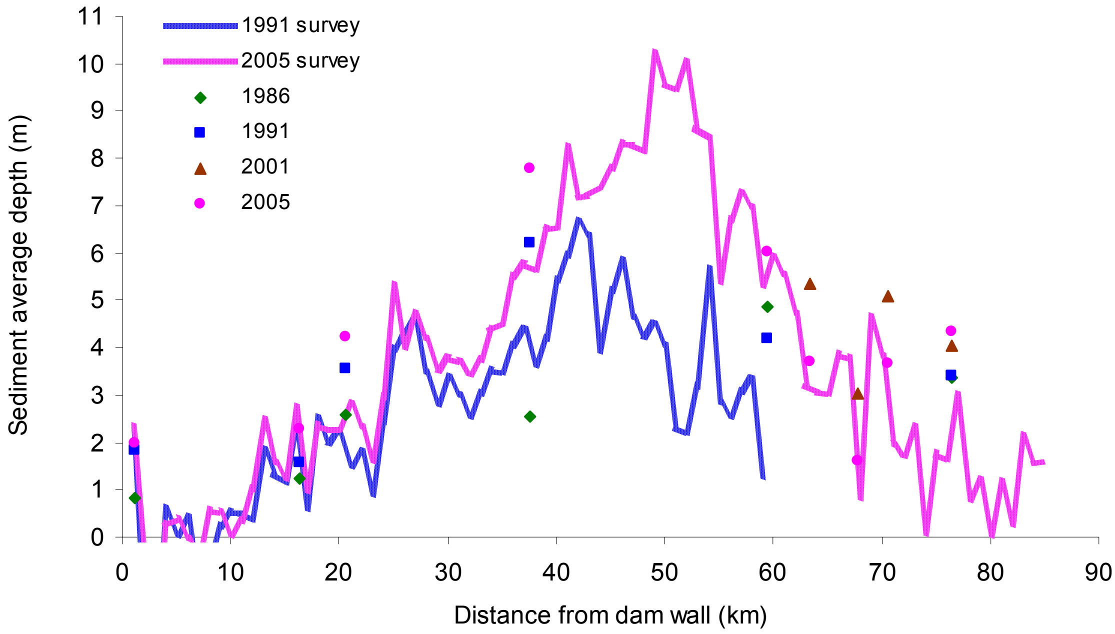


Figure 17 Average sediment depth including historical cross sections

7.4 Inflow data for Lake Argyle

The amount of sediment deposition is very dependent on the cyclonic and monsoonal events in the catchment. Most of the rain in the catchment falls during the wet season in January to March. It is important to take into account the big flow events between surveys when discussing the rate of sediment deposition.

The Water Corporation provided monthly estimates of reservoir inflow for 1971–2005 and these were converted to annual inflow (Fig. 18). Various assumptions were made since not all of the required data for the model was available.

The Water Corporation made the following key assumptions in the current water balance analysis:

- Flow years start in October and end in September; for example, the year 1971 is from October 1971 to September 1972.
- The reservoir's full supply level was changed from 86.25 to 92.23 m AHD in January 1995 when the spillway was raised by about 6 m.
- The spill volumes are not measured directly but estimated using the spillway rating curve.
- Evaporation and rainfall data are from the Kimberley Research Station (002014).
- Releases for the Argyle village and the Argyle Diamond Mine (ADM) are via valves and the values are mostly obtained from past annual reports. This information was not available for 1991–96. Representative values have been used in the calculations for the time being as it is assumed that errors will not cause major differences in the inflow estimates. If these release values become available the inflow estimates can be corrected.
- Before 1972, when the dam was constructed, streamflow was measured at the Coolibah Pocket gauging station (809 302).
- The 'cease to flow' level for the pre-1995 period has been revised to 86.68 m AHD.

The average annual inflow to the Ord River Reservoir during 1971–2005 was 4750 GL. This is 10% higher than the long-term (1911–2005) average inflow estimates of 4300 GL. Although the dam was only completed in November 1971, inflows to Lake Argyle prior to this were estimated using the Water Corporation's water-balance model.

The average flow between hydrographic surveys (1971–91) was 3775 GL and increased to 6210 GL during 1992–2005. The total flows were 79 300 GL and 86 900 GL respectively. Figure 19 highlights the slightly higher monthly high–medium flows observed during 1992–2005 compared to the period 1971–91.

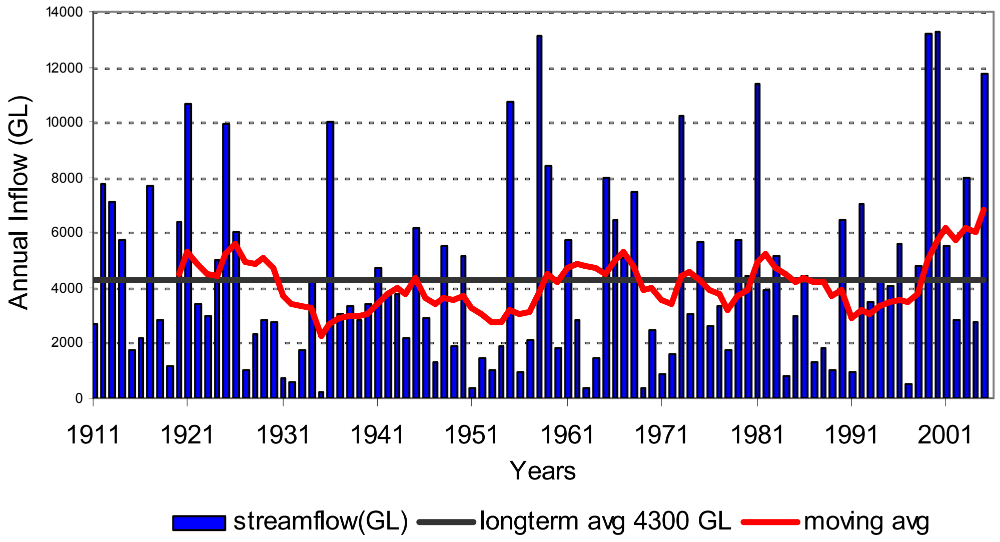


Figure 18 Ord River Dam annual inflow

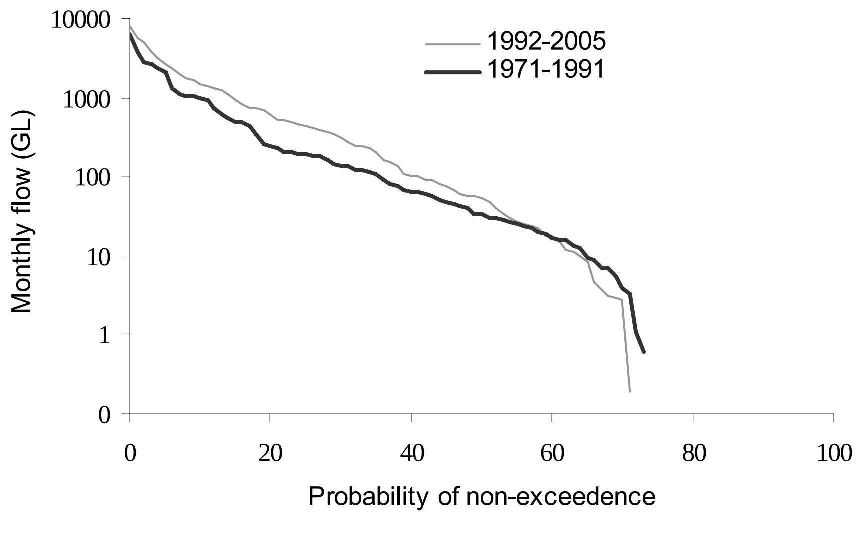


Figure 19 Monthly flow duration curve for the inflow to Lake Argyle

7.5 Revised estimates of average sediment inflow rates

The revised estimated average sediment inflow rate to Lake Argyle for the 35 years since dam construction is 12 Mtpa (Table 14). The average reservoir inflow was 4750 GL for this period, slightly above the long-term average of 4260 GL. The sediment inflow rate for the 14 years since the previous survey was slightly less: 10 Mtpa. The previous sedimentation rate, from dam construction to the first (1991/92) survey, has been revised from 20 (Table 5) to 13 Mtpa (Table 11).

The previous estimate was reported as 20 Mtpa after the 1991 survey (Mauger & Hawkins 1994), when it should have been reported as 18 Mtpa (Section 6.3). A revised rate of 13 Mtpa (Table 12) was estimated for 1971–91, after changing some of the assumptions made by Mauger and Hawkins (1994). The average inflow to the reservoir for this period was below average at 3775 GL.

The revised estimated volume of coarse sediments in the channel between the dam wall and Section 7 for the period 1971–91 is 90.9 Mm^3 (Table 8) compared with 76.6 Mm^3 shown in the Mauger and Hawkins (1994) report (Fig. 6). The pre-dam DEM was adjusted to match the elevations in the 1970 survey. The pre-dam surface was also re-aligned to match the 2005 sediment surface in areas where the channel banks did not align very well.

The estimated volume of coarse sediments deposited in the previously unsurveyed section of the Ord and Bow River channels between Section 7 and Section 11 Ord River and Section 12 Bow River in 1991 was overestimated. The revised estimate for the missing volume of sediment upstream of Section 7 is 26 Mm^3 (Section 7.3). Mauger and Hawkins (1994) used Wark's (1987) 69 Mm^3 estimate of sediment volume for this section of the lake. This figure was estimated by interpolating cross-sectional areas and multiplying the distance between the historical cross sections 7 and 11/12. Since the cross-sectional areas of Sections 7 and 9 were not much changed between 1985/86 and 1991/92, Mauger and Hawkins decided this volume of sediment accumulated before 1985/86 and not much had accumulated after 1985/86.

The estimates of soft sediments are less certain than the estimates of coarse sediments. If it is assumed that the rate for soft sediments estimated between 1971–91 was the same as the rate (10 Mm^3/yr) between 1971–87 by Wark (1994), then the volume ratio of soft to coarse sediments for the period 1971–91 is 1.8:1. During the monitoring of sediments 1962–68, the suspended sediment samples for the Ord showed an approximate particle size distribution of 36% clay, 38% silt and 26% sand (Kata 1978). The soft sediments mainly consist of silt and clay and the coarse sediments consists of sand. When estimating the soft sediments in subsequent periods, it was assumed that the soft:coarse sediment volume ratio was 1.8:1, which is the value for the period 1971–91. Since the estimation of soft sediments is so uncertain, consolidation of the soft sediments was not accounted for.

Mauger and Hawkins (1994) also assumed 15 years (1971–85) for the rate of sediment accumulation calculation. This was a valid assumption in 1994 but seems less so now with more information. It has been revised to 21 years (1971–91). This assumption was made since the surveyed line of cross sections 4 and 7 in 1995/86 and 1991/92 were of similar levels (Figs 18 & 20). Mauger thought Section 5 was unreliable since the variations in bank shapes suggested the surveys were on slightly different alignments (Fig. 19). Most of the sediment was deposited between Sections 4 and 7 (Fig. 12), not at Sections 4 and 7. There were large inflows in January and February 1990, which most likely brought in accumulated sediment noticeable mainly between distances 20 and 55 km.

