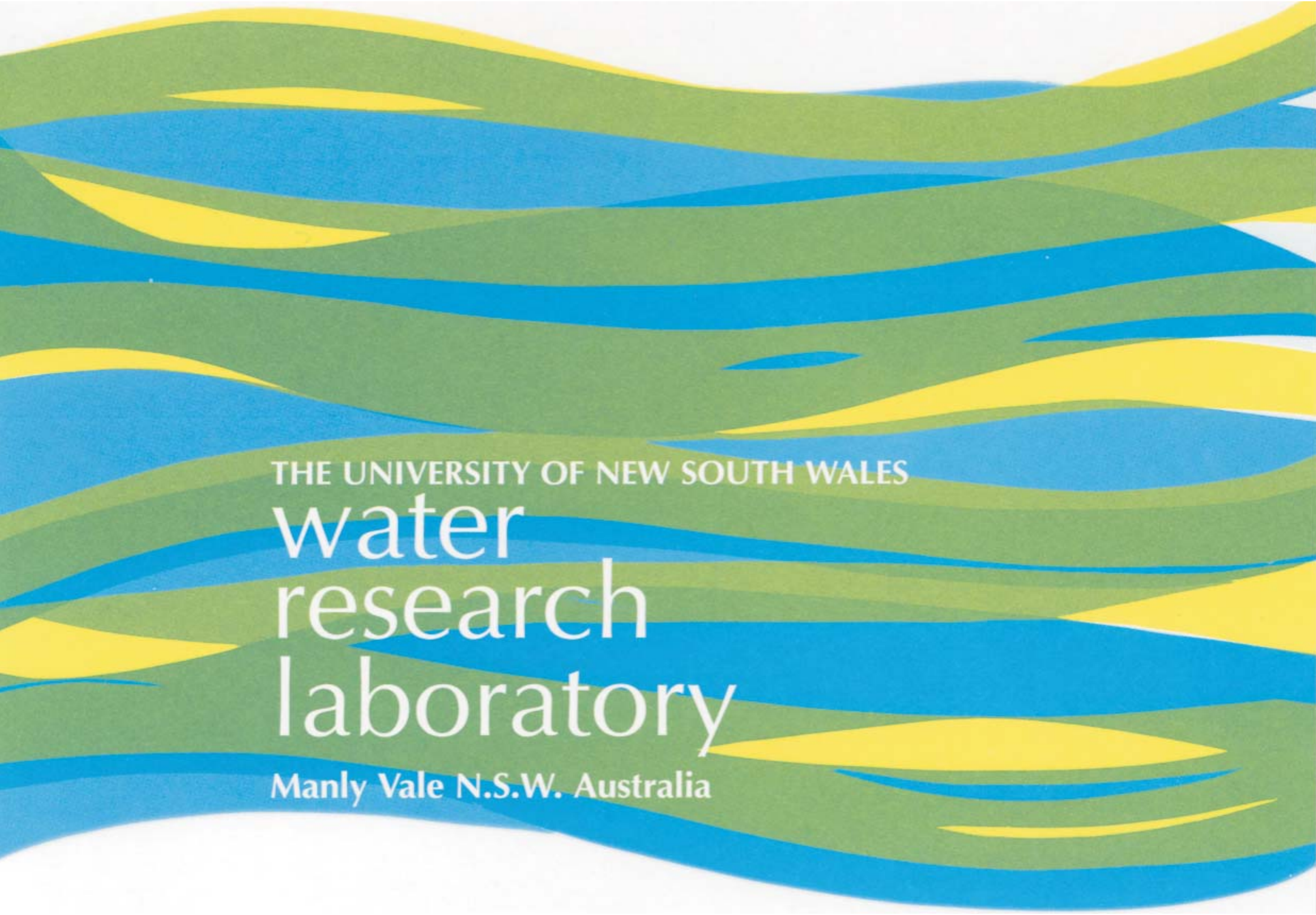

NEPEAN RIVER PUMP AND PIPELINE FOR PENRITH LAKES DEVELOPMENT CORPORATION

by

A M Badenhop, B M Miller, I R Coghlan and K Bishop

Technical Report 2005/16
March 2006

THE UNIVERSITY OF NEW SOUTH WALES
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING
WATER RESEARCH LABORATORY

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1. INTRODUCTION

1.1 Background

The Penrith Lakes Development Corporation (PLDC) has an agreement with the NSW Government to deliver an Urban Development Area and Lakes Scheme upon the completion of quarrying at Penrith Lakes. Design of the Penrith Lakes Scheme commenced in the early 1980's and a current plan of the site is found in Figure 1. Since this time, many studies have been conducted to optimise the design of the lakes and minimise the environmental impact of the plan. An integral component of the plan is sourcing enough water to maintain healthy operating levels for the lakes so that their amenity is reliable. While the lakes currently operating receive only catchment runoff, previous studies (Department of Planning, 1984) confirmed that an alternative source of water would be required to complete the final lake design and that the Nepean River would be the most appropriate source of water for both quantity and quality.

Maunsells have been commissioned by PLDC to design a pump and pipeline system, along with pumping rules, for the extraction of water from the Penrith Weir pool and delivery into the Penrith Lakes. The Water Research Laboratory (WRL) was commissioned as a sub-consultant by Maunsells specifically to investigate the following aspects of the pump and pipeline system.

1.2 Scope

Assessment was made of the available water at Penrith Weir and what volumes are physically available to Penrith Lakes based on a long time-series of both gauged and synthesised flows at Penrith Weir. This assessment included variations to the weir flows with proposed environmental releases from the catchment dams.

Numerical simulation was undertaken of the Penrith Lakes with 95 years of rainfall, river flow and environmental conditions to assess what lake levels may be maintained and how long it may take to initially fill the Penrith Lakes. An extensive range of scenarios were considered with various pumping capacities and pumping rules. The numerical model developed considered water input from the Penrith Weir, local catchment runoff, evaporative losses, groundwater losses, water exchange through the system and water return back to the river. In addition to the water levels in the lakes, the modified river flows and the lake exchange (flushing) flows were extracted from the modelling.

A review was undertaken of the water quality requirements within the Penrith Lakes and the results of previous water quality process modelling. This review made recommendations as to the volume of flushing flows that would be required to provide any significant advantage for lake quality. It also made recommendations as to the water quality that would be acceptable for pumping into Penrith Lakes from Penrith Weir and the suitability of the currently available data for making this recommendation. It was beyond the scope of works here to determine the operational water quality controls for the Penrith Lakes, but rather, this work concentrated on the water quality issues that may be affected by the pump and pipeline.

The environmental flow requirements for the Nepean River from Penrith Weir to the discharge point of the Penrith Lakes Scheme was assessed through field investigations of the ecological requirements and hydraulic behaviour of the barriers to fish passage. This, combined with other previous studies and the findings of the Hawkesbury Nepean Forum on Environmental Flows, provided a recommendation as to the flow requirements of the river.

Finally, the environmental flow requirements of the Nepean River were considered along with the water quality requirements and water balance needs of the Penrith Lakes to make recommendations as to the pump capacity and the cease to pump rules for a transfer of water from Penrith Weir and into Penrith Lakes. Recommendations were also made for further data collection programs which may assist optimizing these pumping rules in the future.

2. FLOWS AT PENRITH WEIR

2.1 Available Data

Flow data for the Nepean River was obtained from two different sources for the period January 1, 1909 to December 31, 2004. Data for the first period: January 1, 1909 to December 24, 1995 was sourced from WRL Technical Report 2003/01 (Hawkesbury-Nepean Estuary Saline Dynamics Model Calibration). This report used flow values from a SMEC-HSPF Model for the Nepean River at Yarramundi. The second data source was the Sydney Catchment Authority (SCA). The SCA provided historical gauge data for flow rates of the Nepean River at Penrith Weir from December 25, 1995 to December 31, 2004. It should be noted that the data provided by the SCA contained some voids, apparently due to occasional equipment malfunction or damage. These voids were replaced with the median flow value for the data set. This total time series was used as the basic input for the model and all other environmental parameters were incorporated in the model for this same period of time.

Issues with the accuracy of gauging at Penrith Weir have been raised in the Hawkesbury-Nepean River Management Forum final report (2004), with the Penrith Lakes Water Committee (2005) citing errors in the order of 70%. Greatest inaccuracies are believed to occur at low flows (less than 150 ML/day), as small changes in water depth correspond to large changes in flows due to the width of the weir. The accuracy of the measurement is limited by the accuracy of the sensor and therefore the relative error will be highest at low flows. Blockage of the fish way intake also leads to inaccuracies in the measurements. The accuracy of the water level measurements converted to flows is best at medium flow rates. WRL has investigated the accuracy of the rating curve during flood studies and has found no documented knowledge of the accuracy of the rating curve below 10 000 cumecs.

2.2 Existing Flow Regimes at Penrith Weir

The current flow regime at Penrith Weir has been analysed in several permutations. In Section 3 of this report, flow rates of 170, 350 and 500 ML/day at Penrith Weir were considered for environmental flow protection. The total probability of exceeding these flow values was calculated for the complete data set, by month (seasonal analysis) and by decade (long term-trend analysis). For these same categories, 90th, 50th and 10th percentiles were also calculated.

Flow statistics for the full 1909-2004 dataset are given in Table 1. These values show that the Nepean River exceeds 170 ML/day only 59% of the time and 350 ML/day just over 30% of the time. The probability of the flow exceeding 500 ML/day is only 5% less than it exceeding 350 ML/day. The median flow of the Nepean River at Penrith Weir over the whole historical dataset is 205 ML/day.

Table 1
Analysis of Total Probability of Flows for Nepean River 1909-2004

Quantity and Units	Value
Probability of flow exceeding 170 ML/day (%)	59
Probability of flow exceeding 350 ML/day (%)	34
Probability of flow exceeding 500 ML/day (%)	29
90th Percentile of Flow (ML/day)	98
50th Percentile of Flow (ML/day)	205
10th Percentile of Flow (ML/day)	4687

Monthly flow statistics for the 1909-2004 dataset are given in Table 2 and Figure 2. These figures show that the Nepean River is very seasonal, with peak flows in autumn through winter and smaller flows through spring and summer.

Table 2
Analysis of Monthly Probability of Flows for Nepean River 1909-2004

Quantity	J	F	M	A	M	J	J	A	S	O	N	D
% > 170 ML/day	51	57	62	67	71	68	67	65	58	51	46	48
% > 350 ML/day	24	33	37	36	37	38	43	40	38	32	27	23
% > 500 ML/day	19	27	31	28	29	33	38	37	34	27	23	17
90th %ile (ML/day)	83	91	105	118	124	124	128	120	102	91	83	77
50th %ile (ML/day)	181	194	230	242	242	231	298	254	207	183	157	167
10th %ile (ML/day)	2293	6716	4890	5513	7631	11356	7879	6297	3739	3661	2719	1474

Flow statistics for each decade of the 1909-2004 dataset are given in Table 3 and Figure 3. These figures show that the Nepean River has experienced extremes of climate, with severe droughts as well as times of abundant water. There were two periods of severe drought felt during this time; one during the early 1940's and another from 1999 to 2004. During these droughts, the median river flow was approximately 145 ML/day and the flow exceeded 90 per cent of the time was approximately 70 ML/day. In stark contrast to this, there were also three decades of relatively abundant rainfall; from 1950 to 1980. During this time median river flows were in the order of 300 ML/day, with 10 per cent of flows exceeding 12,000 ML/day.

Table 3
Analysis of Probability of Flows for Nepean River 1909-2004 by Decade

Quantity and Units	1909-1918	1919-1928	1929-1938	1939-1948	1949-1958	1959-1968	1969-1978	1979-1988	1989-1998	1999-2004*
% > 170 ML/day	61	53	64	39	68	67	76	63	52	42
% > 350 ML/day	36	30	34	18	47	43	45	37	28	14
% > 500 ML/day	29	26	26	15	42	37	40	30	24	8
90th %ile (ML/day)	99	96	120	78	115	101	128	99	101	69
50th %ile (ML/day)	213	181	216	143	302	269	294	221	176	148
10th %ile (ML/day)	4231	4048	3210	1291	12418	6157	8262	3938	4457	430

* Note that last entry of this table from 1999-2004 is not a full decade, however the results are still valid over this period.

2.3 Changes to Environmental Flow Regimes at Penrith Weir

The need for environmental flows along the Hawkesbury-Nepean has recently been reviewed in the final report of the Hawkesbury-Nepean River Management Forum (HNRMF, 2004). Key recommendations relevant to the scope of this report are outlined in Table 4. Note that environmental flows have been defined in terms of transparent and translucent flows. Transparent flows occur when the same volume of water that enters a dam is allowed to pass through the dam (ie. none is stored). Translucent flows are a percentage of the flow that enters a dam or weir that must be allowed to pass through, and are usually a percentage that must pass through in excess of the volume of transparent flow.

Table 4
Recommendations of the Hawkesbury Nepean River Management Forum (2004)

WFE1	Environmental flows for the upper Nepean River system and Warragamba River. *That the following environmental flow regimes replace existing provisional flows in conjunction with recommendations PEF11-PEF14 inclusive.* Upper Nepean Dams Translucent flow of 20% and Transparent Flow 80th percentile
WFE6	Management of Environmental Flows *That the management and operational principles for the release of all environmental flows ensure that:* • *Environmental flows should be allowed to pass downstream of weirs;* • *Environmental flow releases should be protected from extraction*
PEF8	Protection of Environmental Flows from extraction *That the environmental flows recommended by the Forum be protected from extraction through compliance with the Water Management Act 2000 as environmental health water.*
PEF20	Penrith Lakes *That water quality and quantity issues relating to the management of the Penrith Lakes Scheme be clearly defined and appropriate conditions included within the water management plan to ensure protection of river health in river reached downstream of Penrith Weir.*

The HNRMF found that the environmental flow option that would provide the best water quality outcome for the Hawkesbury-Nepean River was 20% translucency combined with 80th percentile transparency releases from dams in the upper Nepean. For flows exceeded more than 80% of the time (i.e. low flows), the water coming into the dams should equal the water leaving the dam, and for any flows greater than this value, 20% of the inflow volume higher than the transparent flow should also be released. The most appropriate scenario for Warragamba Dam was found to be 95th percentile transparency and 80% translucency. Investigations into causes of algal blooms found that blue-green algae (cyanobacteria) are less likely to build up in the river if the flow is greater than 170 ML/day at Penrith Weir. If the recommended environmental flows are adopted, the flow rate of 170 ML/day at Penrith Weir should be exceeded 97.5% of the time, however it is currently only exceeded 61% of the time (HNRMF, 2004).