Table 12 Revised sediment inflow rate for 1971–91

Sediment type	Density (t/m^3)	Volume (Mm^3)	Weight (Mt)	Years for deposition	Volume rate (Mm^3/a)	Sediment inflow rate (Mtpa)
Coarse in channel	1.27	117	149	21	5.6	7.1
Soft in lake	0.57	210	120	21	10.0	5.7
Total		327	269	21	15.6	12.8

Table 13 Sediment inflow rate for 1992–2005

Sediment type	Density (t/m^3)	Volume (Mm^3)	Weight (Mt)	Years for deposition	Volume rate (Mm^3/a)	Sediment inflow rate (Mtpa)
Coarse in channel	1.27	60	76	14	4.3	5.5
Soft in lake	0.57	109	62	14	7.8	4.4
Total		169	138	14	12.1	9.9

Table 14 Sediment inflow rate for 1971–2005

Sediment type	Density (t/m^3)	Volume (Mm^3)	Weight (Mt)	Years for deposition	Volume rate (Mm^3/a)	Sediment inflow rate (Mtpa)
Coarse in channel	1.27	177	225	35	5.0	6.4
Soft in lake	0.57	319	182	35	9.1	5.2
Total		496	407	35	14.1	11.6

Sediment inflow rates between surveys

The sediment inflow rate to Lake Argyle has decreased from 12.8 Mtpa to 9.9 Mtpa for the 1971–91 and 1992–2005 periods between surveys. The average flows for each time period were 3775 GL and 6210 GL respectively. The sediment inflow rate was of similar magnitudes, even though the average flow was higher. This could reflect the improvement in the rehabilitation of the vegetation cover in the ORRR but it is difficult to draw any conclusions from two data points of similar magnitude. Sediment accumulation is not just a function of inflow but can be influenced by rates of sediment supply and the positioning of storms in such a large catchment.

In future surveys it may be possible to estimate, by using aerial photography, a sediment surface for the edges of the channel, bars and terraces not accessible by boat. Creation of the derived DEM should include adjustments for vegetation present on the bars and terraces.

Sandercock showed that periods of erosion contributing large amounts of sediment to the channel reaches also occurred in the past, before European settlement.

7.6 When did most of the sediment accumulate?

Using Kata's relationship, it is possible to estimate the amount of suspended sediment that would have been present in the river flow at the Coolibah Pocket gauging station if the Ord River Dam had not been constructed. This would also assume that the sediments erode at the same rate as they did during the period 1955–68 when the sediment samples were collected. The Coolibah Pocket gauging station was located near the dam site. This relationship makes it possible to estimate the years that contributed the most sediment.

Kata's annual relationship of flow versus sediment (Section 5.2; Fig. 3) was applied to the annual flows for the period 1971–2005 for an indication of the years when most sediment accumulated. An addition of 20% of the suspended sediment load would conservatively estimate the bed sediment transport.

Total sediment loads were calculated between the main hydrographic and historical section sediment surveys (Table 9) using Kata's relationship. A flow year is October to September.

Table 15 Sediment loads using Kata's relationship and hydrographic surveys

	Kata's relationship				Hydrographic surveys	
Period between surveys	Cumulative suspended sediment load (Mt)	Cumulative bed sediment load (Mt)	Cumulative total sediment load (Mt)	Cumulative percentage change of sediment build-up (%)	Cumulative revised sediment loads (Mt)	Cumulative percentage change of sediment build-up (%)
1971–1986	301	60	361	38	N/A	N/A
1987–1991	343	69	411	43	269	66
1992–2005	794	159	952	100	407	100

The total weight of sediment estimated by Kata's relationship, 952 Mt (Table 15) was more than double 407 Mt (Table 14) estimated from the latest survey. Kata's method gave estimates before the dam was built when other methods were not possible. Its disadvantages were that the highest floods could not be sampled for sediment which meant the graph had to be extrapolated to estimate them, it applied at only a couple of points in the river and the sediment flow was not always the same at a given flow rate. The bed load was not directly measured. To take into account the overestimation of sedimentation in Kata's annual relationship the annual sediment values were scaled down so the total sediment values from 1971 to 2005 matched the current survey (407 Mt).

The latest survey results did not include sediment on the bars and inset terraces upstream of the lake edge not covered by water. This would not account for all this difference.

The sedimentation is influenced by the wet years, with nearly 50% of the sediment sourced from only 5 of the 35 years: the 1973, 1981, 1999, 2000 and 2005 high flow events (Fig. 18).

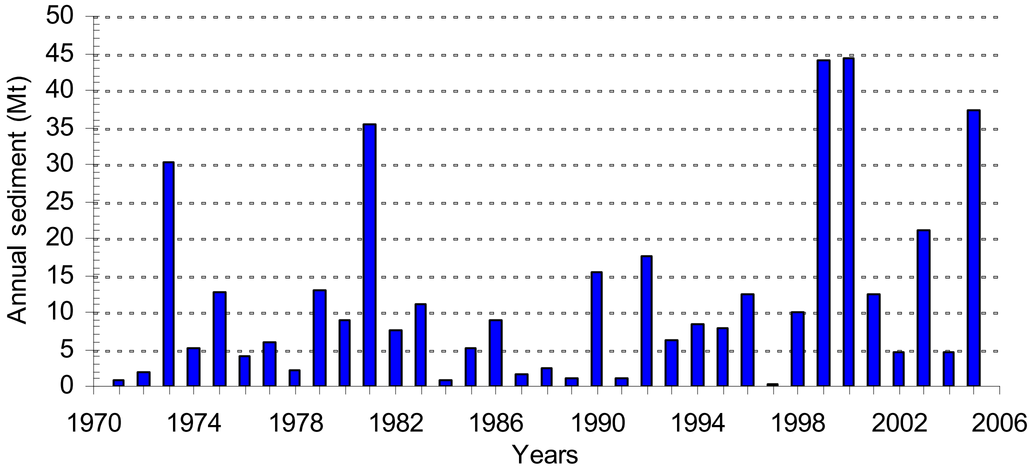


Figure 20 Estimated annual sediment deposition

7.7 Will Lake Argyle fill with sediment?

The capacity of the Ord River Reservoir is 10 763 gigalitres (GL) or 10 763 Mm^3 at full supply level (92.23m AHD). The amount of sediment accumulated in the last 35 years to Section 9 is at least 496 Mm^3 (Table 14). This includes estimates of fine and coarse sediments. The sediment volume amounts to 5% of the reservoir's capacity at full supply level.

The suspended sediments that settle on the lake bed are estimated to account for 65% of this volume. They have a mean depth of 200 mm after 16 years of accumulation. The soft sediments have not been surveyed recently, with the last cores being analysed in 1988.

It is difficult to estimate how long it would take to fill the lake since most coarse sediments are accumulating in the back of the lake (Fig. 11). A delta is forming between distances 37 and 59 km. When the dam is 100 years old (2071) around 15% of Lake Argyle could be filled with sediment.

8 Conclusions & recommendations

8.1 Conclusions

The sediment inflow rate for the last 35 years has been reduced to 12 million tonnes per annum (Mtpa). Previous estimates from 1978 (Kata 1978), 1986 (Wark 1987) and 1991 (Mauger & Hawkins 1994) overestimated the sediment inflow rate.

The estimated average sedimentation rate from dam construction to 1991 is not very different from the rate from 1991 to 2005.

Nearly half of the sediment currently in Lake Argyle was deposited in the 5 years with high flow events.

Currently, the sediment accumulated in the last 35 years has filled 5% of the reservoir volume at full supply level. When the dam is 100 years old (2071) sediment could reduce the capacity of the reservoir by 15%.

The soft sediment accumulated on the lake bed has not been surveyed since 1987 (analysis in 1988). It accounts for 65% of the current sediment volume.

An animation (see DVD) shows the coarse sediment build-up in the Ord and Bow River channels to 1991/92 and 2006.

Most of the sediment in the Ord River channel has accumulated between 25 and 67 km from the dam wall.

The Ord River channel is full or nearly full between 38 and 55 km from the dam wall.

Between 38 and 53 km from the wall, the average depth of sediment deposited in the channel was 4.7 m in 1991 and 8.7 m for the same reach in 2005.

8.2 Recommendations

- A new stage to surface area and volume table needs to be developed for the reservoir to take into account the current sedimentation and used to monitor storage.
- A future survey of the sediments in Lake Argyle should take place around 2021. It is best to pick a time when the lake level is high for the channel survey and low for core sampling of the lake bed.
- The soft sediment on the lake bed accounts for 46% of the total sediment load weight and 65% of the sediment volume in Lake Argyle but has not been measured since 1988. Soft sediment deposition could be measured by sampling and dating long cores to work out if there have been significant changes in sedimentation rates in the past 35 years. The area of the lake bed where it accumulates should also be investigated.

- At least three tide recorders should be tested before any future surveys of the sediment in Lake Argyle commence. They should be spaced so that one is near the dam wall, one in the mid-area and one at the end of the lake. This survey used two tide recorders and found a lake level anomaly that remains unresolved. The bench marks used in this survey should be checked to see if any recent seismic activity was the cause of the lake anomaly.
- Future surveys of the coarse sediment in the lake should be extended beyond where the channels were full or nearly full in 2006. They should be extended from 38 to 55 km from the dam wall. Before the survey commences, the 1986 DEM should be checked to see that it covers enough of the lake bed in this region.
- Photogrammetric mapping from aerial photographs could be used to investigate the amount of sediment accumulated above the water level in the upper reaches of the lake.
- The northern 1968 DEM and orthomosaic generated from 1968 aerial photographs could be ordered from Landgate to cover the old Ord River channel from the dam wall to 38 km. It should also cover a larger proportion of the lake bed where the channel is full and overspilling. This would give a good quality complete consistent pre-dam surface for future surveys and sediment volume estimations. The cost estimate from Landgate in August 2007 was $8000. It would take two months to produce and would require vertical and horizontal control points to be supplied to perform the geo-referencing of the digital surface and orthomosaics.

Appendix A — Whelan Survey Report

Report

to

Department of Water Western Australia

LAKE ARGYLE SEDIMENT SURVEY

CONTROL SURVEY AND LAND CROSS-SECTION COMPONENT

November 2006

TABLE OF CONTENTS

1. INTRODUCTION

In October 2006 Whelans were commissioned by Department of Environment to complete a sediment survey of the old Ord River bed below Lake Argyle. The major component of this survey was a bathymetric survey of long sections over the lake and this work was sub-contracted to 3D Marine Mapping Pty Ltd.
The other survey required was the establishment of a control network, and 9 cross sections of the Ord and Bow Rivers at pre determined locations.
Whelans Kununurra office undertook these surveys during November 2006 at about the same time as the lake bathymetry survey.

2. METHODOLOGY AND EQUIPMENT USED

The only available State Geodetic survey control (SSMs) in the general area, and accessible were PL1 and PL1T, both SSMs on the water tank hill above the boat ramp and near the village. SSM PL1T was also the SSM used to control the previous 1992 sediment survey, and as such it was fundamental to use this mark again. However, as all the cross sections to be surveyed were about 60 – 70 kilometres upstream from Lake Argyle village and only accessible by boat (or helicopter), it was decided to establish a new "primary" control point somewhere upstream and closer to the junction of the Ord and Bow Rivers. The reasons for this were twofold – firstly to establish suitable control coordination much closer to the area of survey, and secondly to enable a check measurement onto some other known control – rather than relying on an unclosed and unchecked spur.

An existing , previously coordinated photo control point at "flying Fox Knoll" (referred to hereafter as KNOLL) was the obvious choice – it was about 40 kilometres upstream from PL1T, about 20 kilometres from the Ord/Bow junction, was accessible by boat, and was previously coordinated from another SSM network near Argyle Diamond Mine. Its position was known to within 30mm XYZ and had itself been established from 2 known marks (i.e. check redundancy).

The datums used for the entire surveys and works are Horizontal – GDA94 (MGA94), and vertical – AHD – all based on GPS observations.

Two Trimble 4700 series survey accuracy receivers were set up on SSMs PL1T and LIS146 and left to log data all day. Meantime 1 other Trimble 4700 receiver was taken to KNOLL and multiple baselines were observed between PL1T, LIS146 and KNOLL. The resultant closures from PL1T were well within acceptable limits, about 40mm XYZ (over a distance about 40 km). Vertical closure from LIS146 was about 150mm, however as the RL on this SSM is a lesser order and originally GPS heighted, the data was rejected in favour of PL1T.

In summary, for the coordination of KNOLL, 4 baselines measure in 2 separate GPS surveys from 2 different SSM networks about 100 km apart gave results that agreed within 40 mm XYZ. We also verified, by spirit level, the absolute height difference between PL1 and PL1T – agreed with given.

From KNOLL, we leapfrogged a GPS traverse to control points established at each cross section and closed back to KNOLL. The sequence of points was KNOLL – 7 – 14 – 15 – 16 – Ord9 – KNOLL. Each segment of this traverse was observed twice (2 baselines between 2 control points) for a minimum 20 minutes each, changing the antenna heights. The total length of this traverse was 51 kilometres and misclose was 34mm horizontally and 18 mm vertically. No adjustment was done to the control point values.

Control point 11 (at cross section 11) was observed as a spur from Ord 9, 2 baselines. Control points 12 and 13 were observed after the main survey and accessed by helicopter during a separate photo control survey for DOE. For these 2 points GPS receivers were left running at KNOLL and Ord9, and baselines observed to both 11 and 12 with a third receiver, hence 2 baselines to each point. Closure to points 11, 12 and 13 were acceptable.

CONTROL POINT LIST				
CONTROL POINT	EAST (MGA94)	NORTH (MGA94)	RL (AHD)	CODE
KNOLL	456823.180	8178268.270	96.900	SPK-KNOLL
7	463538.030	8168274.540	91.125	SPK-7
9	470430.053	8158585.800	93.542	SPK-ORD9
11	474253.494	8149861.355	92.370	SPK-11
12	459867.856	8151868.292	95.906	SPK-12
13	455270.430	8141864.960	103.496	SPK-13
14	463014.490	8164712.675	91.340	SPK-14
15	463815.320	8161056.410	91.810	SPK-15
16	466248.585	8161583.468	92.252	SPK-16
19	461622.185	8153998.585	91.413	SPK-BOW9

Once the control points were coordinated, we then used Topcon Hyperlite GPS RTK (real time kinematic) system to set out predetermined ends at each cross section, and survey between these ends with same GPS. Topcon was utilised for the section survey as it has the additional "GLONASS" constellation capability, and operates far better in dense vegetation, as was experienced through this entire project.

At sections 11, 12 and 13 we could only access the sites once and therefore could not accurately predetermine the control point coordinate prior to cross section survey. At these sites we used hand held GPS to mark the ends and then did a feature survey extending about 30-50 metres each side of the section centreline. This enabled us to post process the exact section later in the office – i.e. to computer "extract" as the required section from a DTM (digital terrain model.

It should be mentioned that at each section we had to establish the control points in locations that was very close to the section line, was accessible, and totally clear of vegetation and tree canopy – the only suitable places were close to the water edge on sand and mud banks. Hence these points will not exist after the first rains and river flow. Any future surveys will need to be re established from KNOLL.

The cross sections were surveyed from water level each side of river up the banks and to the required ends on both sides. No survey was done within the main river water bodies.

Computer software used to process the field survey data included:

- Trimble Geomatics Office (TGO) – for all static GPS baselines
- MS Excel – for checking Topcon coordinate files and converting to CSV files
- Ultra Edit – for any data (codes) editing
- ACSP – a survey package used by Whelans for onscreen data assembly and editing
- AutoCAD – for final presentation of data.

3. GAUGE BOARDS/TIDE RECORDERS

Two tide recorders were established by 3D Marine Mapping for their own reference, one near the Dam wall boat ramp (boat ramp), the other in the Ord River near section 7 and Downstream of Ord/Bow junction (Ord).

Whelans were asked to establish an AHD level close to each of these recorders in order that the tide recorder data could be post processed and calibrated to AHD datum.

For boat ramp we painted a mark on an insitu pointed rock about 5 metres from the permanent gauge board, to which the tide recorder was attached. Static GPS baselines were observed the same day (about 5pm) as we observed from PL1T to KNOLL and we believed we had 2 baselines, one each from PL1T and LIS146. As the baseline distance was within 2 kilometres, we observed for about 20 minutes.

3D Marine Mapping used the AHD RL we provided, however there was concern that the resultant level disagreed with the gauge board by about 87mm.

We then did several GPS RTK check shots to our “rock”, the water level, the gauge board, and several other old level points and bench marks we found, all from PL1T, and these shots confirmed that our original one static GPS baseline was in fact in error, and the Gauge board calibration was correct. Shots on the water level agreed with the gauge board reading.

So in the end our GPS readings from PL1T agreed exactly with the boat ramp gauge board reading.

The other gauge board (Ord) was levelled by GPS RTK readings from control point 7. We used Topcon RTK and took 2 lots of 20 readings (i.e. 40 total) to the top of the white PVC tube that was secured to an old tree in the river. Set 1 gave an RL of 92.096, set 2 = 92.090, average 92.093m AHD. No other readings were taken to this mark, and no reference was left that could be checked in the future.

4. WATER LEVEL ANOMALY

During post processing of all data it was apparent there was a difference in the water surface level between the 2 tide recorders in the order of 300mm (over a distance of about 60km).

All Whelans GPS baselines and data was rechecked and reprocessed and produced identical results and miscloses as when first processed, which ordinarily would be considered as more than acceptable. Apart from the difference in Water levels, all indicators and minimal miscloses in our baselines and traverses suggest the data is correct.

A further check was undertaken on 16/11/07 when Duncan Palmer of DOE read the boat ramp gauge board, water level = 91.02m. AT about the same time on the same day Whelans spirit levelled from KNOLL to the nearby water level (100m away), and came up with a water level of 90.805m, a difference of 215mm. What is interesting is that this 215mm difference over about 40 km upstream is in same proportion as 321mm over about 60km at Ord gauge board.

A possible future check could be to observe GPS baselines (2 bases, 1 rover) from 2 SSMs direct to water levels at boat ramp and KNOLL on the same day. This would confirm the difference in water level.

Mark Albers

20 April 2007

Appendix B — 3D-Marine Mapping Survey Report

Report

to

Department of Water Western Australia

Sediment Survey of the Old River Channel
Beneath Lake Argyle
October 2006

Prepared by: RH Lange
Licensed Surveyor
Date 1st May 2007

3D Marine Mapping Pty Ltd
ABN: 65 007 751 304
1st Floor, 11 King William Street
KENT TOWN SA 5067
PO Box 1000
Kent Town SA 5071

Telephone: (08) 8130 1666
Facsimile: (08) 8362 0099
Mobile: 0418 810 752
Email: langeb@ozemail.com.au

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This report has been prepared by 3D Marine Mapping Pty Ltd
ABN: 65 007 751 304
Of 1st Floor, 11 King William Street Kent Town SA 5067

Scope

Limits and scope as described in the tender documents for the supply of Hydrographic Survey Services in the Department of Water, RFQ 0070-2006. 3D Marine Mapping Pty Ltd provided survey of the lakebed (water) component of the survey, modelling, plans, cross-sections and calculation of volumes for the prime contractor, Whelans, who provided survey of land based sections and horizontal and vertical control.

Survey Methodology

Bathymetric survey for the determination of sediment in the old river channel beneath lake Argyle was undertaken in the following manner: -

Bathymetry using a GeoSwath Plus interferometric survey system providing total bottom coverage of the survey area.

The equipment has been used for a variety of surveys to monitor the seabed for channels, harbours and water storage areas. The procedures developed for these surveys have shown to provide accurate, consistent and reliable repeatability of results.

The integrated field systems used for data acquisition comprise a number of high resolution/accuracy instruments as detailed below. The combined error budget of the system will provide a precision per reduced data point as detailed below.

The field survey work was undertaken using a local trailerable 8.0m aluminium vessel registered as a fishing vessel with WA Dept. of Transport. The GeoAcoustics GeoSwath Plus sounding system is deployed using an over-the-side mount attached near the centre of gravity of the vessel. A TSS DMS 02 motion sensor fitted in the vee-plate between the swath transducer plates logged heave, roll and pitch of the transducer head, and an SG Brown Meridian gyrocompass was used to correct for heading. A Trimble Ag332 differential GPS receiver using Omnistar correction service was used to provide sub-metre horizontal positioning accuracy. Navigation was in real time using Trimble HydroPro and all data will be collected in WGS 84 coordinates.

A single run with the GeoSwath 32 system using 250kz transducer plates provides bottom coverage up to 10 to 12 times the water depth. Track lines were run at suitable intervals to provide a minimum 20% overlap of swaths ensuring total bottom coverage. The track coverage history of the GeoSwath system was used to ascertain that full coverage has been achieved. Sound velocity profiles using a ValePort 650 SVP were taken throughout the water column at selected locations to enable the data to be rectified for refraction. A number of check lines were run to validate the survey. A Tritech single beam high frequency (200hz) transducer mounted with the swath transducers provided an independent check on the swath soundings.

Two continuously logging Valeport 740 tide gauges were deployed to monitor the lake levels throughout the project, one at the downstream and one at the upstream end of the lake.

The swath data was processed using GeoSwath Plus software programmes to correct for vessel motion (i.e. heave roll and pitch), squat, speed of sound and water level datum. The data was gridded to the desired density using GeoSwath Gridder.

Acquisition

Water depth data was acquired along the courses of the old Ord and Bow rivers under Lake Argyle between the 25th and 31st October 2006.
The data was acquired using a GeoAcoustics "GeoSwath Plus" Interferometric wide swath sonar system using a Trimble DGPS system with OmniStar derived position correction fed through a Navigation laptop running Trimble "HydroPro" survey navigation software.

Runlines were calculated based on the centrelines of the rivers as supplied by Whelans, and runline spacings of 50- to 80-metre separation were used (depending upon water depth) to provide 100-per-cent total bottom coverage of the old river beds.
Where the current course diverged from the original centreline, the swath system was used to search the new course, and river edges.
The river Ord was surveyed to chainage 85km where the water level became too shallow to navigate by boat, similarly the Bow River for approx. 9 km from the confluence with the Ord River.
A separate set of calibration runlines was run and static offsets for the transducer set-up calculated according to the manufacturer's instructions. These offset values are incorporated into the processing software parameters.

Depths were reduced to hourly lake levels as recorded by a ValePort 740 portable tide gauge deployed adjacent to the dam designated "Boat Ramp" with elevation surveyed from SMM PLIT, and a ValePort 740 portable tide gauge deployed at the vertical control mark at approx 64 km chainage designated "ORD" with elevation surveyed from control point "KNOLL".
Vertical control was provided by Whelans, and it was noted that a comparison between water level at the two control points shows a vertical discrepancy of 400-milimetres.
This gives the lake an effective "slope" of 1-in-160 (Dam uphill). The datum was nevertheless adopted following discussion with the client.
As the processing software does not make a linear interpolation between to tide/level gauge positions, but uses whichever is nearest, a further three (3) "interpolated" tide/level gauges, at equi-spaced locations between the two actual loggers, were adopted to reduce potential "steps" in the processed depths to less than 0.1metre.
The average lake level over the period of the survey was 91.25-metres AHD.

Datum

Horizontal datum is GDA94. Co-ordinate grid system is MGA94 zone 52.
Vertical datum is Australian Height Datum (see above).

Processing

Data was processed using GeoAcoustics swath processing software which reduces depth data to tide (water level) and compensates for dynamic motion of the vessel/transducers logged in real-time by a TSS DMS03 Motion Reference Unit (MRU) and for variations in the speed of sound in the water column logged several times a day across the survey area by a ValePort Sound Velocity Probe (SVP). Various filters were employed to remove noise from the raw data set and produce a filtered set that was subsequently gridded to mean depths based on a 5-metre bin size. It is this 5-metre-grid DEM that is the basis for the 3-D model presented here and the subsequent volume calculations.
Modelling was done using Terramodel survey and CAD software.