The environmental flows at Penrith Weir are sourced from Warragamba Dam and the flow passing through the upper Nepean weirs at Pheasants Nest and Broughtons Pass, which are fed by environmental flows from Cataract, Cordeaux, Avon and Nepean Dams. At the time of writing, the current environmental flow regime has no translucent flow allowance, instead it has only a 95th percentile transparent flow. The total of these flows that could reach Penrith Weir in the absence of any other extractions is 45.5 ML/day. However, under the recommendations from HNRMF (2004), it is proposed that each of these transparent flows be increased. These recommendations would see the environmental flow at Penrith extended to 125.6 ML/day. On top of this, translucent flows of 20% would be added. This means that for when flow is in excess of the transparent environmental flow value, 20% of this surplus must also be protected from extraction. The values of these flows are shown in Table 5.

Table 5
Current and Proposed Environmental Flow Regimes for the Upper Nepean System and Warragamba River

Location	**Current Translucent Flow (%)**	**Current Transparent Environmental Flow (percentile)**	**Current Volume of Environmental Flow Release (ML/day)**	**Proposed Translucent Flow (%)**	**Proposed Transparent Environmental Flow (percentile)**	**Proposed Transparent Environmental Flow Release (ML/day)**
Pheasants Nest Weir	0	95th	10.5	20	80th	63
Broughtons Pass Weir	0	95th	1.7	20	80th	20.3
Warragamba Dam	0	(unknown)	33.3	20	95th	42.3
Total Flow at Penrith Weir	0	-	45.5	20	-	125.6

If the proposed environmental flow releases are implemented, flows at Penrith Weir will significantly increase. It is important to note that current statistical flows at Penrith Weir have been used for the purpose of assessing extraction volumes in this study. Trigger flow rates for pumping are therefore dependant on current environmental flow releases. Should the proposed environmental flow releases be adopted in the future, the triggers would need to rise by the additional environmental flow release volumes as they will be protected from extraction. The precise methodology for determining this increase has not been determined in this study.

3. WATER BALANCES IN PENRITH LAKES

3.1 Overview

WRL configured a dynamic water balance model of the Penrith Lakes Scheme with the latest (2005) design as seen in Figure 1. The model was configured in order to assess the impacts of various pumping regimes on the Penrith Lakes Scheme in terms of water extraction from Penrith Weir, remaining flow for environmental requirements of the Nepean River, Penrith Lakes levels and flushing/return to river volumes.

The premise of the model is the use of the Nepean River as a source of water for the lakes with water from the Nepean River pumped into Main Lake A and the option to pump internally from Main Lake A into the Regatta Lake. While this configuration does not reflect the Deed arrangements, Keogh (2004a) demonstrated that adequate control of lake levels in the Regatta Lake and the other main lakes could be best maintained by pumping water from the river into Main Lake A and pumping to the Regatta Lake from Main Lake A as required. When water was pumped directly to the Regatta Lake, operating levels (Table 6) were consistently exceeded. The model included the four treatment lakes upstream of the Regatta Lake as well as the four main lakes within the scheme (the Regatta Lake, Main Lake A, Main Lake B and the Wildlife Lake). In addition, a treatment lake for water pumped from the Nepean River was included in the model design. The lakes were interconnected via a series of culverts, lake-to-lake weirs and lake-to-river weirs. However, it should be noted that weirs overtop only during flood conditions. Lake-to-river weirs overtop only during flood events greater than the 1 in 20 year flood, with the exception of the Wildlife Lake which overtops in the 1 in 5 year flood. Figure 4 shows a schematic of the model configuration.

The relationship between lake water level, volume and surface area was determined for each lake by ArcInfo GIS analysis of the 2005 scheme design drawing supplied to WRL by PLDC.

Culvert and weir flow was defined using relationships of discharge to water level on either side of the culvert or weir. The water level in the Nepean River was calculated using rating curves previously determined at the four river-to-lake weir locations (Anderson et al., 2004). The mathematics used in the model are provided in Appendix A.

The model was configured to output daily lake levels, input and output flows for each lake, volumes pumped and return flows to the river.

3.2 Data Used in the Model

3.2.1 River Flow

Flow data records for the Nepean River were gained from two different sources for the period January 1, 1909 to December 31, 2004. Data for the first period: January 1, 1909 to December 24, 1995 was sourced from WRL Technical Report 2003/01 (Hawkesbury-Nepean Estuary Saline Dynamics Model Calibration). This report used flow values from a SMEC-HSPF Model for the Nepean River at Yarramundi. Sydney Catchment Authority provided historical gauge data for flow rates of the Nepean River at Penrith Weir from December 25, 1995 to December 31, 2004. Voids were replaced with the median flow value for the data set.

3.2.2 Climate Data

Historical daily rainfall and evaporation records were obtained from the Bureau of Meteorology. For rainfall, data series from 3 recording sites were used to determine the best approximation for the Penrith Lakes Catchment Area; Penrith Lakes AWS was used in preference to Penrith Ladbury Avenue, and data from Prospect Dam was used only when data was not available for both Penrith Lakes AWS and Penrith Ladbury Avenue. As a result, the Penrith Ladbury Avenue site was predominately used for the time series from 1909 to 2004 and Penrith Lakes AWS for 1995 to 2004.

The closest evaporation site with a record longer than 10 years was Prospect Dam, which has records extending back to 1974. This data was normalised according to a method applied by GHD (1981) using a conversion factor of 1.18 for pre-June 1974 records and 1.03 for post June 1974 records between Prospect and the Penrith Lakes sites. This conversion was necessary as the method of measurement had changed. These recordings were not always regular and some large sections of the series were missing data. Regular reliable data were only available for one twelve year period. Voids in this period were filled by fitting a curve to the data and synthesising values according to the regression analysis. This twelve year series was repeated from 1909 to 1995. Data for the period 1995 to 2004 was recorded much more consistently, hence it was not necessary to modify the values once the conversion factor was applied.

3.2.3 Catchment Runoff

Keogh (2003, 2004a) developed a rigorously calibrated catchment runoff model for the Penrith Lakes system. To establish the model, Keogh extensively analysed catchment landuse and subcatchments to define the most accurate catchment network for use in ARBM-RAFTS modelling tools. Daily results for simulations from 1951 - 2000 were provided by PLDC for use by WRL. In order for WRL to extend these results to a 95 year simulation period, these results were fitted with individual regression analysis curves for each lake, as a function of daily rainfall. The periods 1909 - 1950 and 2000 - 2004 were then generated by WRL directly from rainfall data. The regression analysis for each lake are shown in Appendix B.

3.2.4 Groundwater

The Independent Expert Panel (2004) review of groundwater information concluded that Penrith Lakes would create a regional groundwater sump, and that this could not currently be quantified. The main source of groundwater would be from rainfall infiltrating the lower terrace. Seepage from the Nepean River through the clay barrier and flow through low permeability shales underneath the lake and Rickabys Creeks Gravels to the east would contribute much smaller volumes of groundwater. The Panel found that the amount of groundwater could not be quantified, however, the proportion of groundwater to stormwater inflow is expected to be small. GHD (1981) estimated seepage loss from a design surface area of 725 ha to be approximately 3000 ML/year with a recharge catchment slope of 0.03, and a hydraulic transmissivity of 10^{-4} cm/s for the compacted fill. They determined that although natural groundwater flow has been diverted around the site, seepage loss will occur through the compacted fill. Keogh (2003) tried to estimate the impact of groundwater flow into the lakes caused by rainfall infiltration through the compacted fill lining of the lakes (hydraulic conductivity $K = 10^{-6}$ m/s and found the maximum inflow likely to be 0.8 ML/yr, which would clearly be insignificant. Due to the inconclusiveness of the studies, the GHD (1981) value was used as a conservative (high) constant seepage loss from the lakes.

3.2.5 Lake Design and Operation

Lake volumes and surface area relationships were created based on the Penrith Lakes design issued January 25, 2005.

3.2.5.1 Operating Levels

Current operating levels for the lakes were provided by PLDC and are summarised in Table 6. It should also be noted that the Memorandum of Understanding between PLDC and the Olympic Coordination Authority (OCA) in 1999, included the provision that the operating height for the Regatta Lake would be 15 m with operational variation of 14.75 – 15.4 m (Independent Expert Panel, 2004).

Table 6
Penrith Lakes Scheme Lake Operating Levels

Lake	Operating Level (m RL)	Drawdown to be exceeded only 5% of the time (m)*
Cranebrook Lake	18	n/a
Boyces Lake	18	n/a
North Pond	16.5	n/a
Middle Basin	15.9	n/a
Final Basin	15.45	n/a
Regatta Centre	15	0.25#
Main Lake A	14	0.5
Main Lake B	12	0.5
Wildlife Lake	10	0.5

*This is equal to the 95th percentile drawdown
Deed allows 0.5 m.

3.2.5.2 Weir levels

The 1987 Deed envisaged weirs that would allow 1 in 2-5 year ARI floods to enter the Wildlife Lake, and 1 in 20 year ARI floods to enter the Regatta and Main Lakes. However, the Penrith Lakes Water Committee draft review (2005) recommended that the weir height for the Wildlife Lake be increased to 1 in 10 year ARI flood levels. They also investigated increasing the weir levels for the main lakes to 1 in 50-100 year ARI flood levels, however PLDC advised that these levels would increase scouring due to the higher head levels. The weir dimensions used in the model are detailed in Table 7.

Table 7
Weir Dimensions used in WRL Water Balance Model

Lake	Lake-to-River Weir Details			Lake-to-Lake Weir Details	
	RL (m)	Length (m)	ARI (years)	RL (m)	Length (m)
Regatta Lake	24	500	20	21.1	185
Main Lake A	22	420	20	20.7	470
Main Lake B	21	440	20	20.1	300
Wildlife Lake	21	500	3-5	10.8	270

3.2.5.3 Culverts

Culverts have been included in the Scheme design to connect the lakes for lake level maintenance and draining the lakes in storm events. WRL was commissioned by PLDC to investigate appropriate culvert design for the lakes scheme. At the time of water balance model development, the culvert design had not been finalised. The dimensions used to define the culverts in the model are based on the latest results in WRL Technical Report 2004/13 (Anderson et al., 2004) and are shown in Table 8.

Table 8
Culvert Dimensions used in WRL Water Balance Model

Lake	Culvert Details			
	Number	Length (m)	Width (m)	Breadth (m)
Regatta Lake	1	177	1.2	3.6
Main Lake A	2	205	1.2	4.2
Main Lake B	1	210	1.2	3
Wildlife Lake	1	150	0.6	1.2

In this study, no operational controls such as sluice gates were used on the culverts. These may be implemented in the future to optimise lake levels.

3.3 Scenarios Considered

Several scenarios were simulated to determine the impact of pumping rates on the lake water levels and flushing flows. The emphasis of the models was the impact of different pumps, cease-to-pump rules and pumping either all water available or only sufficient water to maintain operating levels.

The scenarios modelled are detailed in Table 9. Lake level controls on pumping indicate that pumping from the river occurs only when lake levels in Main Lake A or B are less than the operating level and the flow over Penrith Weir is greater than the minimum flow over Penrith Weir.

Table 9
Scenarios Modelled

Scenario	Minimum Flow Preserved Over Weir	Type of Pumping	Pump Capacity	Lake Level Control	Other
A	-	None	-	-	No pumping
B	170 ML/day	Variable	1.7 m^3/s	No	
C	170 ML/day	Variable	1.7 m^3/s	No	Catchment inflows ↓ 20%
D	350 ML/day	Variable	1.7 m^3/s	No	
E	170 ML/day	Variable	1 m^3/s	No	
F	170 ML/day	Variable	1.7 m^3/s	Yes	
G	500 ML/day	Variable	1.7 m^3/s	No	
H	170 ML/	Fixed	1.7 m^3/s	No	
I	350 ML/day	Fixed	1 m^3/s	No	
J	170 ML/day	Variable	2 m^3/s	No	
K	170 ML/day	Fixed	1 m^3/s	No	
L	500 ML/day	Fixed	1 m^3/s	No	
M	350 ML/day	Fixed	1.7 m^3/s	No	
N	500 ML/day	Fixed	1.7 m^3/s	No	
O	350 ML/day	Variable	1 m^3/s	No	
P	170 ML/day	2 Stage Fixed Rates	0.7 m^3/s + 0.3 m^3/s	No	
Q	350 ML/day	2 Stage Fixed Rates	0.7 m^3/s + 0.3 m^3/s	No	
R	170 ML/day	Fixed	1 m^3/s	No	Filling scenario
S	350 ML/day	Fixed	1 m^3/s	No	Filling scenario
T	500 ML/day	Fixed	1 m^3/s	No	Filling scenario
U	170 ML/day	Fixed	1.7 m^3/s	No	Filling scenario
V	350 ML/day	Fixed	1.7 m^3/s	No	Filling scenario
W	500 ML/day	Fixed	1.7 m^3/s	No	Filling scenario
X	170 ML/day	Fixed	1.0 m^3/s	Yes	
Y	350 ML/day	Fixed	1.0 m^3/s	Yes	
Z	170 ML/day	Fixed	1.7 m^3/s	Yes	
AA	350 ML/day	Fixed	1.7 m^3/s	Yes	
AB	170 ML/day if flow > 500 ML/day recorded for ≥ 3 consecutive days in past 2 months, else 500 ML/day	Fixed	1 m^3/s	No	Bishop's Fish Rule

For each scenario water could be pumped from Main Lake A to the Regatta Lake provided the levels in the Regatta Lake were below the operating level. The capacity of this pump was 0.5 m^3/s. Pumping ceased when flow at Penrith Weir exceeded 5000 ML/day to avoid poor water quality as recommended by Keogh (2004a). Over the historical period, this would reduce the time that pumping could occur by 9.6%. With a 1 m^3/s fixed rate pump this reduces the volume of water that can be pumped on average by 3037 ML/yr.

To determine the drawdown statistics in the lakes, the initial lake levels were set at the lake operating levels (Table 6). For the filling scenarios the initial lake level was 0.5 m water depth. Note that if a fixed rate pump was used, pumping could not commenced until the flow over the weir exceeded the sum of the minimum flow over the weir and the maximum pumping rate for each pump. The maximum pumping rate is 86.4 ML/day for a 1.0 m^3/s pump, and 147 ML/day for both the 1.7 m^3/s and 2.0 m^3/s pump (due to the constraint of pumping a maximum of 147 ML/day).

3.4 Comparison of Lake Levels Under Various Pumping Rules

This section describes the drawdowns expected within the Penrith Lakes Schemes based on various pumping rules. These were compared with the operating rules which require that the Regatta Lake drawdowns be no more than 0.25 m (although 0.5 m is specified in the Deed) and that Main Lakes A and B and the Wildlife Lake drawdowns only exceed 0.5 m for 5% of the time. Percentages are based on the number of days in the 95 years of simulated record.

3.4.1 No Pumping Scenario

Table 10 presents the drawdowns in the lakes if no water is pumped from the Nepean River. The drawdown levels are unacceptably high 10% of the time. Most importantly, the median condition has excessive drawdown for Main Lakes A and B.

Clearly, an additional source of water is required to satisfy the Penrith Lakes operational requirements.

Table 10
Conditions with No Pumping from River (Scenario A)

Lake	Drawdown (m) Exceeded X% of the time		
	5%	10%	50%
Regatta	0.4	0.3	0.0
Main Lake A	6.1	5.5	2.0
Main Lake B	6.2	5.9	2.8
Wildlife Lake	0.9	0.7	0.1

3.4.2 High Rate Pumping Scenario

The high rate pumping scenario was based upon a fully variable rate pump with a maximum pumping rate of 1.7 m^3/s, with a cease to pump rule such that the flow remaining over the Penrith Weir was not below 170 ML/day. These constraints were derived from engineering and previous agreements.

Table 11 presents the drawdowns from this scenario. It is important to realise that even under these pumping conditions, the drawdowns occurring 5% of the time are still larger than the 0.5 m desired under the operational rules. As such, the operational rules must be expected to be occasionally breached under any pumping rule.

Table 11
Conditions with Maximum Pumping from River (Scenario B)

Lake	Drawdown (m) Exceeded X% of the time		
	5%	10%	50%
Regatta	0.3	0.1	0.0
Main Lake A	0.7	0.5	-0.1
Main Lake B	0.8	0.6	-0.2
Wildlife Lake	0.6	0.4	-0.5

The distribution of these events that breach the operational rule can be seen in Figure 5. This graph shows that the operational rule is not breached on an annual or seasonal basis, but based on longer term drought trends; hence its affects are randomly scattered across the time series. There are periods such as 1940 and 2003 when the operational rule could be expected to be breached continuously for a long period of time.

3.4.3 Comparison Of Different Pumping Rates

In order to assess the advantage of pumping with a 1.7 m^3/s pump versus a 1.0 m^3/s pump, scenarios were considered with fixed rate pumps (i.e. off or fully pumping) with cease to pump rules of remaining flow of 170 ML/day, 350 ML/day and 500 ML/day. Pumping continues whenever possible regardless of the level in the lakes.

For all scenarios other than the no pumping scenario, the median conditions of Lake levels are less than 0.1 m drawdown. As such, none of these median statistics are presented in the following tables.

Table 12 and Table 13 show the comparison of these scenarios.

Table 12
Drawdowns Exceeded 5% of the Time
Fixed Rate Pumps and Various Cease to Pump Rules

Cease to Pump	**170 ML/day**		**350 ML/day**		**500 ML/day**	
Pump Rate (m^3/s)	**1.0**	**1.7**	**1.0**	**1.7**	**1.0**	**1.7**
Scenario	***K***	***H***	***O***	***M***	***L***	***N***
Regatta	0.4	0.4	0.4	0.4	0.4	0.4
Main Lake A	0.9	0.9	1.2	1.1	1.4	1.2
Main Lake B	1.3	1.2	1.7	1.4	3.1	1.6
Wildlife Lake	0.7	0.7	0.8	0.8	0.8	0.8

Table 13
Drawdowns Exceeded 10% of the Time
Fixed Rate Pumps and Various Cease to Pump Rules

Cease to Pump	**170 ML/day**		**350 ML/day**		**500 ML/day**	
Pump Rate (m^3/s)	**1.0**	**1.7**	**1.0**	**1.7**	**1.0**	**1.7**
Scenario	***K***	***H***	***O***	***M***	***L***	***N***
Regatta	0.2	0.2	0.2	0.3	0.3	0.3
Main Lake A	0.7	0.6	0.8	0.8	1.0	0.9
Main Lake B	0.8	0.7	1.1	0.9	1.9	1.1
Wildlife Lake	0.5	0.5	0.6	0.6	0.6	0.6

It can be seen that only in the cease to pump rule of 500 ML/day is there any significant difference achieved in the long term statistical levels in the lakes by using a 1.7 m^3/s pump rather than a 1.0 m^3/s pump.

3.4.4 Comparison of Two Phase Pumping over Single Phase Pumping

The cease to pump rules have been specified such that the defined flow rate must be maintained over Penrith Weir. With a single phase pump, this means that pumping cannot commence until the weir flow rate is the sum of the pumping rate and the preserved rate. However, in the case of a two phase pumping arrangement, a first pump can commence at a certain rate, then the second pump start later. This allows for a greater proportion of time that pumping could occur, albeit often at a lower rate.

Table 14 presents drawdowns occurring 5% of the time from the comparison between a single pump of 1.0 m^3/s rate with two pumps of 0.7 m^3/s and 0.3 m^3/s rates while the preserved Penrith Weir flow is either 170 ML/day or 350 ML/day.

Table 14
Drawdowns Exceeded 5% of the Time
Single and Two Phase Pumping – Two Cease to Pump Rules

Cease to Pump	**170 ML/day**		**350 ML/day**	
Pump Rate (m^3/s)	**1.0**	**0.7 + 0.3**	**1.0**	**0.7 + 0.3**
Scenario	***K***	***P***	***O***	***Q***
Regatta	0.4	0.4	0.4	0.4
Main Lake A	0.9	0.9	1.2	1.2
Main Lake B	1.3	1.2	1.7	1.7
Wildlife Lake	0.7	0.7	0.8	0.8

It can be seen that two phase pumping does not provide any significant advantage to Lake levels. However, other engineering reasons may prevail why two stage pumping would be advantageous.

3.4.5 Comparison of Pumping only When Lake Levels are Low

All of the scenarios considered above assume that pumping will occur whenever there is sufficient flow in the river. The waters pumped into the Penrith Lakes in excess of what is required for water balance will contribute to a flushing flow which in turn will return to Nepean River. These aspects of the additional pumping are discussed further in Sections 4 and 5.

Table 15 compares drawdowns occurring 5% of the time whilst pumping continuously with drawdowns occurring whilst pumping only when Lakes A or B are low. Results are for a single pump of 1.0 m^3/s rate with the preserved Penrith Weir flow either 170 ML/day or 350 ML/day.

Table 15
Drawdown Exceeded 5% of the Time: Comparison of Continuous Pumping to Pumping only When Lakes are Low – Two Cease to Pump Rules

Cease to Pump	**170 ML/day**		**350 ML/day**	
Pump Rate	**1.0 m^3/s**	**1.0 m^3/s Only when low lakes**	**1.0 m^3/s**	**1.0 m^3/s Only when low lakes**
Scenario	***K***	***X***	***O***	***Y***
Regatta	0.4	0.4	0.4	0.4
Main Lake A	0.9	1.0	1.2	1.3
Main Lake B	1.3	1.4	1.7	1.8
Wildlife Lake	0.7	0.8	0.8	0.9

It can be seen that as far as water balance is concerned, there is no disadvantage in pumping from the river only when lake levels are low.

3.4.6 Trigger Rule as Proposed by Bishop

A pumping rule was proposed by Bishop (2004) which considered raising the limit of pumping from 170ML/day to 500ML/day if there had not been a flow of 500ML/day occurring for a duration longer than 3 days within the past 60 days. The reasoning behind this pumping rule is described in more detail in Section 5.

Modelling of this rule showed that there was only 62 days in the past 95 years where pumping would have needed to cease if the trigger rule were in place. As such, there is no statistical change to the levels in the Lakes by applying this rule.

3.4.7 Volumes Pumped

The volume of water pumped is presented here in Table 16 so that other engineering decisions may be based upon this information. The volumes are presented as the average volume pumped per year for each of the scenarios discussed in Section 3.4.

Table 16
Average Volume Pumped Per Year For Various Scenarios

Scenario	Average Volume Pumped Per Year (ML)
A	0
B	19,199
K	10,075
H	14,395
O	7,090
M	10,423
L	5,443
N	9,024
P	10,891
Q	6,790
X	3,353
Y	2,790
AB	10,022

3.5 Lake Filling Times

3.5.1 Assessment Method

The time to fill the Penrith Lakes Scheme was assessed using the water balance model developed to determine the pumping rules for the Lakes Scheme. Several scenarios were simulated in order to determine the likely time taken for the lakes to fill, subject to a number of different pumping rules.

It was assumed that the Regatta Lake was already at operating level and that there was water to a depth of 0.5 m in each lake (from rainfall and other inputs prior to pumping), before the filling simulation commenced. To gain a complete spectrum of filling times for each scenario over the historical period, the model was started from the beginning of each year from 1909 until the present. As a result there were up to 92 runs completed for each scenario, taking into account all historical climate conditions; droughts and periods with above average rainfall. These results indicate best and worst case scenarios for expected filling times, and have been presented as percentiles of years-to-fill. It should also be noted that Lake B always filled after Lake A, and hence may be used as an indicator for when all lakes have been filled.

The scenarios that were undertaken to properly ascertain the filling time were:

- Scenario 1 – pumping at a rate of up to 1.0 m^3/s when flows in the Nepean River exceeded 170 ML/day (fixed rate pumping)
- Scenario 2 – pumping at a rate of up to 1.0 m^3/s when flows in the Nepean River exceeded 350 ML/day (fixed rate pumping)
- Scenario 3 – pumping at a rate of up to 1.0 m^3/s when flows in the Nepean River exceeded 500 ML/day (fixed rate pumping)
- Scenario 4 – pumping at a rate of up to 1.7 m^3/s when flows in the Nepean River exceeded 170 ML/day (fixed rate pumping)
- Scenario 5 – pumping at a rate of up to 1.7 m^3/s when flows in the Nepean River exceeded 350 ML/day (fixed rate pumping)
- Scenario 6 – pumping at a rate of up to 1.7 m^3/s when flows in the Nepean River exceeded 500 ML/day (fixed rate pumping).

3.5.2 Results

The results of the filling simulations are given in Table 17. The most likely scenario is that of Scenario #2, using a 1.0 m^3/s fixed rate pump to extract water from the river above a flow of 350 ML/day. In this scenario, the median time to fill all of the lakes was 2.6 years. With more stringent pumping rules and in a time of drought, filling time may exceed 13 years. During a wet period, the lakes may fill in under a year. The more likely scenarios saw the time to fill the lakes oscillate between 2 and 3 years.

Table 17
Number of Years to Fill Lakes A and B

Scenario	**1**		**2**		**3**		**4**		**5**		**6**	
Percentile	**Lake A**	**Lake B**	**Lake A**	**Lake B**	**Lake A**	**Lake B**	**Lake A**	**Lake B**	**Lake A**	**Lake B**	**Lake A**	**Lake B**
5th	0.75	0.96	1.07	1.4	1.16	1.49	0.53	0.69	0.64	0.83	0.72	0.87
50th	1.66	2.27	2.59	3.31	3.12	3.79	1.23	1.39	1.48	2.2	1.85	2.58
95th	4.46	5.71	8.97	11.08	11.17	13.46	3.26	4.16	5.71	6.26	5.72	7.86

An example of the spread of years required to fill the lakes (using Lake B as an indicator) can be seen in Figure 6. This shows a plot of the number of years required to fill Lake B in Scenario #2 (1.0 m^3/s, 350 ML/day), based on starting the filling in every year from 1909 to 1990. 1990 was the most recent year in which the model could commence running and lake filling be completed.

4. INTERNAL LAKE WATER QUALITY

The Penrith Lakes design seeks to manage water quality by using smaller lakes (Cranebrook Lakes, North, Middle and Final) located upstream of the main lakes for sedimentation and treatment of the water received from Vincent Creek, Farrells and Scope Creek. Water from the Nepean River will be pumped into a treatment lake and then into Main Lake A, with the option to pump from Main Lake A into Regatta Lake. Recreational lakes will utilise submerged macrophytes, and the wildlife lake emergent macrophytes to improve water quality (Varley, 2004).

The investigation of water quality detailed in this report focuses primarily on the relationship between pollutants and their movement through the lakes due to the specific flows of water through the system, rather than recommending specific treatment methods. In particular, the effects of flushing flows are investigated.

4.1 Water Quality Requirements

Water quality requirements for the lakes were established in the 1987 Deed of Agreement based on the end use of each of the lakes, as detailed in Table 18.

Table 18
End Uses of Lakes as Specified in the Deed

Lake	**End Use**
Main Lakes A & B	Aesthetic value Water surface sports primary and secondary contact Fishing
Rowing Lake	Lake water management Water surface sports –secondary contact. Aesthetic value
Treatment Lake	Lake water management Water surface sports – secondary contact Aesthetic value
Wildlife Lake	Lake water management Wildlife habitat including aquatic and shoreline habitat. Scientific and educational Aesthetic value
Detention Basin	Lake water management. Aesthetic value

Source: Schedule 7 Deed of Agreement Appendix A

All of the end uses listed in Table 18 are those specified in the original Deed. Since that time however, the rowing lakes have become international facilities – the Sydney International Regatta Centre and Penrith Whitewater Stadium. As a result, secondary contact standards are no longer acceptable and primary contact guidelines must be satisfied (ERM Australia, 2001). Adjustments to the end use goals of the lakes have been recommended by the Penrith Lakes Water Committee in their Draft "Review of the Water Principles and Water Plan" in March 2005. The Committee had a low level of confidence that primary contact water quality standards can be consistently achieved in the main lakes and also require that the rowing lakes are maintained to a higher level than the deed.

For these reasons, the Committee have recommended:

- Primary contact water quality in the Regatta/Warm-Up Lake to allow current activities in that lake and at the Whitewater Stadium
- Secondary contact water quality in the main lakes to permit a wide range of water-based activities
- A dedicated swimming precinct associated with a commercial/tourist precinct plus a cordoned-off swimming area within the Warm-up Lake.

Source: Penrith Lakes Water Committee (2005)

These recommended changes are expected to be incorporated into the draft amended SREP 11 being prepared by DIPNR at the time of writing, and in turn, the current Deed may also be amended to incorporate any changes made to SREP 11 (this is currently under negotiation between PLDC and NSW Government) (Penrith Lakes Water Committee, 2005). As part of this scenario, the objective ecological values would be Low for Regatta Lake, and Moderate for Main Lakes A & B and Wildlife Lake. The water quality characteristics for ecological values are defined by ANZECC water quality criteria (Table 19) and the % of time cyanobacteria are visible (20% for Low and 15% for Medium). Low and Moderate ecological value waters achieve the ANZECC guideline values 70% and 80-90% of the time respectively.

The Independent Expert Panel (2004) advised that the current ANZECC and NHMRC requirements for primary and secondary contact recreation should be adopted, in conjunction with recently agreed cyanobacteria guidelines for the site determined by DIPNR and NSW Health. All of the relevant criteria are combined in Table 19.