The 5m-binned DEM data is presented as an shp (ESRI) file, an ASCII comma delineated file and a set of A1 pdf-plans at 1:25,000 scale.

One set of plans (dwg-No., 6 sheets) shows the current sediment surface below the lake as a set of colour-coded contours and elevations. Labelled elevations are in a hydrographic chart style (metres and decimetres) and are selected as the highest point (shoalest water depth) within a specified circle of influence, the parameters of which are noted in each plan’s title block. Their colour coding is identical to that of the contours.

A second set of plans (dwg No. , 6 sheets) shows colour-coded isopach contours of the total accumulated sediment (and where relevant, erosion) since the pre-dam surveys.

A third set of plans (dwg No. , 6 sheets) shows colour-coded isopach contours of the total accumulated sediment (and where relevant, erosion) since the 1991/92 surveys. As above, please refer to the plan keys for colour coding information.

The pre-dam survey is an amalgamation of the DEMs provided from 1965 and 1968 aerial photography supplied by the client.
An "Average Deposition/Sedimentation" value for each kilometre section from the dam to km 85 where the 3DMM data runs out has been calculated using Terramodel software.
A set of isopach points is created by projecting points from one DEM onto the triangulated surface of a second DEM (and vice-versa) and each vertical separation is recorded as a point in the isopach model. From this model, a fill (deposition) volume and an excavation (erosion) volume is derived.
The average deposition value recorded in the spreadsheet was calculated from the net deposition (sedimentation minus erosion) volume divided by the triangulated area of the volume calculation. Some sections show net erosion.
It should be noted, however, that the pre-dam DEMs are on a large grid size compared to the 3D Marine Mapping survey which cause inaccuracies in the

isopach, particularly at slopes and edges. It should also be noted that the accuracy (95% confidence) of our data is calculated approximately thus:
0-12m depth: +/-0.1m
12-25m depth: +/-0.2m
25-50m depth: +/-0.3m
Depths near the dam, for example, were in the third category, which for an average volume calculation's triangulated area of approx. 500,000m2 would equate to a volume accuracy tolerance of +/-150,000m3. Accuracies for the original 91 and 92 surveys would be no better.

In addition to the plans and volumes table, two sets of A4-sized cross-sections are provided.
The first set shows comparative sections for each survey (pre-dam to 2006) at every km section. Vertical exaggeration is 10-fold.
The second set shows comparative sections for each survey (pre-dam to 2006) at every one of the key sections (provided by Whelans). These sections include land data acquired by Whelans in 2006, post-3DMM's hydrographic survey. Vertical exaggeration is 10-fold.
For each set, the different surfaces are colour coded and the names (dates of surveys) prefixed "ZE" (Z-value Elevation) in the labelled table below. Cross-section location, orientation and other parameters are listed on each section.

Supplied data

Survey Report (Word document).

Shape file of 5-metre sediment surface and deposition isopachs DEM.
ASCII Points file (e,n,z) of 5-metre sediment surface and deposition isopachs DEM.

Excel Spreadsheet file of volumes calculations.

Pdf A1-sized plans (6 sheets) of sediment surface as of October 2006.
Pdf A1-sized plans (6 sheets) of deposition thicknesses (isopachs) since pre-dam.
Pdf A1-sized plans (6 sheets) of deposition thicknesses (isopachs) since 1991/92 surveys.

Pdf A4-sized plans (sheets) of comparative cross-sections of past and present surfaces for every kilometre along the river courses.
Pdf A4-sized plans (sheets) of comparative cross-sections of past and present surfaces for each key section identified.

Equipment

GeoSwath is a PC based, shallow water (up to 200 metres water depth), swath bathymetry system, which meets IHO standards for hydrographic survey and yet costs little more than a conventional dual frequency echo sounder. The low cost of the system makes swath bathymetry available to a significantly wider user base.

The GeoSwath swath bathymetry system offers swath coverage of up to 12 times water depth to a maximum of 600 metres and unlike other swath bathymetry systems, GeoSwath allows the user to carry out the majority of data processing tasks in parallel with acquisition. This low 'time to chart' feature means that on most reasonable sized surveys, draft charts are available within 10-20 minutes of completion of the survey.

The GeoSwath swath bathymetry system is easily portable and can be deployed using an overside mount on vessels of opportunity or a hull mount for more permanent installations. In common with other GeoAcoustics products GeoSwath is modular allowing users to utilise existing equipment such as motion sensors and positioning systems.

The GeoSwath real-time swath bathymetry features include calibration, test and diagnostic software. The post processing/QA software includes calibration functions that calculate static factors, ray bending and speed of sound corrections. Depth and contour graphics can be output in a range of file formats including ASCII, HPGL and DXF for use in proprietary CAD packages and customer's software.

A **Trimble DMS232** GPS receiver is used to provide sub metre positioning data into HydroPro. The DMS232 has an integrated 12 channel receiver/dual-channel MF differential beacon receiver/satellite differential receiver, and has dual-frequency capability delivering decimetre accuracy using OmniStar XP/HP correctional services.

The **ValePort 650 SVP** is used to calibrate acoustic systems. The probe continuously measures and logs sound velocities throughout the water column as it is lowered into water. It has a resolution of 0.1m/sec and is accurate to +/- 0.3m/s. Velocity profiles of the water column in the survey site are entered into the GeoSwath system to correct for sonar refraction.

Trimble HydroPro is a comprehensive hydrographic navigational and data acquisition system. The software operates on a notebook computer and provides real time guidance information to the helmsman. Charts or DXF files showing details of the survey area can also be displayed on the screen to aid navigation. Inputs from the digital gyrocompass are used to precisely calculate offset positions for ancillary devices such as the echo sounder. Grid coordinates computed in HydroPro are input into the GeoSwath system.

The **SG Brown Meridian Surveyor Gyrocompass** provides heading information at 10hz to HydroPro, the DMS05 motion reference unit and to GeoSwath.

The **TSS DMS-05** is a compact and highly accurate motion reference unit. It has a roll and pitch angular resolution of 0.025°. The MRU is mounted underwater with the swath transducer plates and is used to compensate the swath data for roll, pitch and heave.

3D Marine Mapping Pty Ltd has designed mounting systems and constructed crates to provide cost effective transportation of equipment and portability of mounting and erecting systems on vessels of convenience.

4.6. Summary: GeoSwath Calibration

1. Measure all offsets
2. Record **Latency** calibration lines using **GeoSwath32**, *(Same line (twice) into slope or over feature at different speeds).*
3. Record **Yaw** & **Pitch** calibration lines using **GeoSwath32**, *(three alternate parallel straight lines with 100% overlap preferably into a slope).*
4. Record **Roll** calibration lines using **GeoSwath32**, *(three alternate parallel straight lines with 100% overlap on flat seabed)*
5. Process all **'Latency'**, **'Yaw** & **Pitch'** and **'Roll'** calibration lines using Swath32, *(with offset measurements, Tide & SVP applied).*
6. Run **processed** Latency calibration lines through **Grid calibrator,** *(refer to section on Grid Calibration).*
7. Run **processed** Yaw & Pitch calibration lines through **Grid calibrator** and calibrate for **Yaw**, *(do this for both Port & Starboard with previous latency result still in calibration module).*
8. Run **processed** Roll calibration lines through **Grid calibrator** and calibrate, *(do this for both Port & Starboard with previous latency & Yaw results still in calibration module).*
9. Run **processed** Yaw & Pitch calibration lines through **Grid calibrator** and calibrate for **Pitch**, *(do this for both Port & Starboard with previous latency, Yaw & Roll results still in calibration module).*
10. Once all calibration parameters have been found they can be put into **GeoSwath32** or **Swath32** and the raw data processed accordingly.

    Remember to save your control file once these calibration parameters have been entered into the program!

    For confirmation that the calibration has worked you can re-process all the calibration lines with the parameters applied, then repeat the calibration process. The resultant parameter offsets from the second calibration should all be close to zero.

Appendix C — Data collection — more detail

C.1 Historical cross sections to be done next time

All historical cross sections (except 14, 15 and 16) were outlined in two Water Authority reports (Wark1987; Mauger & Hawkins 1994) and shown on Water Authority plan numbers 36537-35-38 to 54 (survey dates 1970, 1986 and 1991). The 1992 survey data is on a spreadsheet named Ordsect.wk1 (Mauger & Hawkins 1994). This spreadsheet also contains the sediment levels derived from the 1955/61 DEM.

Additional cross sections 14, 15 and 16 were included in the October 2006 (2005 flow year) survey to cover the region of the lake where large amounts of sediment were thought to be deposited. They were originally located and surveyed by Sandercock (cross section numbers 13, 17 and 16 in Sandercock, 2003) and had been previously surveyed in 2000. Historical cross section numbers 7, Ord River 9 and 11 were also surveyed by Sandercock in 2000 (cross section numbers 18, 7 and 2 in Sandercock, 2003).

There were some problems in locating the coordinates of these historical cross sections. Water Authority plans referred to the surveyed Public Works Department (PWD) bench marks (points of known position and height). The locations of the PWD bench marks were not found in old surveying publications, through enquiries to the Water Corporation or by searching Landgate's Bench Marks and Standard Survey Marks dataset. Coordinates for historical cross sections 4, 5 and 7 were obtained from the ocres.dgn MicroStation file (Mauger & Hawkins 1994).

To estimate coordinates of the historical cross sections 2, 3, 9 Ord River, 9 Bow River, 11, 12 and 13 plans PWD WA 36537-35-2, 6, 16, 18, 20, 21 and 22 were scanned and ortho-rectified to the hydrography linework in the department's linear hydrography dataset using Esri's ArcMap 9.1 software. The coordinates of historical cross sections 14, 15 and 16 were estimated by scanning Figures 6.30 and 6.44 from Sandercock (2003) and ortho-rectifying them in the same way.

C.2 Channel bed elevation surfaces

1955/61 pre-dam channel bed elevation surface

In 1994, a pre-dam elevation surface was created by digitising the 1955 and 1961 elevation contours and generating a surface. The 1955/61 contours were derived from aerial photography. This pre-dam surface was still used in 2007 when calculating volumes from the dam wall to 38 km. Beyond 38 km from the wall a new 1968 elevation surface of the channel bed created in 2006 was used for the pre-dam surface. It was of better quality than the 1955/61 pre-dam surface.

History of surface creation

In 1994, contour plans prepared in 1965 were digitised by the Water Authority. They were obtained from aerial photographs taken in 1955 and 1961. The plans were produced by the Mapping Branch, Surveyor Generals Division, Department of Lands and Surveys. The contour plans were in vertical intervals of 10 feet at a scale of one inch to 20 chains. They had a local datum: Wyndham Low Water Mark Ordinary Spring Tide (LWOST). LWOST is 4.29 m below the Australian Height Datum (AHD 84).

The contours near the channel were manually digitised into a Microstation file, minor contour modifications made (Mauger & Hawkins 1994) and imperial units transformed by computer into Australian Mapping Grid (AMG) coordinates and AHD levels in 1995. Then, in 2002, the Microstation file was gridded using MAGIC software (Mauger 1996) by the Water and Rivers Commission. A binary raster file was produced by this program and read into Esri's ArcMap 9.1. A grid was created with a Geocentric Datum of Australia (GDA) 1994 zone 52 projection using the Spatial Analyst extension.

1968 pre-dam channel bed elevation surface

A pre-dam surface was needed from 59 km to the upper reaches of the Ord and Bow rivers. Initially, the contour plans used to generate the existing pre-dam surface were going to be digitised and an elevation surface of the channel bed generated from them. However, the original 1955/61 contour plans were microfiched then destroyed. The microfiche plans were of such poor quality that it was not possible to digitise them.

Phil Smyth from Landgate generated a good quality DEM and orthomosaic (at a cost of $4000) using aerial stereo-paired photographs taken in 1968. The 1968 DEM was used from 38 km from the wall along the old Ord River channel to the upper reaches of the Ord and Bow rivers. Vertical and horizontal control points needed to generate the DEM were provided by the surveying company Whelans with help from the department. Due to the remote location this required hiring a helicopter. The DEM took two months to produce.

The 1968 surface has a grid size of 10 m, with a vertical accuracy of +/- 1.0 m and better horizontal accuracy. In July 2007, enquiries were made to Landgate to generate the 1968 DEM for the area 0–38 km from the dam wall. For consistency and better accuracy it would have been beneficial to have a pre-dam surface and DEM generated from the same year. With a quote of approximately $8000 the DEM was not ordered due to lack of funds.

1991 channel bed elevation surface

An elevation surface of the sediment data was created from the 1991 echo-sounded hydrographic survey. The surveyed data was compiled from a trial survey completed on the southern portions of the lake between Sections 5 and 7 prior to the complete 1992 survey. The 1991 run lines 'zig-zagged' along the channel from Section 5 to Section 7 (Fig. 3, Mauger & Hawkins 1994). The data from this trial survey was used to calculate the sediment volume between 38 and 59 km (Fig. 6). During the complete 1992 survey, the lake level was lower (82.7 m AHD) and the survey boat could not reach as far up the Ord River as in 1991 (lake level 87.6 m AHD).

History of surface creation

Approaching Section 7, the coverage of the channel width was reduced due to the low water level. To provide an interpolation between the survey area and the banks of the original channel, a suitable contour from the digitised 1955/61 channel contours was added to this set of data. The layout of the run lines is shown in Figure 3, Mauger & Hawkins (1994).

The echo-sounding data was processed using Microstation software and the resulting file was gridded using the department's MAGIC software (Mauger 1996). A binary raster file was produced and read into Esri's ArcMap 9.1 software. A 25-m grid was created using the Spatial Analyst extension. The DEM projection is GDA 1994 zone 52.

1992 channel bed elevation surface

This is a gridded elevation surface of the sediment data obtained from the 1992 echo-sounding hydrographic survey (Mauger & Hawkins 1994). The cell size is 25 m and the projection is GDA 1994 zone 52. They used this surface for the volume calculations from the wall to 38 km but not from 38 to 53 km since not all of the channel bed surface was captured for these reaches. The 1991 surface was used instead since it had better capture of the sediment surface.

History of surface creation

The survey covered the length of old Ord River channel from the dam wall to the maximum distance upstream reachable by boat, about 53 km from the dam (Fig. 3, Mauger & Hawkins 1994). Echo-sounding data from the run lines was input into Microstation. Points along the run lines were drawn parallel to the channel for the generation of the grid to work properly (Page 15, Mauger & Hawkins 1994) The Microstation file was gridded using DoW's MAGIC software. A binary raster file was output from this program and read into Esri's ArcMap 9.1. A grid was then created using the Spatial Analyst extension.

C.3 Calculating sediment deposition and volumes

3D-Marine Mapping used the software Terramodel to perform the volume calculations. The average depth of accumulated sediment was calculated for the periods pre-dam–1991 and the pre-dam–2005 by projecting points from one DEM onto the triangulated surface of the second DEM (and vice versa). Each vertical separation was recorded as a point in the corresponding isopach (contours of sediment thickness) model. From these models a fill (deposition) volume and excavation (erosion) model were derived.

The average deposition value was calculated from the net deposition (minus erosion) volume divided by the triangulated area of the volume calculation. Some sections showed net erosion. The pre-dam surface consisted of two separate DEMs. The 1955/61 DEM in the northern area of the lake had a 25-m grid size. The 1968 DEM in the southern portion of the lake and the upper reaches of the Ord and Bow rivers was more accurate with a 10-m grid size. The 1991 (combined from the 1991 and 1992 surfaces) elevation surface had a 25-m grid and was derived from 200 m surveyed lines. The 2005 elevation surface was the most accurate with a 5-m grid derived from surveyed 3DMM (three dimensional millimetre measurements) points. Appendix C.2 has more detail on the DEMs. The pre-dam and 1991 DEMs were on a larger grid size than the 2006 DEM which caused inaccuracies in the isopach, particularly at the slopes and edges of the channel.

The average depth of sediment, volume and accumulated volume were not reported for distances 0 to 10 km from the dam wall. Volumes ranging from ± 1 Mm^3 were calculated for each 1 km section of channel in this region, but when they were accumulated they resulted in a total of -0.7 Mm^3. The channel banks did not align well for most of the sections between 0–10 km. The channel walls are steep and reach depths of up to 24 m. Another factor that could have caused errors is that the channel curved sharply at the start of the dam, then between distances 2–3 km, 6–7 km and 8–10 km. The water above the sediment at the bottom of the channel varied from 37 to 44 m in these reaches.

The cross section at 0 km had the worst alignment. The average calculated deposition depth between the distances 1–10 km from the dam wall varied between -3 to 2 m while the depths in the middle of the channel varied between 0.2 to 5.2 m. The negative deposition depth between sections 2–3 km and 6–8 km was caused by the misalignment of the banks resulting from the steep slopes, deep water and sharp turns of the river channel. It is unlikely that there is more than 0.5 m of sediment in these channel reaches. If a survey is performed in the future, the 2005 sediment surface will hopefully align to the new surface.

The errors in digitising the 1955/61 elevation surface (pre-dam) from old plans could have resulted in errors in elevation of ± 10 feet or ± 3 m on the channel banks. The 10 foot contours were very close together at the banks close to the dam. The errors at the bottom of the channel would not have been so big, since the channel bottom is flatter. However, they could have been more than ± 1 m. In this deep water, the 2005 sediment surface could have errors of ± 0.3 m.

Appendix D – Products from the 2005 survey

Whelans supplied a survey report (Appendix A) and 3D-Marine Mapping supplied a survey report (Appendix B) and plans of the 2005 sediment surface, isopach contours of the 1971-2005 and 1991–2005 sediment deposition and cross sections at 1 km distances and where the historical sections cross the river channels. The Department of Water supplied the sediment layer animation.

Whelan survey report

A five-page report was received from Whelans, written by Mark Albers, Licensed Surveyor (Appendix A). Whelans established a control network and nine cross sections of the Ord and Bow Rivers at pre-determined positions. Whelans undertook these surveys during late October 2006 (at the end of the 2005 flow year) at the same time as the lake bathymetric survey. The report explains the methodology and equipment used, gauge boards, tide recorders and the water level anomaly.

3-D Marine mapping survey report

A nine-page report was received from 3D-Marine Mapping, written by Robert Lange, Licensed Surveyor (Appendix B). 3D-Marine Mapping did the bathymetric survey for the determination of sediment in the old Ord River channel beneath Lake Argyle and the data processing component of the contract. Their report has sections on survey methodology, acquisition, datum, processing, supplied data, equipment and Geoswath calibration.

Plans of current 2005 sediment surface

Six A1 sized plans (at 1:25 000 scale) of the 2005 sediment surface as a set of colour-coded contours and elevations were supplied in electronic (pdf) format. The extent of these plans is the same as that of the sediment surface described in the previous section. Labelled elevations are given in hydrographic chart style (metres and decimetres to AHD).

Plans of isopach contours of the total accumulated sediment surface from pre-dam to 2005

Six A1 sized plans (at 1:25 000 scale) of the colour-coded isopach (deposition thickness contours) showing the total accumulated or eroded sediment since the pre-dam DEM were submitted in electronic (pdf) format. The pre-dam DEM was that derived from the 1961/65 and 1968 aerial photographs. The extent of the pre-dam–2005 isopach plans is the same as that of the sediment surface described in Section 6.3.

Plans of isopach contours of the total accumulated sediment surface from 1991 to 2005

Six A1 sized plans (at 1:25 000 scale) of the colour-coded isopach contours of the total accumulated or eroded sediment since the 1991/92 (1991 flow year) survey were supplied in electronic (pdf) format. The extent of the 1991/92–2006 (1991–2005 flow year period) isopach plans is the same as the sediment surface discussed in Section 6.3.

Plans of 1-km Ord River sections showing sediment levels in pre-dam, 1991 and 2005

Cross section plans of the Ord River channel were supplied on 93 A4 sheets in electronic (.pdf) format. An AutoCad digital file (.dxf format) of these cross sections was also supplied. They show the comparative sediment elevations pre-dam and in 1991 and 2005. The vertical exaggeration is tenfold and the elevations are given in metres and decimetres to AHD. The pre-dam levels were captured to 93 km from the Ord Dam wall, 1991 levels to 59 km and the 2005 levels to 87 km.

Plans of historical cross sections

3D-Marine Mapping supplied ten A4 sized historical cross section plans (pdf format) identified by the distance in metres from the dam wall for the 1, 3, 4, 5, 7, 14, 15, 16, 9 Ord River and 11 sections. An AutoCad digital file (.dxf format) of these cross sections was also supplied. The pre-dam levels were displayed to 93 km, 1991/2 levels to 59.5 km, and the 2006 levels to 87 km. These plans had elevations in metres and decimetres to AHD shown every 20 m along the section. The pre-dam and 1991 levels were generated from the DEMs supplied by the Department of Water.

Whelans supplied three A1 sized plans named Cross Section 12, 13 and 9 Bow River. These plans had 2006 elevation values shown in metres and centimetres every 5 m along the section. All plans were supplied in pdf format.

The survey boat could not reach some of the cross sections (Sections 9 and 12 Bow River and Sections 9 and 11 Ord River). Hence only the portions of the historical sections which were above water were captured. Section 13 Bow River was completely dry and was fully captured.

2006 sediment survey of Lake Argyle

A five-minute animation of three sediment layers in the old Ord River channel underneath Lake Argyle and the upper reaches of the Ord and Bow rivers was made by the Department of Water and edited by a consultant, Tony Malkovic. This animation is presented on a DVD supplied as part of this report.

The software used to make the animation was Esri's ArcGIS 9.2, ArcScene as part of the 3-D Analysis Extension. The pre-dam layer is dark brown, the 1991 layer white and the 2005 layer dark green. The three sediment layers used are those mentioned in Sections 4.2, 5.4, 6.2 & Appendix C.2. The 1968 DEM at 10-m grid was resampled to 25 m pixels for the animation.

Cross section lines at 1 km intervals were also shown with colours matching the sediment layers. The animation concentrated on cross sections at distances of 20.5, 32, 37.5, 49, 53 and 59.5 km upstream of the Ord Dam wall and also on a cross section 1 km upstream of the confluence of the Ord and Bow rivers, along the Bow River.

The camera followed the old Ord River Channel just showing the pre-dam surface and the 1 km cross sections. At the cross sections mentioned above, the camera stopped, displayed the 1991sediment layer and then the 2005 sediment layer. It was possible to see the sediment build-up at each cross section.

The background of the lake and hills used in the animation was Bands 3, 2, and 1 at 25 m resolution of the Landsat 7 Mosaic of Australia acquired in July 1999 from the Australian Centre for Remote Sensing (ACRES). The digital elevation model (DEM) for the background was the WA DEM at approximately 90 m cell from GeoScience Australia.

Appendix E – Current sediment analysis

E.1 Key section details

To appreciate the size of the river channel and sediment erosion or deposition in each section, all graphs have the same vertical scale. All sections face upstream, away from the dam.