Table 19
Combined Guidelines for Lake Water

Indicator	**Trigger Value**		**Source**
Chlorophyll-a (µg/L)	5		1
Total Phosphorous (µg/L)	10		1
Filterable Reactive Phosphorous (µg/L)	5		1
Total Nitrogen (µg/L)	350		1
Oxidised Nitrogen (µg/L)	10		1
Ammonium (µg/L)	10		1
Dissolved Oxygen (% saturation)	90-110		1
pH	6.5 – 8.0		1
Turbidity (NTU)	1 - 20		1
Health related	**Primary**	**Secondary**	
Intestinal enterococci	95th percentile ≤ 40 /100 mL	95th percentile ≤ 200 /100 mL	2
Microcystin or cylindrospermopsin toxins	< 5 µg/L		3
Total cyanobacterial biovolume	< 8 mm^3/L OR < 2 mm^3/L if toxin information unavailable.		3

1. ANZECC (2000) Water Quality Guidelines for Slightly Disturbed Freshwater Lakes and Reservoirs
2. NHMRC Australian Guidelines for Recreational Use of Water
3. DIPNR & NSW Health

4.2 Water Quality Issues

Achieving the water quality guidelines for Penrith Lakes will depend on the sources of pollution entering the lakes and the manner in which they persist in the lakes. The most significant pollutants at Penrith Lakes are likely to be human pathogen microorganisms (indicated by streptococci), cyanobacteria (blue-green algae), nutrients and salts.

Water quality monitoring has been conducted at the three southern detention basins, rowing lakes and Main Lake A since 1995. During this time, the lakes have been operating as a closed system with inputs from only runoff, discharges from quarry pits and tailing dams and flows from Scope and Farrells Creek (no input from the Nepean River). The detention basins have been found to be effective in reducing turbidity, nutrients and bacteria, however water quality issues are greater during wet weather and guideline values are sometimes exceeded within the rowing lakes after large storms when water quality from the creeks is very poor, with high levels of faecal coliforms, nutrients, turbidity, oil and grease and litter (ERM Australia, 2001).

Specifically, monitoring of faecal contamination indicators has shown that recreational water quality is within guidelines during dry weather flows, but deteriorates with increasing flows (Independent Expert Panel, 2004). 95th percentile inflow of 43 ML over three days is the critical degradation cut-off for the Rowing and Warm-Up Lakes. Due to microbial die-off, water in the lakes will return to primary contact water quality within 4-6 days of a storm event. This problem may be avoided by longer detention times of inflows, especially during high flow events.

Unlike faecal contaminant indicators, cyanobacteria (blue-green algae) increase to toxic levels during periods of low flows; conditions of available sunlight and nutrients have promoted blooms during February of each year with detection through into Autumn. Blooms have been recorded in the Rowing Lake on 19-25th February, 1997 and 7th January – 4th February, 2003. Blooms have also been recorded in the Main Lake A on 24-31st March, 1998, 14th April 1998, February 2003. Another algal bloom was recorded in all completed lakes in February 2004 (Independent Expert Panel, 2004).

These current issues highlight areas of future concern for the completed lakes. The Independent Expert Panel (2004) expect that microbial water quality in terms of human pathogens will be manageable in the long term, however cyanobacteria are likely to be a problem, limiting the ability of the lakes to reach primary contact recreation standards. Cyanobacteria blooms can only occur when the build-up of nutrients is sufficient for their growth, with growth primarily limited by the availability of phosphorous. The availability of nutrients is affected by the rate of uptake by plants within the lakes and other management strategies. Outbreaks occur during periods of high evaporation and sunlight when nutrients are concentrated through water loss. Salt concentration (measured through high Total Dissolved Solids) occurs at the same time and can be an issue for sustaining freshwater ecosystems.

Water quality issues are likely to be greatest in periods of high flows and periods of low flows, and operation of the lakes will need to be flexible and adapt to these different conditions. Flushing flows may assist in the dilution of accumulating pollutants; however the quality of the flushing water must be better than that of the lakes to be beneficial. The quality will depend on the input sources of Scopes and Farrells Creeks and other catchment runoff and the Nepean River (as the most likely water source for the scheme. It should also be noted that Penrith Lakes Water Committee (2005) have recommended that further investigation be conducted into the use of treated effluent from Penrith Sewage Treatment Plant as the water source). Additionally, residence time of water in the lakes system will also have a large impact on determining water quality (ERM Australia, 2001), as non-conservative parameters will not be flushed if they have time to reach equilibrium.

4.3 Water Quality at Penrith Weir

Due to the water quality issues currently experienced at Penrith Lakes, the impact of water from the Nepean River on the lakes is of concern. For this reason, the water quality of the Nepean River at Penrith Weir has been investigated for trends to ascertain if any limits should be placed on pumping during specific periods of flow.

Water quality in the Nepean River and other inflows of Farrells/Scope Creeks and Catchment 88, a typical rehabilitated catchment as assessed by Keogh have been compared in Table 20. On average, water in the Nepean is better quality than water from the other catchments.

Table 20
Nepean River Water Quality at Different Flow Rates

Water Quality Parameter (Average)	**Nepean River (170 – 1000 ML/day)[1]**	**Farrells/Scope Ck station[2]**	**Catchment 88[2]**
Total Nitrogen (mg/L)	0.399	1.88	1.93
NO_x (mg/L)	0.181	0.65	0.36
Total Phosphorous (mg/L)	0.018	0.180	0.180
Turbidity (NTU)	7.4	12.9	490
EC (mS/cm)	0.182	0.077	0.021

1. Source: Keogh (2004a)
2. Source: Keogh (2003)

Water quality data for the Nepean River at Penrith Weir was obtained from the Sydney Catchment Authority. Samples were taken from the weir pool behind the rowing club between 1984 and May 2005. Analytes measured have changed through this time period and thus the lengths of data sets are varied. The sample data available for each analyte with basic statistics is found in Appendix A, with key parameters mentioned in the lake water guidelines shown in Table 21.

Table 21
Statistics of Guideline Parameters Measured at Penrith Weir

Analytes	Trigger Value	No. Samples	Max.	Min.	Median	95th percentile
Chlorophyll-a (ug/L)	5	855	35.98	0	3.4	11.8
Phosphorus Total (mg/L)	0.01	908	0.44	0	0.013	0.054
Phosphorus Filterable (mg/L)	0.005	798	0.27	0.001	0.005	0.016
Nitrogen Total (mg/L)	0.35	448	1.65	0	0.37	0.79
Nitrogen Oxidised (mg/L)	0.01	886	1.8	0	0.12	0.48
Nitrogen Ammoniacal (mg/L)	0.01	865	0.28	0	0.01	0.08
Dissolved Oxygen (%Sat)	90-100	838	159	34	95	119
pH (Field)	6.5-8.0	122	9.6	6.19	7.75	9.3
Turbidity Field (NTU)	1-20	122	30.7	0.7	1.9	7.2
Enterococci	95%ile ≤ 200/100mL	216	2600	0	63	348

It can be seen from Table 21 that the median values for nutrients are equal to or slightly higher than the trigger value for the lake water (Table 19), and therefore these values are likely to be exceeded in the Nepean River 50% of the time. The 95th percentile value for enterococci greatly exceeds the secondary contact trigger value for the lake water. The relationship between the quality of the river water and the receiving lake waters is further discussed in Section 4.5.

To analyse water quality trends with respect to flow, the flow statistics for the days sampled were compared with the flow statistics for whole recorded history of flow for the Nepean (Section 2.2). From the comparison of flow statistics in Table 22, the water quality samples have been analysed over a reasonable distribution of flow, however as the range of parameters measured for each sampling event varied, it should be noted that some parameters have not been measured over this distribution.

Table 22
Flows at Penrith Weir for Days with Water Quality Sampling

Percentile	Flow (ML/day) Days with Water Quality Data	Whole Dataset
10	4750	4687
50	186	205
90	88	98

Analysis of flows on sampling days (24 hour flows) with the water quality data given showed no correlation for Total Nitrogen (R^2=0.316), Total Phosphorous (R^2=0.357), or biological indicators such as enterococci (R^2=0.315), and *E.Coli* (R^2=0.152), but a reasonable correlation for suspended sediments (R^2=0.729) and turbidity (R^2=0.71) (Figure 7). The correlation was likewise poor for all other water quality criteria listed in the guidelines in Table 19. Given that the critical criteria for health issues are the biological indicators and the provision of nutrients causing algal growth, it does not seem appropriate to set an upper limit for water quality based on this data. It should also be noted that only two measurements of E.Coli and fifteen measurements of enterococci had been made during flow rates of greater than 2000 ML/day, and therefore any correlation with flows requires more data.

The seasonality of various parameters was also investigated as seen in Table 23. There does not appear to be any clear correlation of parameters with season, other than perhaps nitrogen, which appears to increase over the winter months. This corresponds with Sydney Catchment Authority's (2004) routine monitoring of water quality trends in the Nepean River, finding that there was some increase of nitrogen and phosphorous during winter months but that the seasonal patterns were not distinct.

Table 23
Seasonality of Parameters at Penrith Weir

Month	N median	P median	SS median	Enterococci median	E.Coli median	Flow median
January	0.29	0.014	2.0	94	28	172
February	0.30	0.013	2.0	49	17	177
March	0.32	0.013	2.0	72	84	219
April	0.32	0.013	2.0	70	58	248
May	0.42	0.012	2.0	86	200	291
June	0.46	0.010	2.0	60	48	166
July	0.46	0.012	2.0	61	30	234
August	0.46	0.017	2.5	36	34	199
September	0.50	0.015	2.0	41	22	190
October	0.41	0.017	2.0	100	70	165
November	0.41	0.013	2.0	51	19	191
December	0.35	0.013	2.0	44	13	164

This conclusion does not support the findings of Keoghs water quality modelling conducted with UWS (2004a). Keogh modelled five upper pumping restrictions (1000, 5000, 10 000, 20 000 ML/day and none) to limit the extraction of poor quality water during flooding. He concluded that no hydrological benefit was gained from pumping when the flow rate was higher than 5000 ML/day and these higher flows are of poorer water quality. Keogh's analysis of the variation of water quality with flow rate at Penrith Weir for measured data from 1992-2004 is shown in Table 24. This report states that more detailed analysis of water quality has been previously made, however as the source was not given, it was not possible to further investigate the analysis and data sources he used. The data used in another report (Keogh, 2004b) indicates that the data may come from event sampling also analysed by ERM Australia (2001). However, as ceasing to pump when the flow in the Nepean River is greater than 5000 ML/day does not greatly affect the water balance of the lakes, it is reasonable to continue to use this upper pumping limit for the protection of water quality.

Table 24
95th Percentiles for Water Quality Parameters at Penrith Weir (Keogh, 2004a)

Water Quality Parameter	**Guideline Value**	**Flow rate ML/day**			
		170 – 1000	**1000 – 5000**	**5000 – 10 000**	**10 000 – 20 000**
Total Nitrogen (mg/L)	0.8	0.778	0.710	0.360	0.774
NO_x (mg/L)	0.5	0.49	0.399	0.242	0.270
Total Phosphorous (mg/L)	0.05	0.0386	0.041	0.066	0.072
Soluble Reactive Phosphorous (mg/L)	0.025	0.014	0.016	0.015	0.025
SS (mg/L)	25	12.0	28.0	38.8	66.4
Turbidity (NTU)	50	11	38	53	103
EC (mS/cm)	<1	0.353	0.290	0.129	0.200
Faecal coliforms (CFU/100 mL)	150	1050	2290	4662	14712
Streptococci (CFU/100 mL)	150	146	1250	1046	1332

ERM Australia (2001) analysed event sampling data from an automatic water quality sampler on the Nepean River at Penrith Weir from June 1991-1992. Their analysis found that water quality was generally suitable for extraction other than during than when water levels are rising prior to the peak flow generated by a storm event (ie. the rising limb of the hydrograph). Given WRL's analysis of water quality data for the Nepean, this correlation is far more likely. The 24 hour flow data for the Nepean River cannot capture the peak hydrograph, as it may pass in under 24 hours and water quality samples were not able to be correlated with instantaneous flow rates. Extraction should therefore be conducted so as to avoid the rising limb of the hydrograph, or the first flush of nutrients and sediments coming off the catchment. The magnitude of storms for which this would be significant could not be assessed with the available data.

4.4 Effectiveness of Flushing Flows

Lake management is necessary to maintain the operating lake levels and the water quality of each of the lakes. Early reports, such as the Department of Environment and Planning (1984) also suggested that flushing would be necessary to maintain the water quality, especially for the appropriate management of phosphorous levels. To maintain water quality and lake levels, it was calculated that about 26 000 ML/year would be required to be diverted from the Nepean.

Flushing is used to move water through the lakes system and dilute pollutants. The effectiveness of any flow used for flushing depends on the quantity of water available, the quality of water available and the corresponding residence time. To achieve flushing in the lakes systems, it has been suggested in the past that all available water would need to be pumped from the Nepean River, with a maximum threshold of 147 ML/day, with pumping permitted only when flows in the Nepean River are greater than 170 ML/day.

To assess the relationship between lake management and water quality, all previous water quality reports have been reviewed. In particular, this review has focussed on determining the impact of a range of flushing flows on water quality, and the amount of water available to achieve that flushing.

WRL's water balance model of the site outputs the volume of water that will flow out of the Lakes system into the Nepean River. When all of the lakes are at their operating level, the main lakes (Regatta, Main Lake A, Main Lake B and Wildlife Lake) will contain a volume of approximately 28,000 ML. The residence time of the water in the lakes can be calculated as an average using the amount of time it would take for all of the lake water to flow into the Nepean River at that flow rate. With a maximum pumping rate of 1.7 m^3/s, it would take 190 days to flush the lakes purely through pumping. To flush the lakes over a short period, such as a month, 11 m^3/s would need to be moved through the system.

Figure 8 shows the predicted amount of water passing through the system back into the river under different pumping scenarios:

- Scenario K: pumping 1.0 m^3/s when flow > 170 ML/day (fixed pump rate)
- Scenario I: pumping 1.0 m^3/s when flow > 350 ML/day (fixed pump rate)
- Scenario H: pumping 1.7 m^3/s when flow > 170ML/day (fixed pump rate)

- Scenario M: pumping 1.7 m^3/s when flow > 350ML/day (fixed pump rate)

4.4.1 Closed System

While the addition of Nepean River water to the lakes is expected to provide better quality water than that currently being harnessed from the catchments, the totally closed system will mean that salts will evapo-accumulate, and the lakes will become a sink for nutrients. Issues currently being experienced in the lakes would be expected to continue and increase. Due to the greater lake area of the final design, these problems will occur on a larger scale without alternative management, and increased treatment prior to release in the lakes.

It can be seen from Figure 8 that in drought years (1940, 1957, 1980, and 1994), the lake will operate as a closed system even if all available water above 170 ML/day is being pumped with a large 1.7 m^3/s pump. As a result, the lakes will require closed system management during these periods.

Therefore, when water quality is at its poorest during drought years, intentionally operating the lakes as a closed system would not impact on the water quality; even with maximum pumping the lakes will effectively be operating in a closed manner regardless.

4.4.2 Slowly Flushed or Regularly Flushed

Keogh (2004a) modelled the lakes as a slowly flushed system, driven by the need to maintain lake levels ie. pumping when necessary to correct the deficit levels in the lakes. He found that while the total dissolved solids levels in the lakes were likely to remain within guideline levels, that the residence time in the lakes would be long enough for all non-conservative parameters to reach equilibrium. Nutrients will assimilate, sediments will settle and microorganisms will either die-off off or continue to grow regardless of the water being pumped into the system.

Keogh (2004a) also found that the highest level of flushing possible given pumping limits from the Nepean would not greatly affect the water quality parameters of the lakes due to the long residence time for any pumping scenario. The residence time is such that the system will establish equilibrium levels based on the ecosystem rather than the additional quantity of water pumped.

Conservative parameters such as salts may accumulate due to evaporation. In the main lakes, the maximum daily concentration of TDS over the 30 years of Keogh's simulation was 675 mg/L for the pumping when needed scenario, compared to 468 mg/L for flushing flows. This is not a significant change and is within the changes possible through lake management. Additionally, the river-to-lake weirs are designed to spill once every 20 years, preventing further salt accumulation through flushing.

Water balance modelling conducted by WRL supports the finding of Keogh. When pumping all water available with a 1.7 m^3/s pump, the greatest amount of water that was pumped over the 95 years of data was just over 35 000 ML/year (Figure 8). With this rate of pumping, the water will have an average residence time of 9.6 months. Median pumped volume is approximately 12 000 ML/year, resulting in average residence time of 2.3 years. This is similar to the mean residence time of 2.1 years calculated by ERM Australia (2001), based on a larger lake volume, and is a longer period of time than that required to flush the lakes. With the extraction rates available from the Nepean River, historical modelling demonstrates that regular flushing of the lakes is simply not possible.

Algal blooms occurring in the lakes between the periods of 1997-2004 could not have been flushed by extraction of river water. Figure 8 shows that for each of these years, flow through the lakes would have been less than the median flow. These flow rates are simply not enough to have the desired flushing water quality effect. In addition, it can be seen from Figure 9 that the water available for pumping is strongly seasonal. The median volume of water available for pumping above 170 ML/day is 0 ML/day during November and December, and less than 25 ML/day during January and February. During this time, all available water will need to be pumped simply to maintain operating levels, regardless of water quality requirements.

4.4.3 Management of a Closed System

A closed system must be managed by the integration of a variety of strategies. These may include:

- Planting of aquatic plants
- Mixing infrastructure
- Treatment ponds
- Coagulation of nutrients
- Aeration devices.

It is beyond the scope of this assessment to discuss the internal lake management issues in greater detail.

4.5 Impact of Input Water Quality on Lakes Scheme

Due to the variety of water sources and complexity of interactions within the lakes system, it is very difficult to predict the impact of extracted Nepean River water quality on the lakes. At the same time as water enters the lakes from the Nepean River, water will be entering the lakes from rainfall which will dilute the lakes with respect to nutrients, microbiological indicators and TDS; water may enter from groundwater with an unknown effect, water will enter from the catchment with loadings that may be higher or lower than the lakes, and water will pass through the lakes and return to the river. Nutrients will be absorbed onto benthic sediments and consumed by ecosystem components, faecal microbiological indicators will die off, while cyanobacteria may consume nutrients and increase.

A basic method for estimating the impact without complex modelling is based on dilutions. A maximum of 147 ML/day will enter the lakes from the Nepean River extraction. At operating level, Main Lake A will hold 17, 400 ML (Note that the calculated volume from the most current design drawing – Jan 2005 - is significantly higher than that previously recorded). Therefore, if water is pumped into Main Lake A and does not pass into any other lakes, it will be diluted 118 times. Therefore, in the situation that the water quality of the Nepean River was loaded with twice the amount of nutrients as the lakes, the concentration of nutrients in Main Lake would increase by 0.8%; if the river held 10 times the amount of nutrients, the concentration would increase by 7.5% (not accounting for absorption and consumption). As a single flux of this amount, the impact is not likely to be large, however continued poor water quality would be cause to cease extraction. If this poor water quality also corresponds with poor water quality being received off the catchments, the effect would be magnified. Note that if poor water quality is primarily correlated to the first flush during storm events, a second storm event occurring in rapid succession will carry smaller loads than the first as pollutants will have built up on the catchment surface over a smaller period of time.

In summary, due to the likely dilutions of water from the Nepean River and insufficient correlation between flow and water quality at Penrith Weir, WRL has not found any basis to limit pumping. As water levels can be maintained pumping water with flows below 5000 ML/day, this limit suggested by Keogh is a reasonable water quality precaution to implement.

5. ENVIRONMENTAL FLOW REQUIREMENTS

5.1 Background

PLDC currently holds an extraction license to extract water from the Nepean River when the flow of the Nepean is greater than 170 ML/day. The extraction rules were created based purely on satisfying the needs of downstream users as perceived by the then Water Resources Commission (Department of Environment and Planning, 1984) and there is no ecological basis for this figure. However, declining river health has been caused in part by the excessive demands and controls placed on the rivers in the forms of pumping, dams and weirs. This has forced governments and users to consider the amount of water and variability required by the river to maintain healthy river functioning, that is, to mimic the natural flows of the river. In turn, it is necessary to consider the impact of extracting water for use in Penrith Lakes on the Nepean River and to determine if the 170 ML/day cease to pump rule with pumping rates of up to 147 ML/day is appropriate for the needs of the river. In this section, analysis of the current and expected future flow regime of the Nepean River has been made, the recommendations of the Hawkesbury-Nepean River Management Forum have been summarised, assessment of environmental flows at Penrith Weir have been made, likely impacts of extraction on the river have been determined and the impact of Penrith Lakes discharging into the Nepean Rivers has been outlined.

5.2 Previous Investigations

5.2.1 Report of the Hawkesbury-Nepean River Management Forum

The recommendations of the Hawkesbury-Nepean River Management Forum (HNRMF, 2004) that impact on the flow of the Nepean River at Penrith Weir have been outlined in Section 2.3. HNRMF included Penrith Lakes and its extraction licence in its final report (2004). It acknowledged that the licence stipulates water may be extracted from the Nepean when flows are greater than 170 ML/day, but that it was expected that approximately eighty percent of the water extracted would return to the Nepean River after flowing through the lakes. To protect the environmental flows, HNRMF (2004) recommended that:

- *The timing and volume of extractions for the Penrith Lakes Scheme are carefully considered in relation to potential impacts on the health of the river, particularly in the river reach between the point of extraction and the point of discharge downstream*

- *The quality of discharge waters from the lakes is sufficient to maintain the quality of the receiving water at a level consistent with protecting the health of the river system in downstream reaches.*

Report recommendation PEF8 (see Table 4) requires the protection of environmental flows from extraction. Flows passing through Penrith Weir will be a combination of the flows released from Warragamba Dam and the flows released from the other upper Nepean dams and weirs.

5.2.2 Department of Environment and Planning (1984)

Department of Environment and Planning (1984) concluded that Penrith Lakes would assist the flow of the Nepean during dry periods as return flows from the lakes would continue to flow into the river, whilst pumping would not be permitted. This scenario would not occur under the current operational plans.

5.2.3 WRL Modelling of Saline Dynamics

Modelling of saline dynamics on the Hawkesbury Nepean estuary was conducted by WRL in 2003 to determine the impact of different water use regimes on different habitats (Cox & Peirson, 2003). Habitat reduction is most severe in regions that generally have low salinity where salinity is increased due to increased tidal penetration as a result of reduced river flow. The least loss of habitat occurred with environmental flows that are equal to those proposed by the HNRMF (2004).

5.2.4 Bishop (2005)

The Penrith Lakes Water Committee (2005) determined the limiting factor to consider with regard to extraction from the Hawkesbury Nepean is the inhibition of fish passage. Bishop (2005) stated that based upon observations, the critical flow for larger fish in the river is likely to be higher than 170 ML/day and possibly higher than 500 ML/day. The stretch of river within the 3 km directly below Penrith Weir has been identified as particularly depth limiting to larger fish (Bishop, 2005) as the river is broad in this stretch. The most limiting point was found to be 2 km downstream from the Boral Bridge (< 4 km from Penrith Weir). Bishop suggested that the cease-to-pump rule may only need to be increased to a value higher than 170 ML/day when there has not been sufficient flow for fish passage for a significant period of time. A suggestion was that "a 500 ML/day cease-to-pump rule applies if there has not been a flow greater than 500 ML/day lasting for 3 consecutive days in the previous two months".

This suggestion was run as a scenario in the water balance model and is discussed in Section 3.4.6.

5.3 Field Assessment of Barriers to Fish Passage

5.3.1 Flow of 70 ML/day

On the 1st June 2005, Keith Bishop, Brett Miller and Mitchell Harley surveyed the length of river from the Boral Bridge to the final barrier to fish passage in this vicinity of the river. The location of each of the barriers along with the region surveyed is shown in Figure 10.

Flow from the SCA's gauging station at Penrith Weir on the 1st June was only 70 ML/day. At this low flow rate, there was significant contraction of flow paths through the barrier sections and indeed all barriers were blocked to fish passage.

Fish passage was assumed to be blocked whenever the criteria in Table 25 were not achieved.

Table 25
Thresholds for Australian Bass Passage Movement

Situation	**Juveniles**			**Adults**		
	Depth (m)	**Velocity (m/s)**		**Depth (m)**	**Velocity (m/s)**	
		Near bed	**Surface**		**Near bed**	**Surface**
Burst (barrier<10m long, or >10m with regular sheltering points)	0.1	0.8	~1.1	0.2	1.5	~2.0
Prolonged (barrier > 10m long & with few sheltering points)	0.1	0.6	~0.8	0.2	1.0	~1.3

Source: Bishop (2005)

With the low flow observed on the day, it would be expected that these observations were for the maximum contraction of riffle bed area.

Figures 11 to 17 show schematically the findings at each location, designated Rapids 1 to Rapids 7.

At each of the rapids there was either blockage to passage due to lack of water depth or velocities being too high. With an increased total volume of river flow and only the same area of riffles, those parts of the system that were currently blocked by depth constraints would quickly move to blockage by velocity constraints. This is due to the relatively large drops in elevation within a short distance which results typically in an upstream critical velocity control.

In the case of Rapids 1, there was the secondary channel which was not flowing at the time of observation but had a much longer and flatter channel slope. It would be expected that with river flows of 170 ML/day that this channel would be open for fish passage.

In the case of Rapids 2, the secondary channel from Rapids 1 effectively provides a bypass.

Rapids 3 provides possibly the most difficult rapid for fish passage. There are two main channels carrying water down either side of an island that may become drowned and provide intermediate channels throughout. The bed slope of the channel was calculated as 0.35 m fall over 50 m. At this slope, with flows in the range of 170 ML/day to 500 ML/day, the flow is expected to be subcritical. However, at the lower end of the range, especially where the available cross section for flow is small, the flow would be expected to be a series of subcritical then critical drops similar to small weirs. This was the condition observed on the 1st June 2005.

With only the two outer channels flowing (as observed on the 1st June), the total channel width is less than 15 m. It was apparent from the field investigation, that the flow would drop through several hydraulic critical controls and would be fairly uniform between. In the range of 50 to 170 ML/day, the flow depths would be estimated to be in the range of 8 cm to 15 cm with velocities varying from 0.6 to 1.2 m/s. Given that the slope is over 50 m, this would be expected to be impassable to fish.

The island in the centre of the rapids was surveyed and found to have the highest section 0.2 m above the lowest section (in the channel on the southern side). A discharge to drown out the entire cross section may be expected to be as high as 800 ML/day. When fully drowned out, the complex flow patterns over the width of the river may be expected to provide fish passage. However, at discharges lower than 800 ML/day, the passage to fish may be provided up the two outer channels as the flow regime changes from one of subcritical with supercritical drops into one of constant subcritical flow. In this instance, while the depth and average velocity would be greater, the peak velocities would be lower.

Using an estimate of 25 m effective channel width, and flow depths 5 cm and 10 cm deeper than observed on the 1st June (total 20cm or 25cm in the main southern channel), the discharges are between 350 ML/day and 500 ML/day. In these instances the uniform flow velocities would be less than 1 m/s.

Rapids 4 had one main channel which operates as a top critical control. The second channel is highly choked by weeds, but is longer and flatter than the first channel. It would be expected that at flows of 170 ML/day, this rapid would provide sufficient depth for passage and peak velocities would only be found at the top of the rapids. The weed may provide further problems for passage.

Rapids 5a and 5b were a complex system of channels that on the 1st June 2005 simply lacked enough depth for fish passage. It would be expected that with flows in the order of 170 ML/day, the depths would be greater than 0.2 m and at least one of the channels would provide passage.

Rapids 6 provides an example of the weed problem occurring in the Hawkesbury and possibility of weeds blocking passage to fish. Removal of the weed requires high (flood) flows which will not be impacted by any pumping from Penrith Weir.

Rapids 7 is a long series of hydraulically critical jumps which was marginally open on the 1st June 2005 even with low flows.

5.3.2 Flow of 580 ML/day

On Wednesday 7th December 2005, Brett Miller (accompanied by PLDC field support) surveyed flows and water depths at Rapids 3. Flow was falling from a reasonably large discharge of 3800 ML/day late in the previous week and was reported from the SCA's gauging station at Penrith Weir as being 580 ML/day on the afternoon of the 7th December.

Flow width on 7th December, 2005 was considerably greater than that observed on 1st June 2005, as the central island had a reasonably large channel down the centre. However, the entire cross section was not drowned out and there were still six or seven islands across the barrier. The two major channels present were on the north bank and the south bank, and two significant, smaller channels flowed through the islands in the centre. The islands in the centre had a maximum elevation of 0.2 m above the water surface (thus if the water level was 0.2 m higher, the entire cross section would be drowned).

The channel on the southern bank was flowing very close to supercritical with typical depths of 0.15 m and velocities between 0.8 and 1.4 m/s at both the bed and the surface. There were some sections very close to the bank where fish may be able to rest, however on the basis of Table 25, the southern channel remained closed to adult bass passage due to depth.

The channel on the northern bank was flowing with typical depths of 0.17 m to 0.25 m and with velocities between 0.8 and 1.2 m/s at both the bed and the surface. Velocities as low as 0.6 m/s were present in some sections under hanging bushes and reeds close to the sides of the channel. On the basis of Table 25, the passage to fish may be closed to juveniles and open to adult bass.

Flows through the central channels were a typical depth of 0.15 cm with the minimum observed 0.11cm. Velocities were a minimum of 0.8 m/s and a maximum of 1.5 m/s through the channels, even close to the overhanging island banks. The flow paths were series of short running narrow uniform channels. The depth would limit passage to adults but the juveniles may find passage through short bursts.

Evidence from debris on the banks showed that the peak water level was 0.4 m higher than observed. On the basis of the observation at 70 ML/day, the discharges to maintain fish passage were estimated as being between 350 ML/day and 500 ML/day. With the additional observations at 580 ML/day, it can be concluded that 500 ML/day would provide fish passage. It is still considered likely that 350 ML/day may provide passage, however it is highly recommended that further field investigations be undertaken to confirm this.