Section 4:

Section 4 is 20.5 km from the dam wall (Figs 1 & 18). The lowest point of the thalweg (the middle of the main waterway) is 34 m beneath the lake (Fig. 18). This section is in the region of the lake that has not accumulated much sediment since the dam was built (Fig. 12). The 1956/61 DEM and November 1970 survey bed shapes look different in Section 4 (Fig. 18). It is possible a shingle bank eroded in 1966 during a high flow event. The photography for the contours at this section was taken in 1961. The accuracy of the vertical height of the DEM would have been at best ± 1 m, even less accurate. The accuracy of the echo-sounding would have been ± 1% of the water depth (approx. ± 0.3 m).

Around 3.7 m of sediment is estimated to have accumulated between November 1970 and October 2006, with not much of that accumulated since 1991.

Section 5:

Section 5 is 37.5 km from the dam wall (Figs 1 & 19). It is in the region of the lake accumulating sediment (Fig. 12). The sediment line for 1986 suggests the survey may have been on a different alignment from the other surveys (Fig. 19). Around 7–10 m of sediment has been deposited in the thalweg at this section since the dam was built, with only 2 m since 1992. The 2006 survey did not capture the bar on the ESE side of the section.

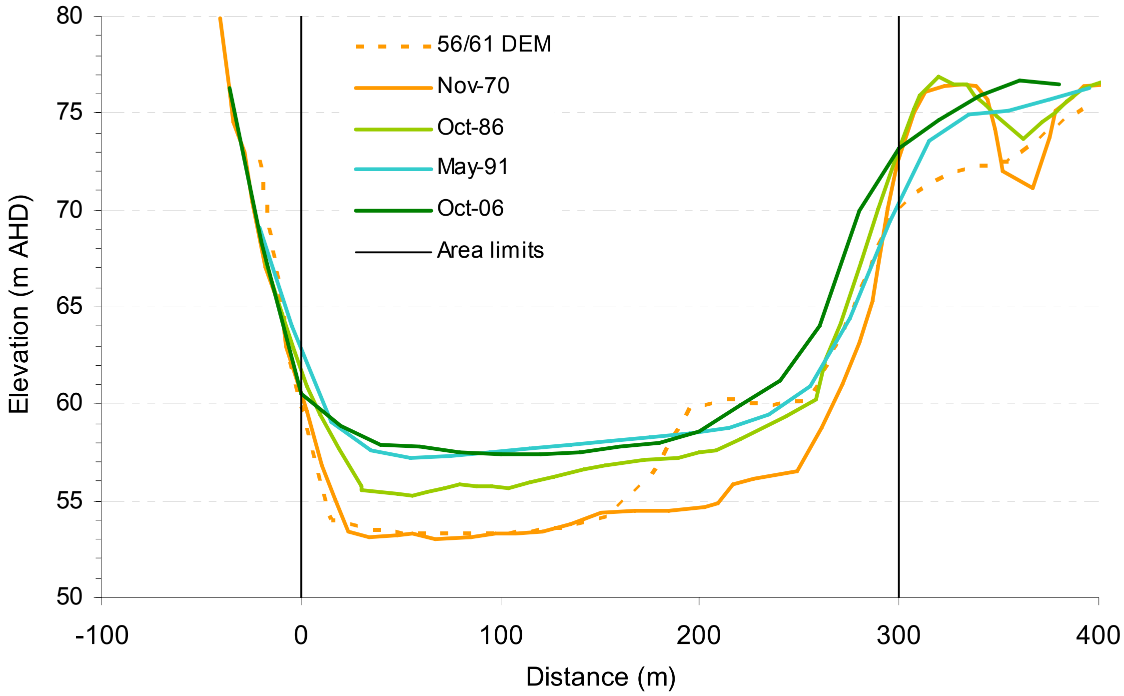

Figure 21 Section 4, 20.5 km upstream

Section 7:

Section 7 is 59.5 km from the dam wall, just past the region of the lake that has the greatest accumulation (Figs 1, 9 & 20). It is only 5.75 km downstream of the junction of the Bow and Ord rivers. The lake now reaches this section when the lake level is higher than 84 m AHD.

The cross section forms part of a large bar attached to the western side of the river (Sandercock 2003). This has formed due to more restricted mobility of the channel in the confined reaches. Before the dam this lateral bar acted as temporary sediment storage for sand and gravel bedload sediments. In high flows, sediments were mobilised and flow resistance modified by the creation of migratory bedforms which transported sediments over the bar surface. During the high flow events in 1956, 1959, 1960 and 1966 riparian vegetation was lost near this bar. Sandercock (2003) analysed aerial photographs and noticed that the riparian vegetation near the channel has returned.

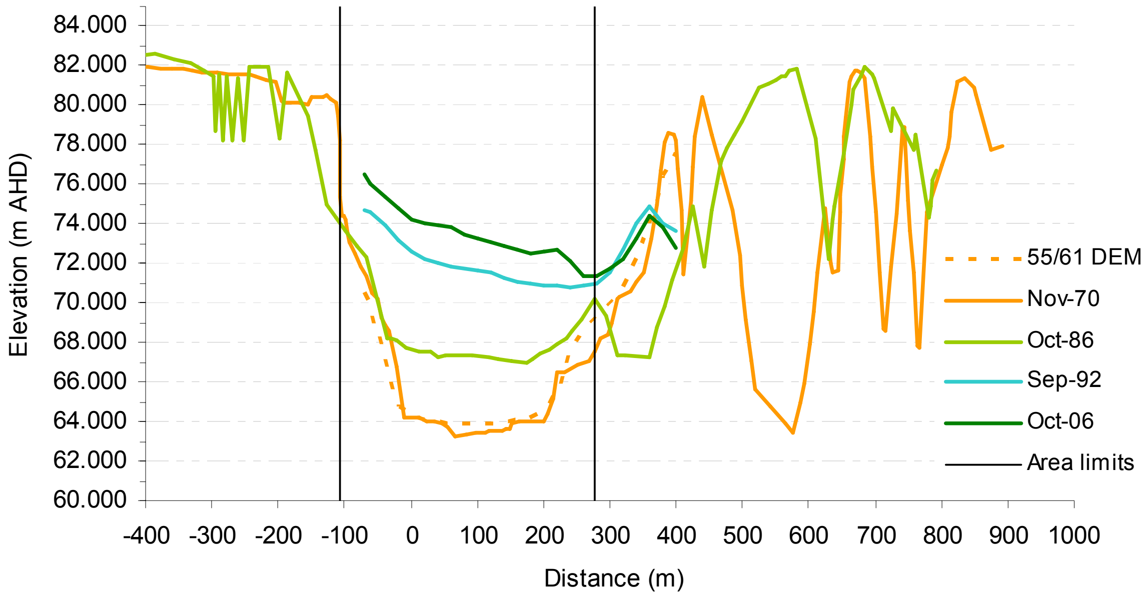

Figure 22 Cross section 5, 37.5 km upstream

Parts of the 1968 DEM are 1 m higher than the November 1970 survey line (Fig. 20). The vertical accuracy of the 1968 DEM is ± 1 m, while the vertical accuracy of the echo-sounding used in 1970 would have been approximately ± 0.05 m for a water depth of 5 m.

The November 1985 sediment line is higher than the May 1991 sediment line. Large flow events in January and February 1991 may have eroded the channel at this section. The lake level was below average during this period (around 80 m AHD), and there were no backwater effects of the lake.

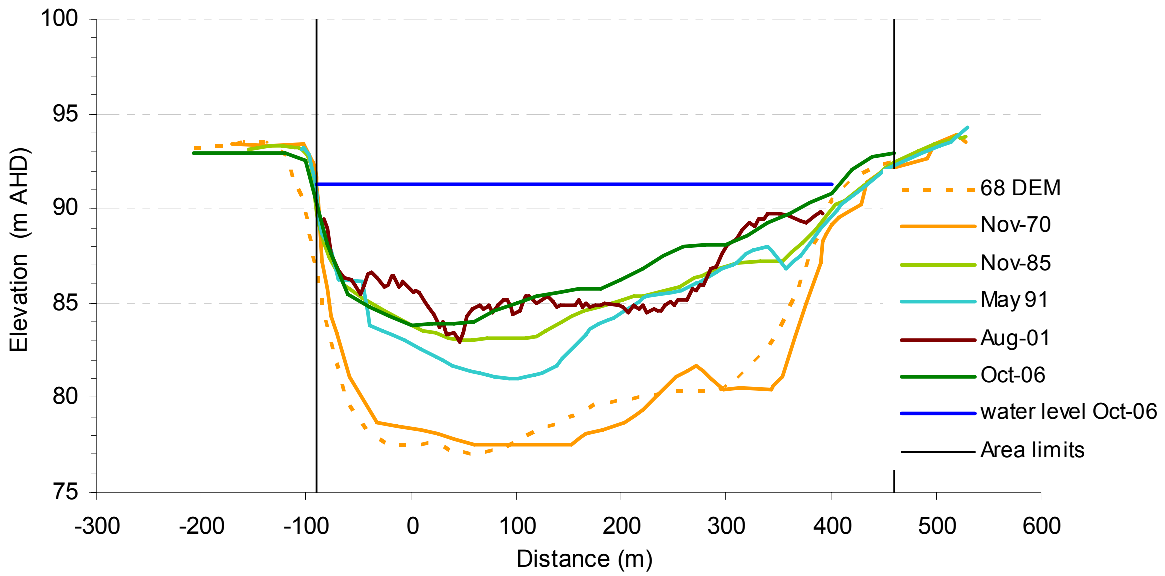

Figure 23 Cross section 7, 59.5 km upstream

The total depth of sediment at this section is around 6–7 m in the centre of the channel. Around 2–3 m of sediment has been deposited since May 1991 near the centre of the channel. The sediment depth did not change much since 2000. A sample taken in the channel bed in the thalweg in August 2001 had a particle size distribution of 82% sand, 15% silt and 3% clay (Sandercock 2003).

Section 15:

Section 15 is 2.25 km downstream of the junction of the Bow and Ord rivers (Figs 1 & 21). The backwater effects of the lake are still present at this section. The lake reaches this section when its level is higher than 84 m AHD. The section was studied in detail by Sandercock (2003). A bar has formed on the ESE side of the section (Fig. 21). On the WNW side, dense riparian vegetation around 20 m high extends 250 m with lower density riparian trees, 8–10 m high, extending past it. There were significant losses of riparian vegetation cover between 1948 and 1968 but the vegetation has since recovered.

Up to August 2001, between 8 and 11 m of sediment was deposited in the channel and around 2–5 m of sediment was deposited over the bar. A sample taken from the channel bed in 2001 had a particle size distribution of 64% sand, 32% silt and 3% clay. By 2006, some of the sediment may have eroded to leave 6–8 m in the channel and 3–5 m on the bar. It is possible the section was not located exactly as in 2000.

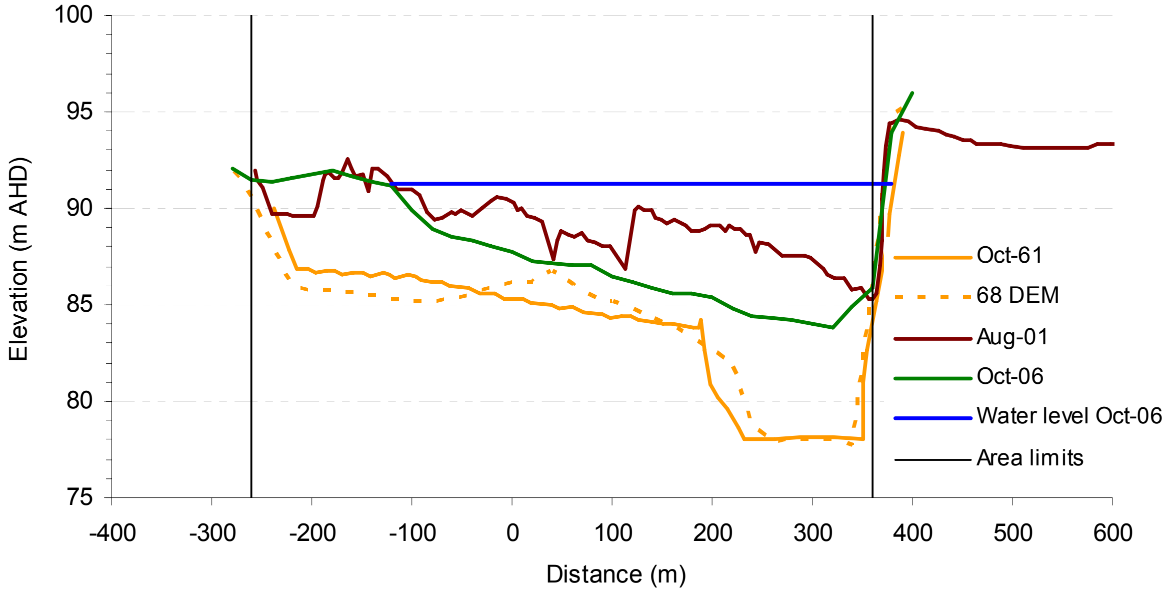

Figure 24 Section 15, 63.3 km upstream

Section 16:

Section 16 is 67.8 km upstream of the dam, 2.4 km upstream of the confluence of the Bow and Ord rivers (Figs 1 & 22) and in a meander bend. The lake reaches this section when its level is higher than 84 m AHD. On the SSW side of the channel there has been 9 m of erosion and on the NNE side up to 9 m of sediment is depositing over the bar (Fig. 22). A sample taken from the channel bed in 2001 had a particle size distribution of 33% sand, 44% silt and 16% clay. Between 1968 and 1992 there was an abrupt shift in the position of the thalweg: the thalweg has cut across the point bar and is now located more centrally in the channel (Sandercock 2003).

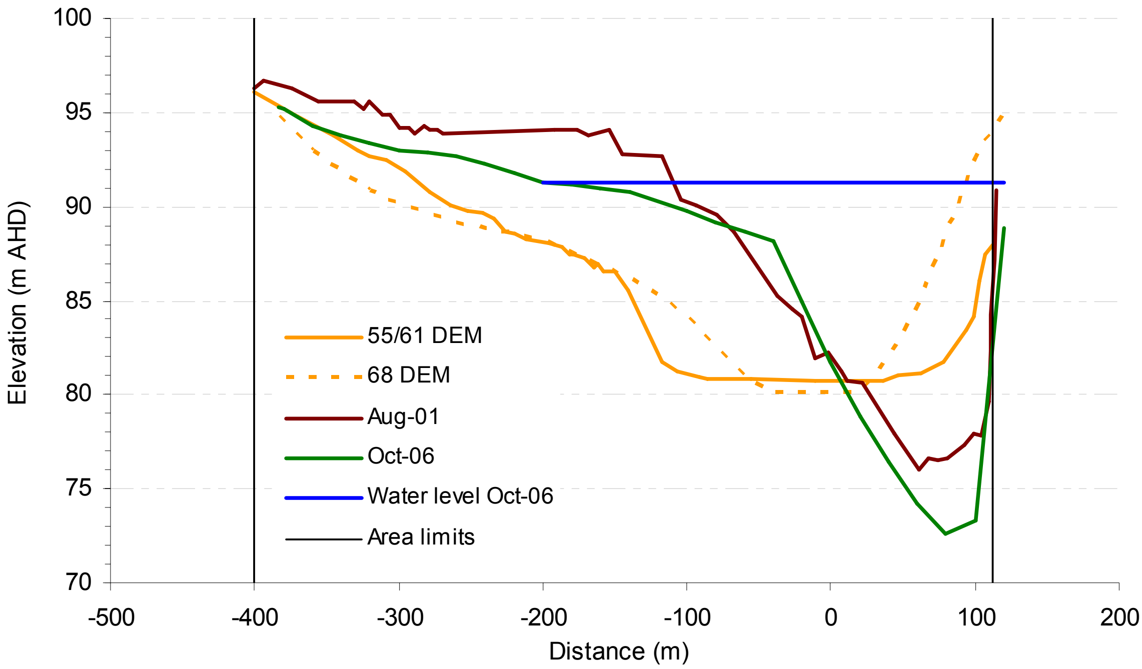

Figure 25 Section 16, 67.8 km upstream

Section 14:

Section 14 is 70.6 km from the dam wall and 5.6 km upstream of the confluence of the Bow and Ord rivers (Figs 1, 23 & 24). The thalweg, situated on the NNW side, is held tightly against the northern bedrock control (Fig. 23). On the SSE side of the section is a bar on which, in 2001, large 3-D bedforms were created when the receding flood waters left behind ponds of water. A 2001 flood event scoured out vegetation in a chute 60 m in length, near distance –220 m. The channel is aggrading its bed. Since 1961, sediment, between 4.3 and 8.6 m deep, has been deposited over the bar. By 2006, the thalweg eroded a further 2.5 m and the bed also lost another 1 m. This may have been due to slightly different alignments of the section. The section location was found by scanning figures in the Sandercock (2003) report.

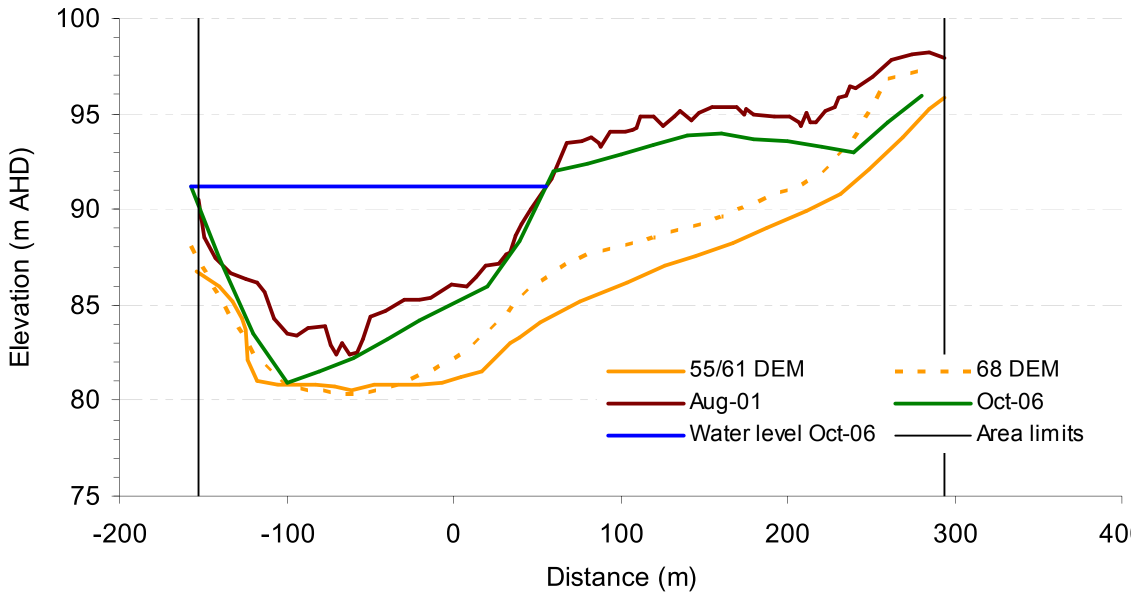

Figure 26 Section 14, 70.6 km upstream

Figure 27 Land survey of Section 14: facing south

Photo by Duncan Palmer on 26 November 2006

Section 9:

Section 9 Ord River is 100 m downstream of Spring Creek (Figs 1 & 25). On the NE side, in 2000, the flood plain had two terraces on it (Fig. 25). In 2006, the survey did not cover all of these terraces, possibly due to thick riparian vegetation cover. Sandercock (2003) studied the section in detail. The lower inset terrace has developed within the last 35 years in response to backwater effects of the dam. Prior to the construction of the dam, this section of the channel functioned as a cross-over zone, where the thalweg switched from the west to the east side of the channel. The channel width has decreased due to the formation of the inset terrace. In 1968, it was 348 m wide, and then by 1991 it was reduced to 248 m. In 2000, it was estimated to be 280 m wide. If the alignment of the section was correct in 2006, the two terraces seemed to have joined and the channel thalweg is banked against the SW side of the section. The depth of sediment varies from zero to 10 m in the thalweg. In 2006 it was at least 11 m on the bar in the area surveyed. In 2000, the sediment was as much as 14 m high on the inset terrace. In 2001, a sample was collected of the channel bed using a grab sampler. Particle-size analysis of this sediment showed it to be predominantly fine to very fine sand (83%) with only 1.4% of the sample in the silt/clay size range.

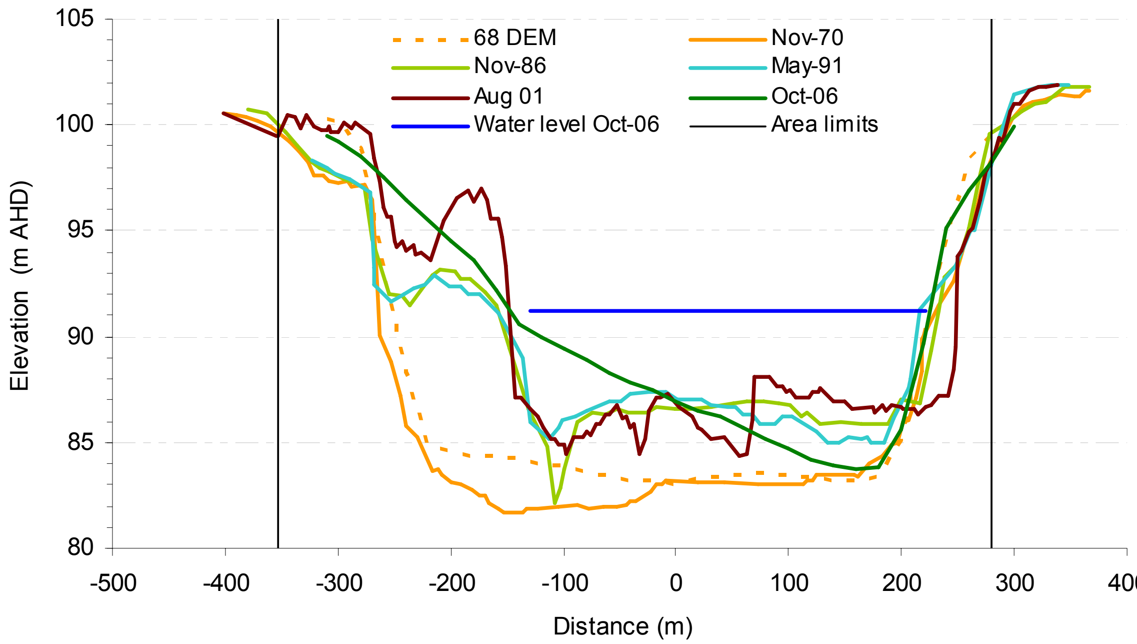

Figure 28 Section 9 Ord River, 76.5 km upstream

Section 11

The boat did not reach Section 11, but small sections of the channel bed not covered by water were surveyed in 2006 (Fig. 29). Section 11 is 87 km from the dam wall and 200 m downstream of Spring Creek. At cross section 84 km, near Section 11, the depth of sediment in 2006 was around 3 m in the centre of the channel. Sandercock (2003) investigated the channel near Section 11 in detail. The channel has begun to aggrade its bed, but has been limited due to confinement of the river. High rates of deposition are occurring over the lower inset terraces that were present before the dam was built. Riparian vegetation appears to exert a particularly important role in inducing deposition at the channel margins. The height of sediment averaged 3.0 m, but was as high as 5 m in 2001 on the WSW bank and extended for 155 m. A sample was taken in this sediment bed, and it comprised 0.3% sand, 67.8% silt and 21.5% clay.