5.3.3 Summary of Findings from Field Investigations

Based on the field investigations, it would be expected that 170 ML/day would provide passage for all of the rapids other than Rapids 3. Rapids 3 would be expected to require 350 ML/day – 500 ML/day in order to provide passage, however further investigations at the lower range of these flows is highly recommended. Should modification of Rapids 3 be made (such as providing a narrow fish channel or steps), the ecologically sensitive flow zone for fish passage in this reach of the river would be around 170 ML/day.

5.4 Impacts of Various Pumping Rules

5.4.1 Pump Sizes of 1.7 vs 1.0 m^3/s

Flow duration curves showing comparison at 170 ML/day are presented in Figure 18.

If the 170 ML/day cease to pump was used, then a 1.7 m^3/s extraction rate would impact more (compared to the 1.0 m^3/s) in the ecologically-sensitive flow zone (350-500ML/day) as relevant to passage availability. The duration of the impact at a river flow of 350 ML/day appears to drop by 30-40% when using a 1.0 m^3/s extraction rates rather than a 1.7 m^3/s.

If the cease to pump flow rate was set at 350 or 500 ML/day then the ecological consequence of either 1.0 or 1.7 m^3/s extraction would be much the same.

5.4.2 Comparison of Various Cease to Pump Limits

Figure 19 shows the flow duration curves for pumping at 1.0 m^3/s with cease to pump limits of 170, 350 and 500 ML/day.

If the ecologically-sensitive flow zone as relevant to passage availability is at the lower end of the 350-500 ML/day range, then

- Clearly with a 350 ML/day cease to pump limit, passage availability is 100% protected
- With a 170 ML/day cease to pump limit, passage availability is under protected
- With a 500 ML/day cease to pump limit, passage availability is over protected.

If the ecologically-sensitive flow zone as relevant to passage availability is closer to 500 ML/day, the passage availability is under protected with both 170 & 350 ML/day cease to pump limits. However, fish passage availability is compromised less if 500 ML/day is required and the threshold used is only 350 ML/day, than if a cutoff 350 ML/day threshold is required and the threshold used is only 170 ML/day.

5.4.3 Continual Pumping versus Pumping when Required

Figure 20 shows the difference in flow duration curves between pumping continuously and pumping only when required.

The reduction in impact on the river is significantly reduced in duration by pumping only when required. If the ecologically sensitive flow rate is approximately 350 ML/day, then moving from the continuous pumping to pumping only when required would reduce the impact duration by about 70-80%. The result is similar if the passage flow threshold is at 500 ML/day.

5.4.4 Fish Passage Rules

A rule was tested whereby pumping was undertaken with a cease to pump limit of 170 ML/day but raised to 500 ML/day if there has not been a flow greater than 500 ML/day lasting for 3 consecutive days in the previous two months. This is compared with a constant cease to pump limit of 170 ML/day in Figure 21. This was to ensure that any openings of Rapids 3 to fish passage were not disrupted if it had been more than two months since the fish passage was last opened.

There were only 65 days over the 95 years of record where this rule would have been implemented. As such, there is no difference in the flow duration curves. However, these 65 days may be crucial in ensuring that fish that have travelled to the base of Rapids 3 are able to further travel upstream.

From this scenario, we can also deduce that if the ecologically sensitive flow rate is approximately 500 ML/day, then fish must wait a maximum of two months for a passage opening in all but 65 occasions over the past 95 years.

5.5 Return Flows to the Nepean River

5.5.1 Quantity

The Hawkesbury-Nepean report (HNRMF, 2005) stated the expectation that 80 per cent of flow extracted from the Nepean River for use in the Penrith Lakes Scheme will return to the river downstream. This was assessed for each scenario in the water balance model, with annual return percentages calculated for each year from 1909 to 2004. These 95 values were then grouped by the likelihood of exceeding 80 per cent return flow and are found in Table 31.

It should first be noted that in many cases the return flows from the lakes to the river exceed that which was pumped from the river originally, giving return flow figures over

100 per cent. This is due to the fact that the lakes have catchment inflows from rainfall and other sources.

Regardless of the pumping scenario employed in the future, 80 per cent of flow will not return to the river all of the time. Scenario J (2.0 m^3/s variable rate pump, cease-to-pump 170 ML/day) performed the best with at least 80 percent of flow returning to the river 74% of the time. The worst case was Scenario F (1.7 m^3/s variable rate pump, cease-to-pump 170 ML/day, pumping when Lake A is low) with at least 80 percent of flow returning to the river only 35% of the time. A more likely set-up is that of Scenario I (1.0 m^3/s fixed rate pump, cease-to-pump 350 ML/day) which had at least 80 percent of flow returning to the river 43% of the time.

Table 26
Probability of Exceeding 80 per cent Return Flow to Nepean River from Original Pumped Volume

	Scenario										
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**
Average Volume Extracted (ML)	-	19,199	19,199	11,762	12,440	4,013	9,625	14,395	6,598	21,342	10,075
Frequency 80% return flow Exceeded	-	70%	64%	54%	57%	35%	47%	59%	43%	74%	52%
Scenario	**L**	**M**	**N**	**O**	**P**	**Q**	**X**	**Y**	**Z**	**AA**	**AB**
Average Volume Extracted (ML)	5,443	10,423	9,024	7,090	10,891	6,790	3,353	2,791	3,578	3,227	4,013
Frequency 80% return flow Exceeded	39%	51%	44%	44%	53%	43%	36%	35%	37%	36%	53%

These results are in contrast to the ERM Australia model (2001) that assumed that an average of 19,703 ML/yr would be extracted from Penrith Weir and 20,400 ML/yr returned (a return flow of 104%).

5.5.2 Quality

The Healthy Rivers Commission Inquiry into the Hawkesbury Nepean Commission (1998) determined the following water quality objectives for the Nepean River:

Total Phosphorous	35 μg/L
Total Nitrogen	500 μg/L
Chlorophyll-A	10-15 μg/L

If the water quality guidelines for the lakes are met, any discharge from the lakes to the Nepean River will meet water quality objectives for the Nepean River. As seen in Table 19, water quality guidelines for the Penrith Lakes will be more stringent than those required for the Nepean River.

Initial studies into the impact of discharge from Penrith Lakes (Department of Environment and Planning, 1984) perceived that any discharge from the lakes would be beneficial to water quality in the river due to the removal of nutrients, particularly phosphorous. However, as the relative quantity would be small, the benefit to the river would depend on the timing of the return flow. As pumping would be possible approximately 60% of the time (when flows were greater than 170 ML/day), but return flows would be expected 80% of the time, flow to the river would be beneficial to the river 20% of the time.

Due to settling of suspended sediments in the slower flow regime and use of nutrients by plants, nutrient concentrations returned to the Nepean River should be less than that the concentrations extracted from the river. The major issue for return flows is therefore likely to be the concentration of chlorophyll-A and is therefore likely to occur in the summer months when flows are low. ERM (2001) stated that the operations plan would need to include the directive to cease release to the Nepean when cyanobacteria counts in the river exceed 15 000 cells/ML.

The impact of discharge from the lakes system on the Nepean River can most simply be assessed as a function of the dilution achieved by the return flows mixing with the Nepean River. Return flows simulated using the water balance model for pumping conducted with a 1.0 m^3/s pump maintaining a flow of 350 ML/day at Penrith Weir and pumping only when levels in Main Lake A and Main Lake B are below operating level (Scenario Y), were compared with the flows in the Nepean River over the whole simulated period (1909 – 2004). Flows returned to the river only 25% of the time. Dilution statistics for the time when flows did return to the river over the simulated period are shown in Table 27.

Table 27
Dilution Statistics for Return Flows to the Nepean River

Statistic	**Number of Dilutions**
Median	359
90th percentile	43
95th percentile	27
99th percentile	12
Minimum	2

In the case of the 99th percentile dilution, if water is discharged from the lakes that has twice the concentration of a particular parameter than the river, the overall concentration of the parameter in the river will increase by 8 %. As a result, water discharged from the lakes is unlikely to cause major degradation to water quality in the Nepean River, unless the lakes were in significant breach of their water quality operating requirements.

6. RECOMMENDATIONS

Recommendations resulting from this study are summarised below:

- A 1.0 m^3/s pump be used to extract water from the Penrith Weir Pool.
- PLDC formally accept and advise all parties that the drawdown criteria cannot be achieved to the 95th percentile limits. It must be advised that the periods when drawdowns exceed the 0.5 m criteria are grouped into very dry years.
- Water quality management programs be based on non-flushing pumping scenarios. There is insufficient pumping capacity or flow in the river to provide flushing flows. Nutrient removal from the Lakes via aquatic flora or other means is required.
- In the absence of further data or modifications a pumping rule of pumping 1.0 m^3/s such that the flow at Penrith Weir is not reduced below 350 ML/day is recommended. Further expanding this rule to pumping only when required for water balance would further reduce any impacts on the Nepean River.
- Rapids 3 should be surveyed when flow is close to 350 ML/day over Penrith Weir.
- Very serious consideration be made of providing a modified rapid of fish passage through Rapids 3. If this were to occur, then the cease to pump limit may be able to be reduced to 170 ML/day.

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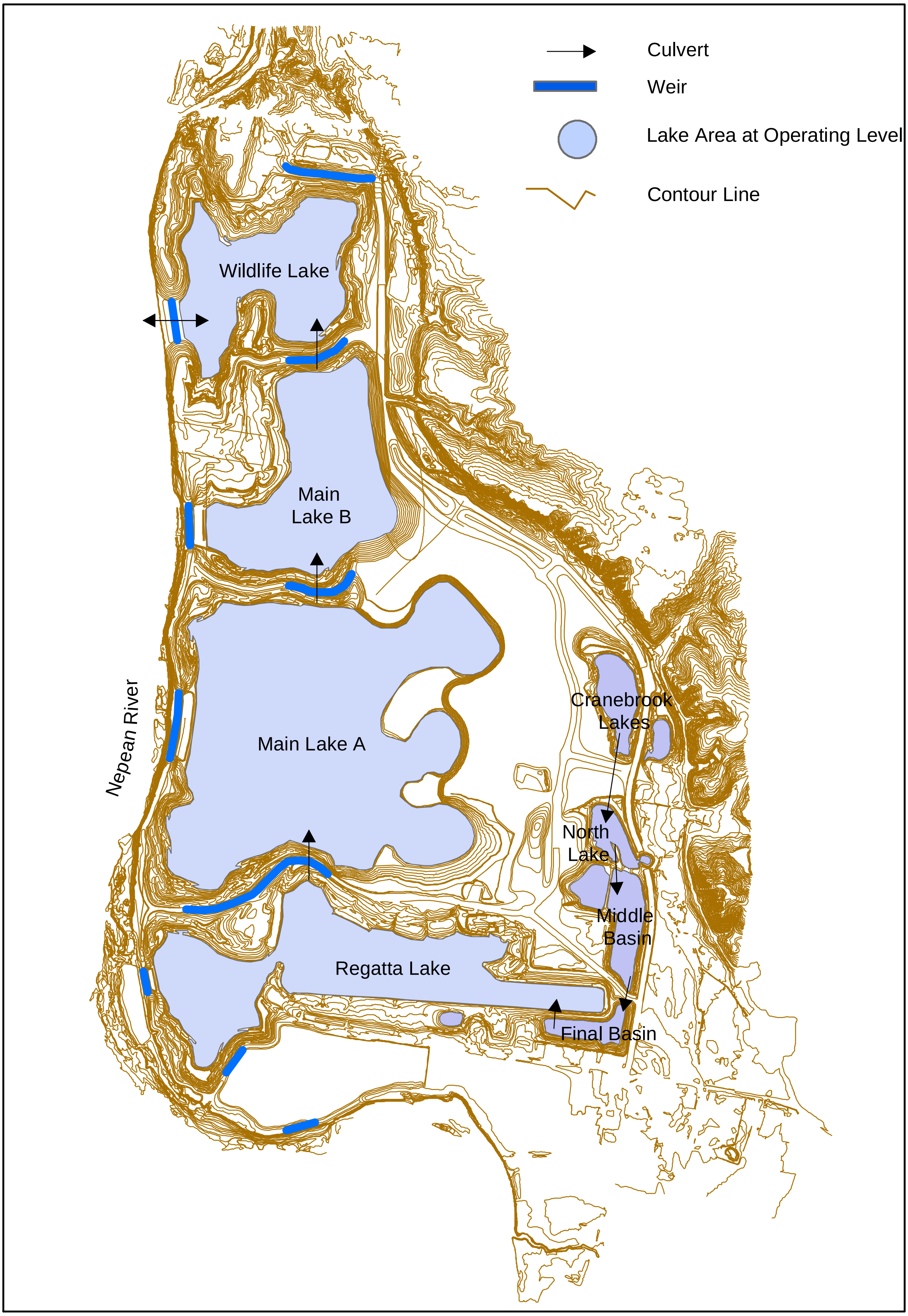

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PLAN VIEW OF PENRITH LAKES DEVELOPMENT SCHEME,
DESIGN JANUARY 2005

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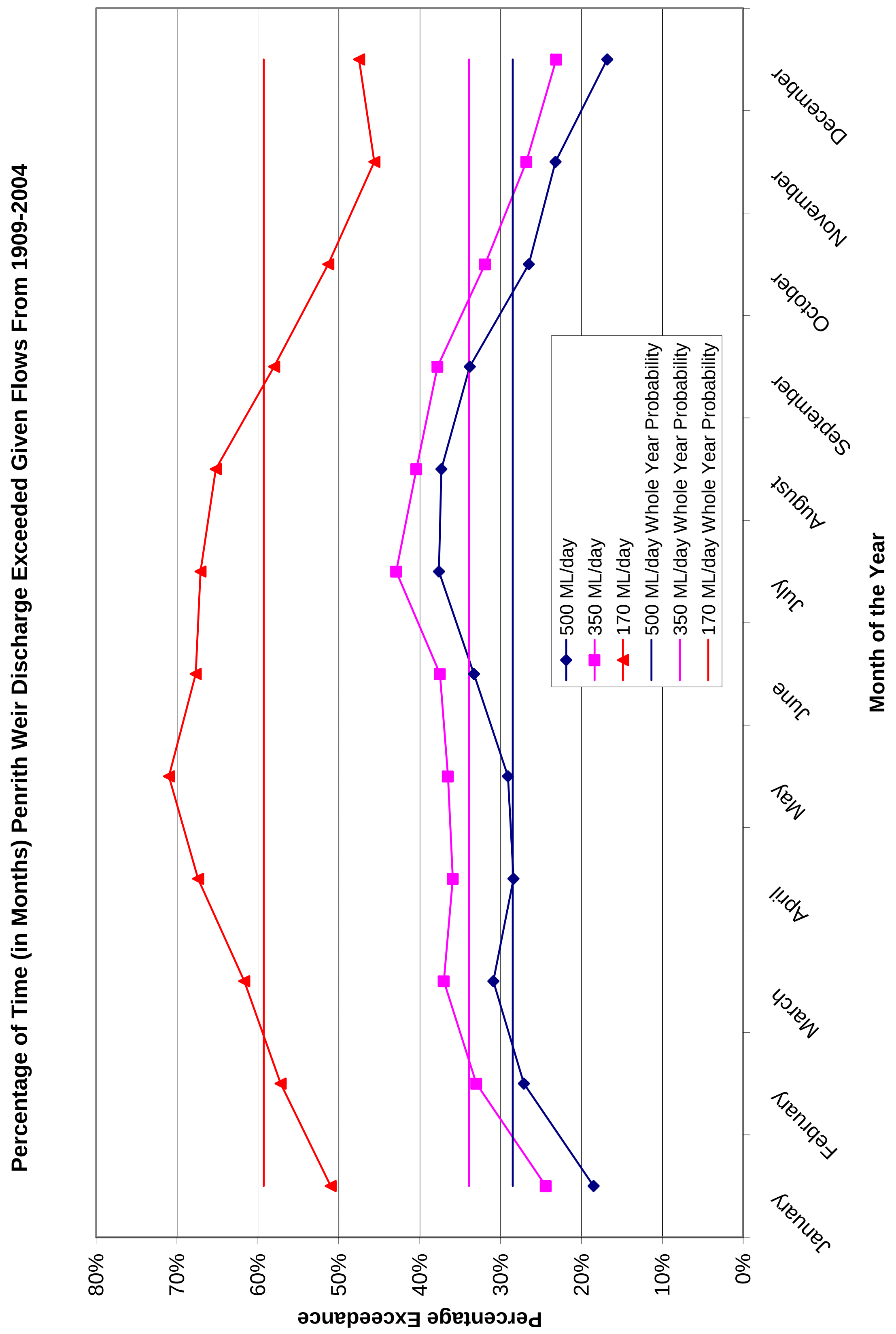