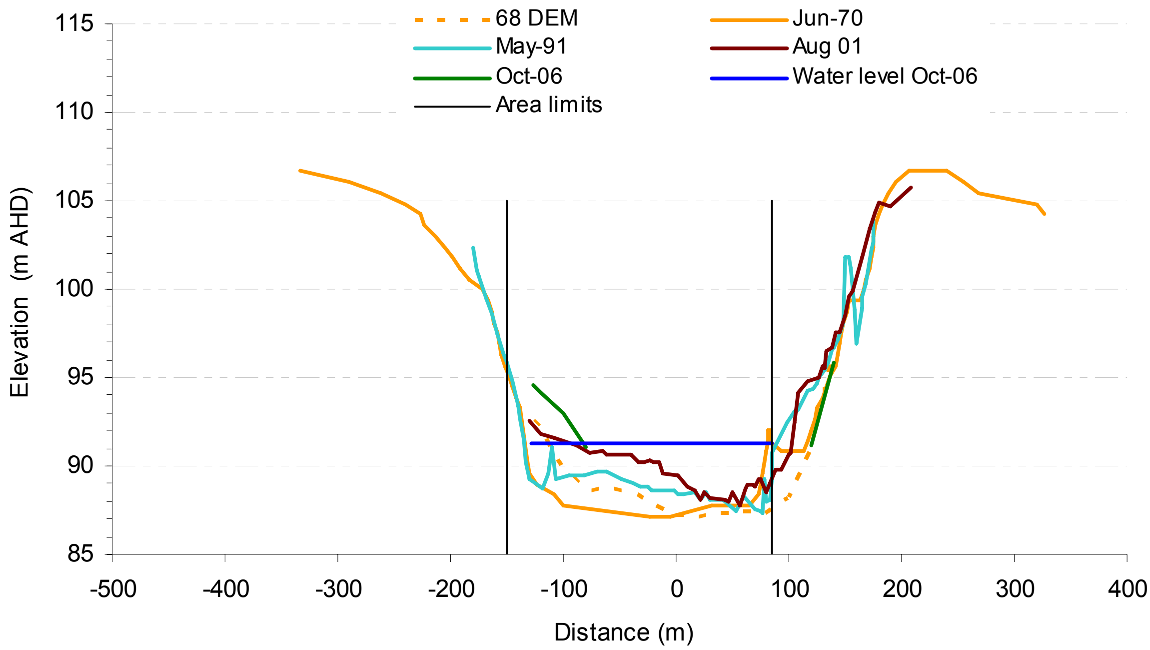

Figure 29 Section 11 Ord River, 87 km upstream

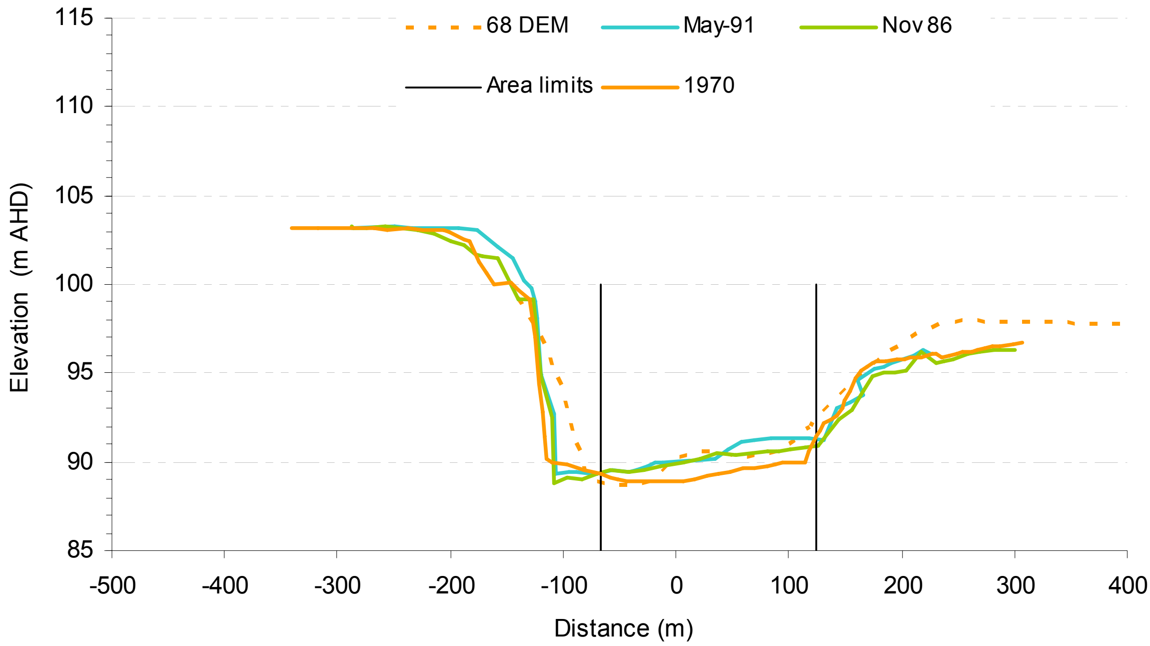

Figure 30 Section 9 Bow River, 10.8 km from the confluence of the Ord & Bow rivers

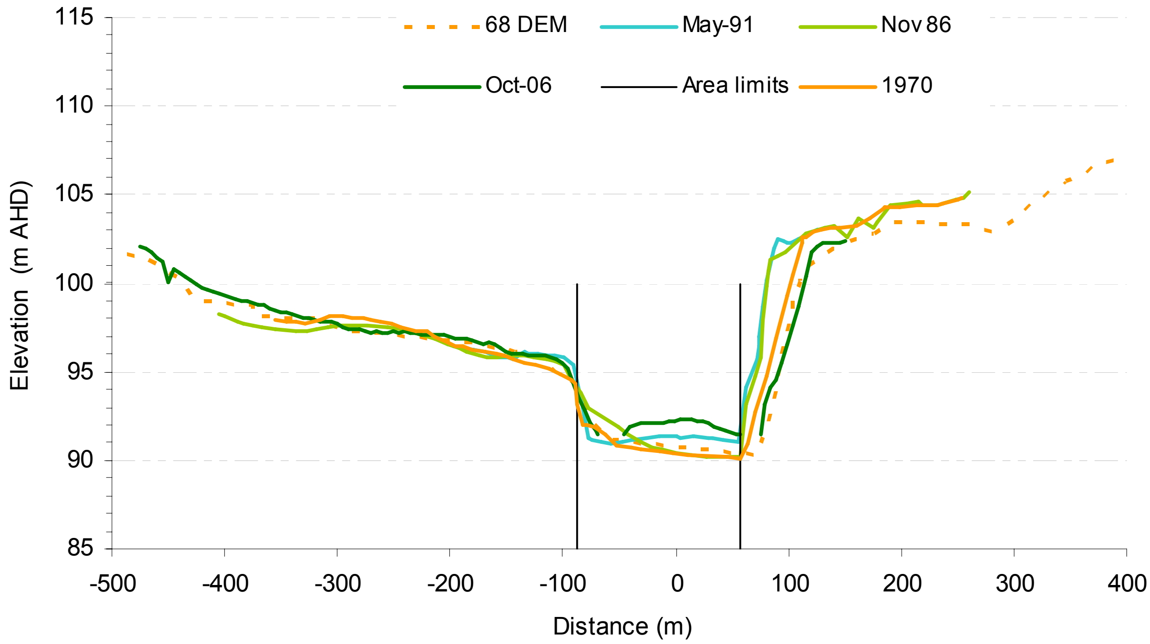

Figure 31 Section 12 Bow River, 13.9 km from the confluence of the Ord & Bow rivers

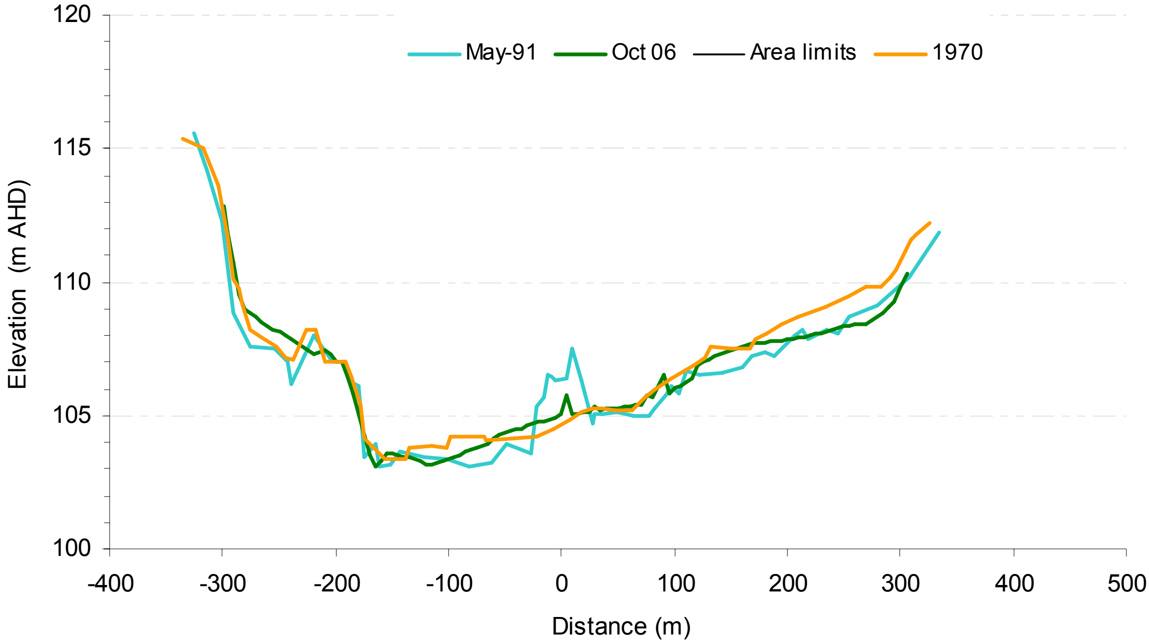

Figure 32 Section 13 Bow River, 26.2 km from the confluence of the Ord and Bow rivers

Section 13

The surveys throughout the years look like they are on different alignments. Areas of sediment deposition could not be inferred from this section.

Glossary and abbreviations

bathymetric survey	A survey of underwater features
chain	A unit of length; 66 feet, equal to 20.1168 metres
geomorphological	The branch of geology dealing with the characteristics, origin, and development of land forms
GL	A unit of volume: gigalitre, thousand million cubic metres ($x10^9$ m^3)
hydroclimatology	The science of how climate conditions affect hydrology
inch	A unit of length; 25.4 mm
interferometric	A method of measuring interference fringes to estimate soundwave wavelengths, wave speeds, angle distances.
m AHD	Elevation, m Australian Height Datum
Mm^3	A unit of volume: million cubic metres ($x10^6$ m^3)
Mm^3/a	Rate of sediment accumulation: million cubic metres per annum
Mtpa	A measure of rate of sedimentation: million tonnes per annum
t/m^3	A density measurement: tonnes per cubic metre
thalweg	The middle of the main waterway

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Department of Water

168 St Georges Terrace, Perth, Western Australia
PO Box K822 Perth Western Australia 6842
Phone: (08) 6364 7600
Fax: (08) 6364 7601
www.water.wa.gov.au