Percentage of Time (in Months) Penrith Weir Discharge Exceeded Given Flows From 1909-2004

WRL

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PROBABLE EXCEEDANCE OF CRITICAL VALUES FOR EACH MONTH OF THE YEAR

Figure

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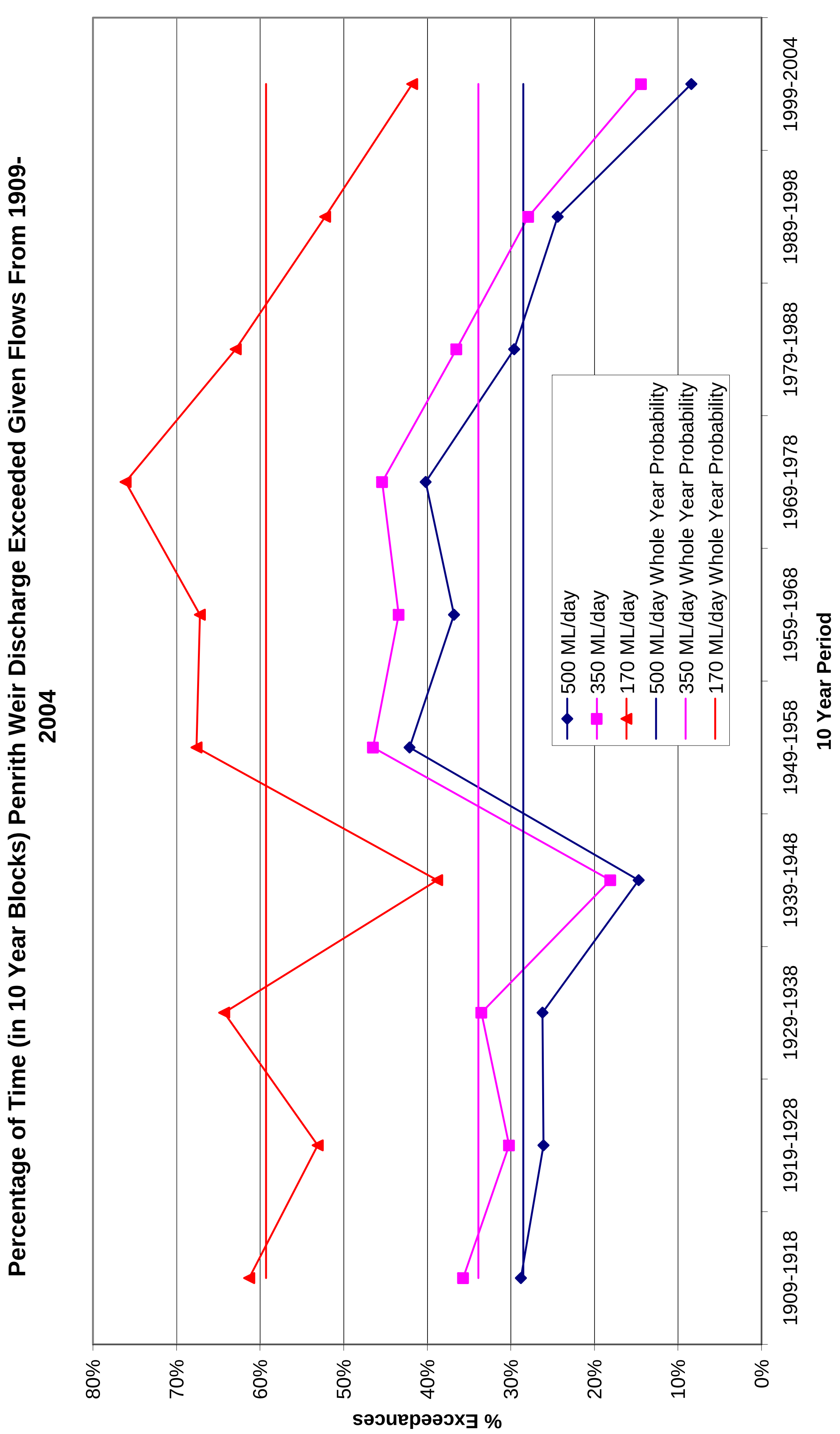


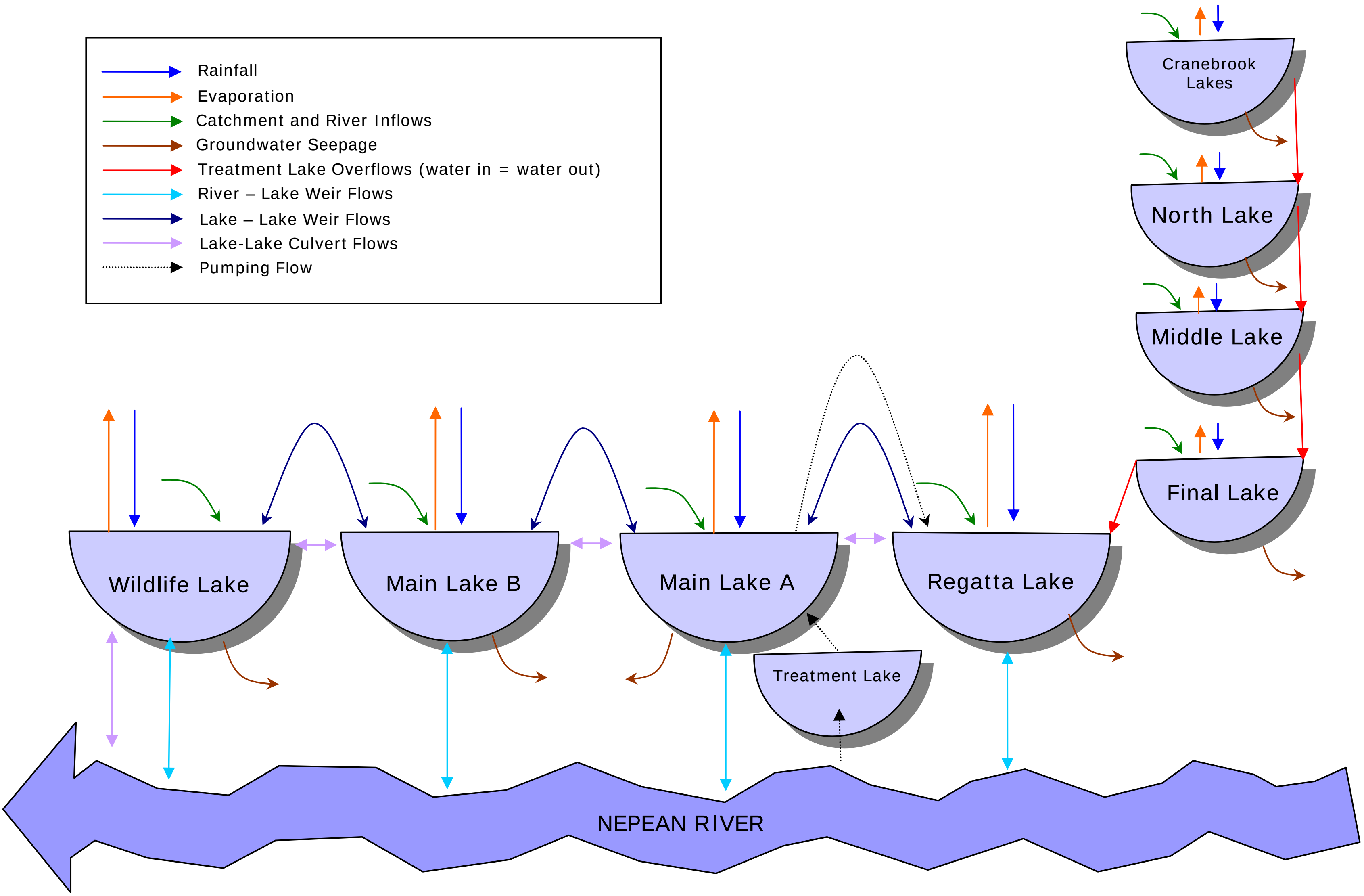
WRL Report No. 2005/16	PERCENTAGE EXCEEDANCES OF CRITICAL VALUES FROM 1909-2004	Figure 3

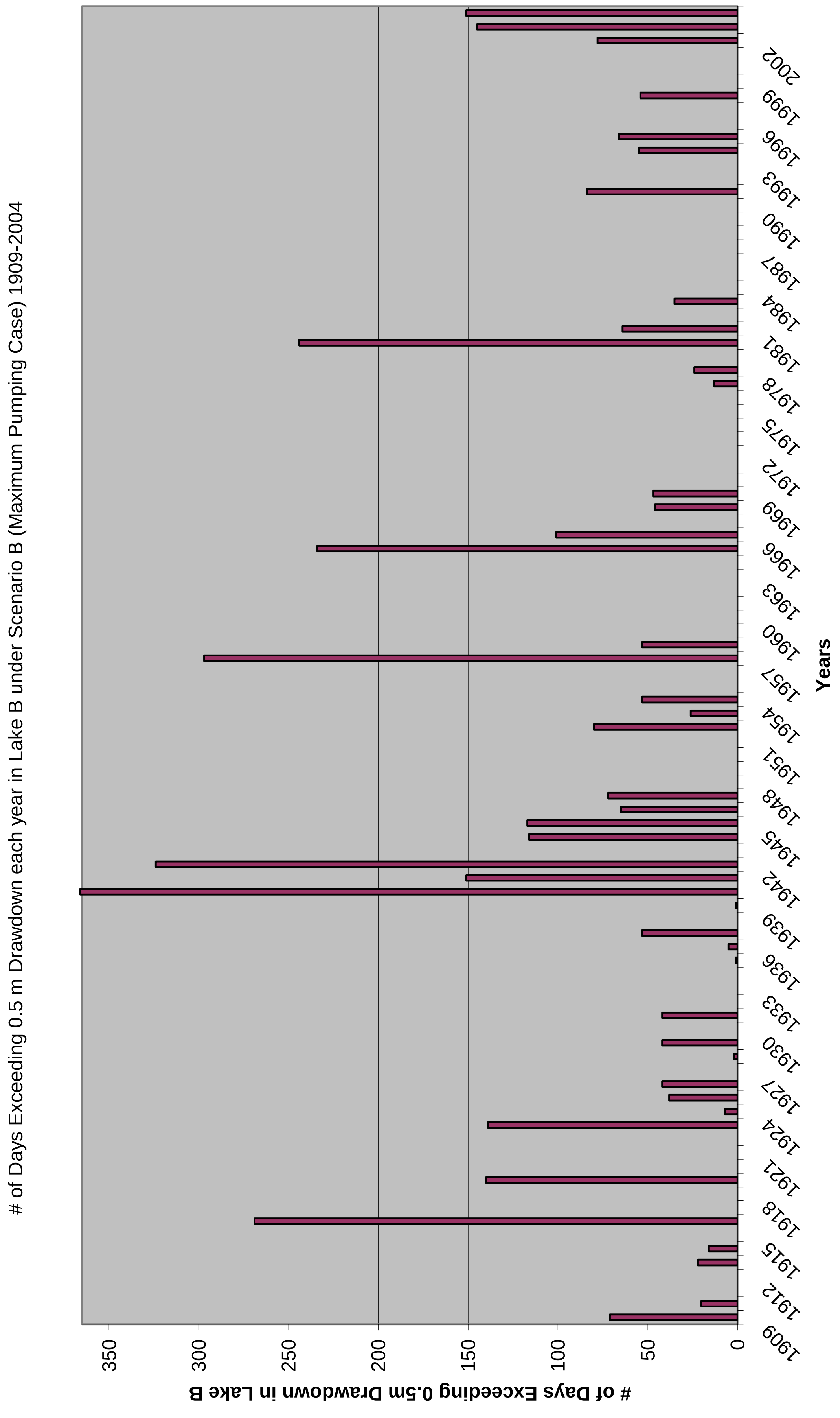
WRL
Report No. 2005/16

PENRITH LAKES WATER BALANCE MODEL SCHEMATIC

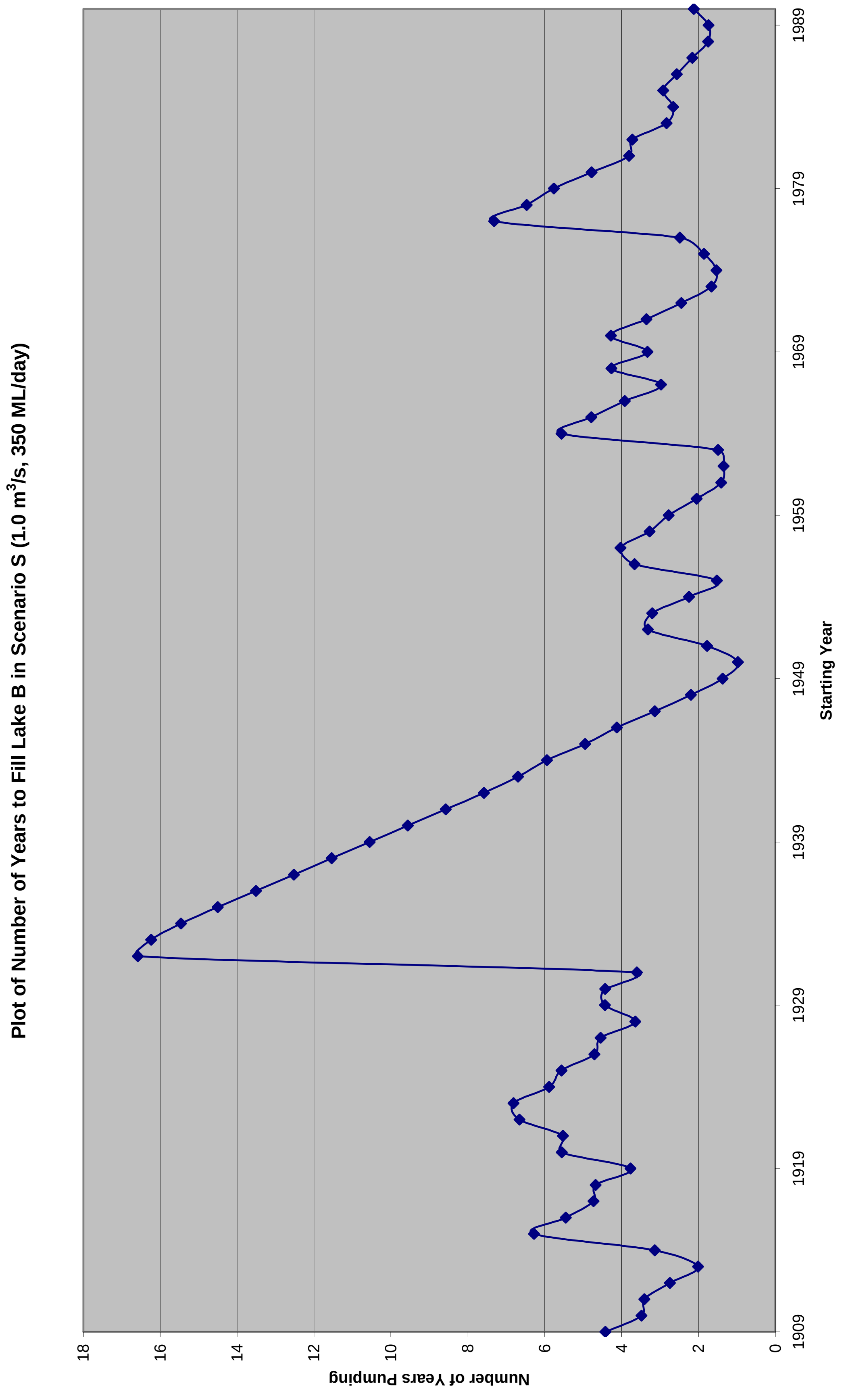
Figure
4

PENRITH LAKES WATER BALANCE MODEL SCHEMATIC





WRL Report No. 2005/16	NUMBER OF DAYS EXCEEDING DRAWDOWN TOLERANCE FOR LAKE B UNDER MAXIMUM PUMPING 1909-2004	Figure 5



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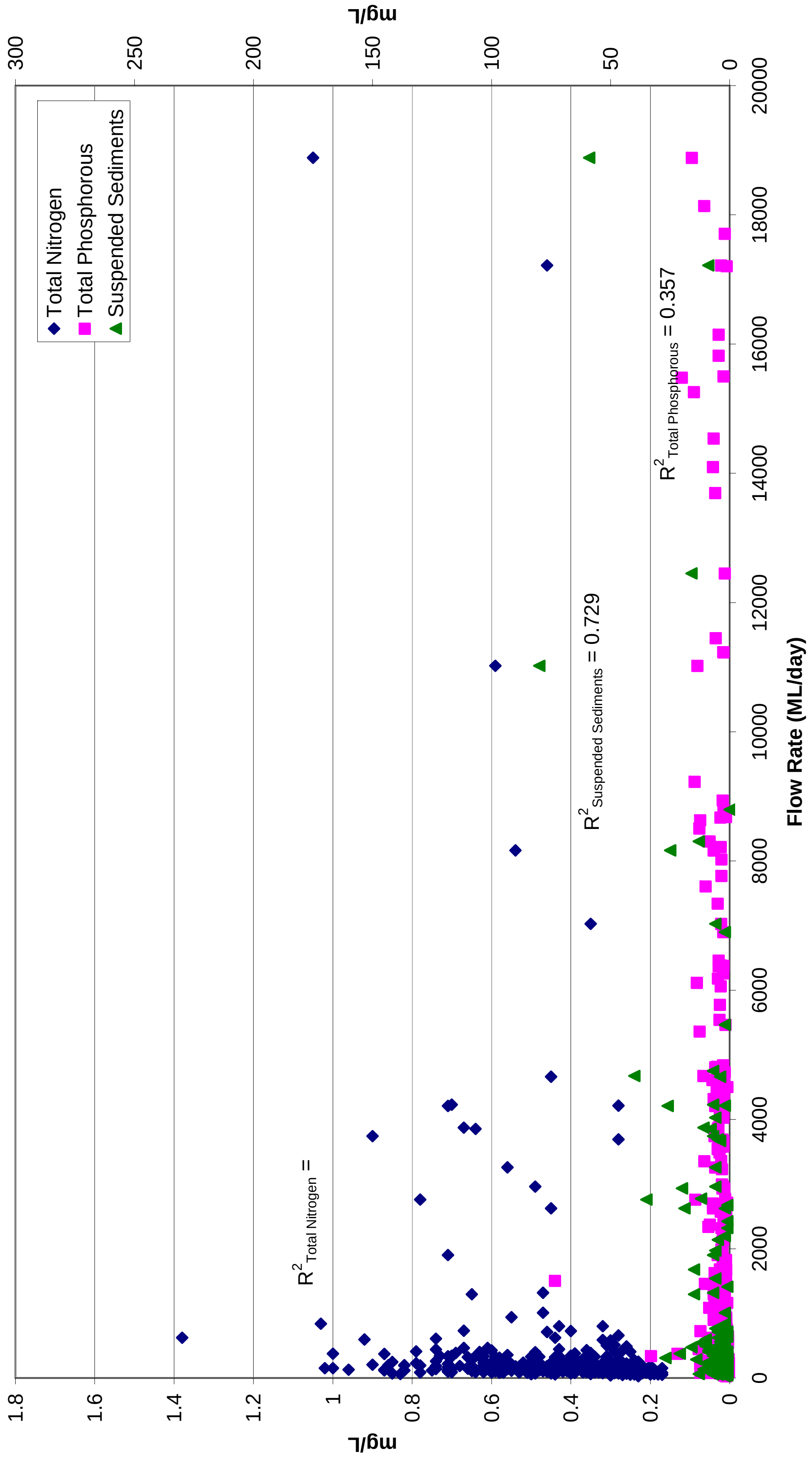
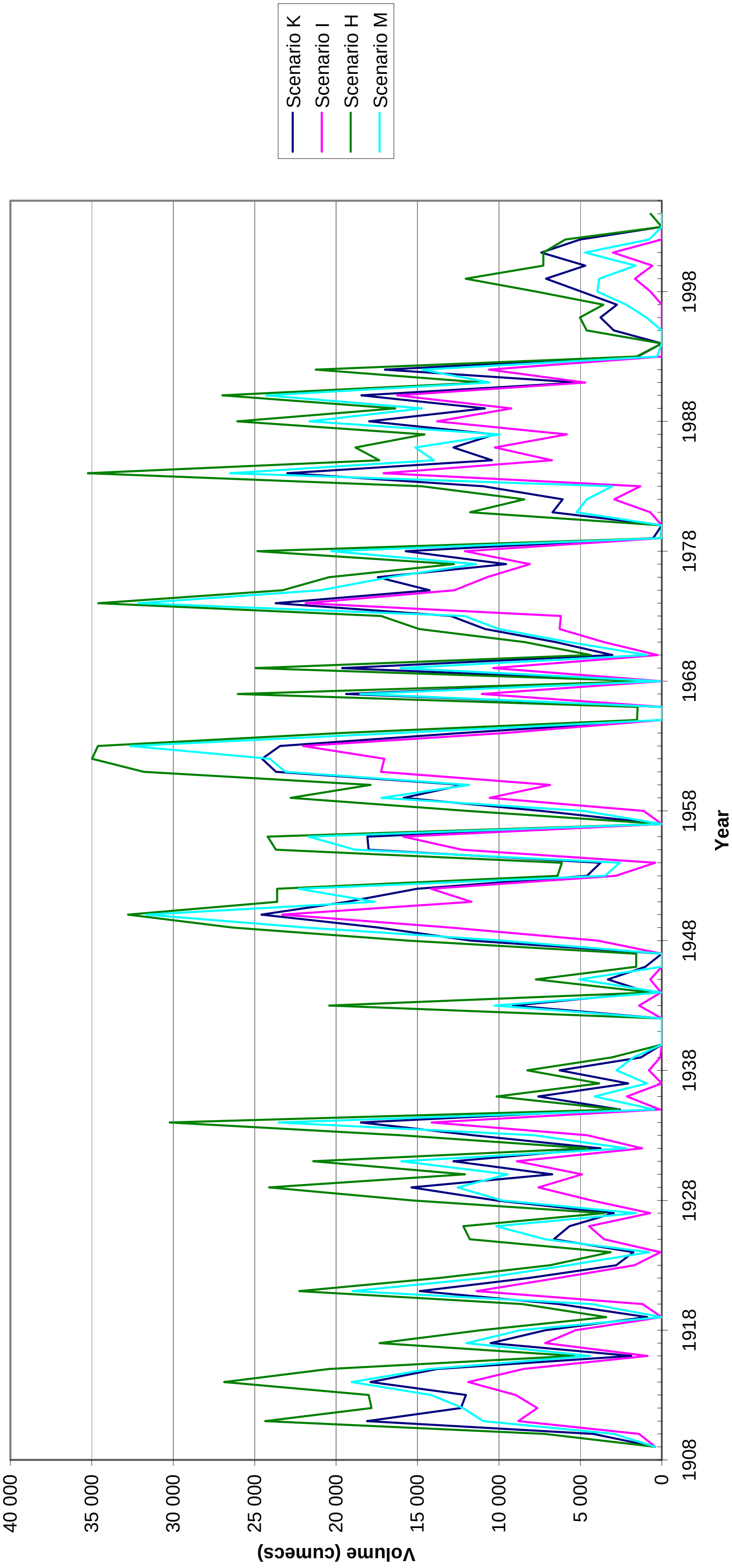
SPREAD OF FILLING TIMES FOR LAKE B UNDER SCENARIO S (1.0 M^3/S, 350 ML/DAY) STARTING AT YEARS 1909-1990

Figure 6

Nutrients and Suspended Sediments in Nepean River at Penrith Weir



WRL Report No. 2005/16	RELATIONSHIP BETWEEN FLOW, NUTRIENTS AND SUSPENDED SEDIMENTS AT PENRITH WEIR	Figure 7

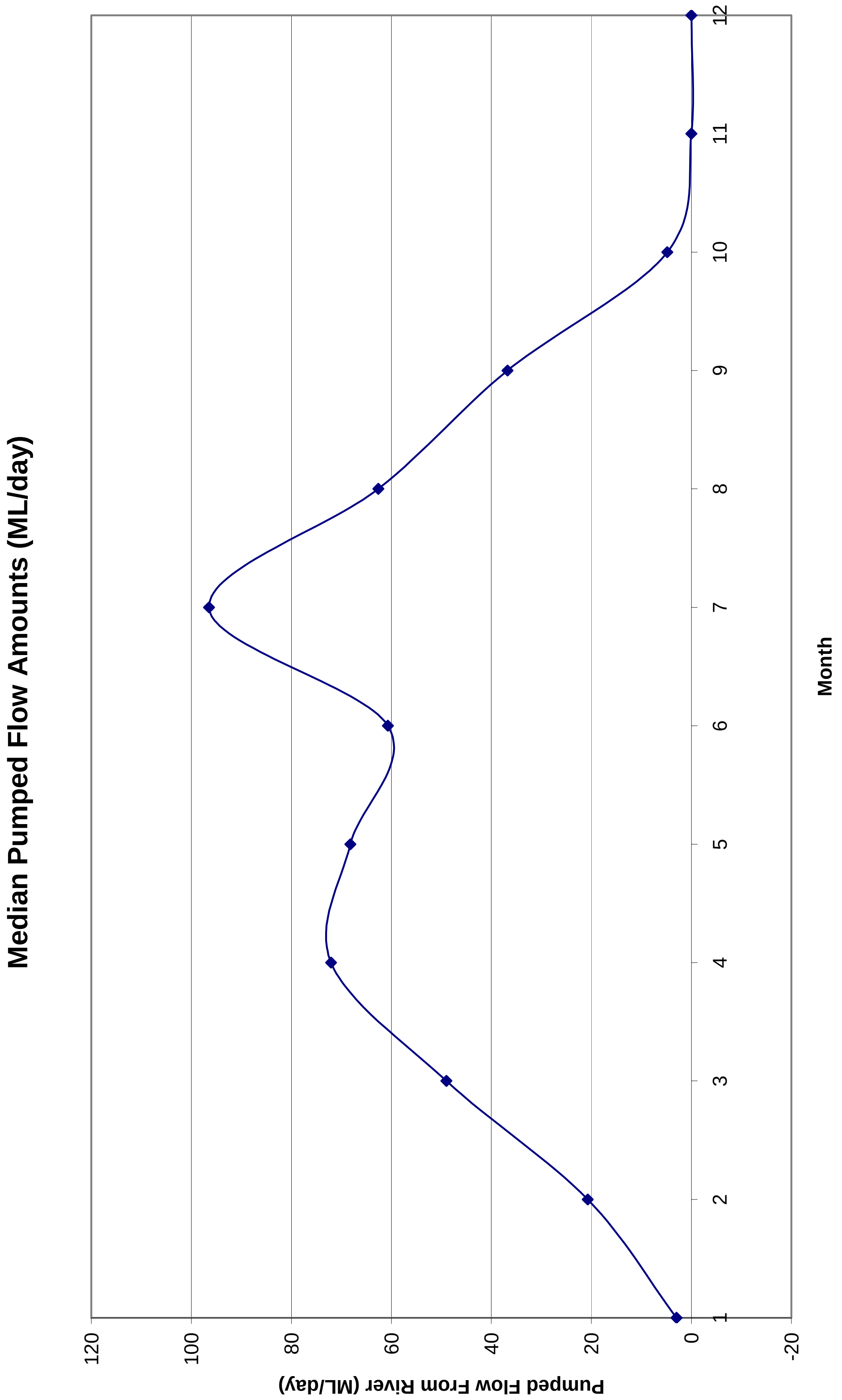

Historical Flushing Flows under different scenarios

WRL

Report No. 2005/16

HISTORICAL FLUSHING FLOWS FOR SCENARIOS K, I, H & M

Figure 8



WRL
Report No. 2005/16

SEASONALITY OF FLOW AVAILABLE FOR PUMPING

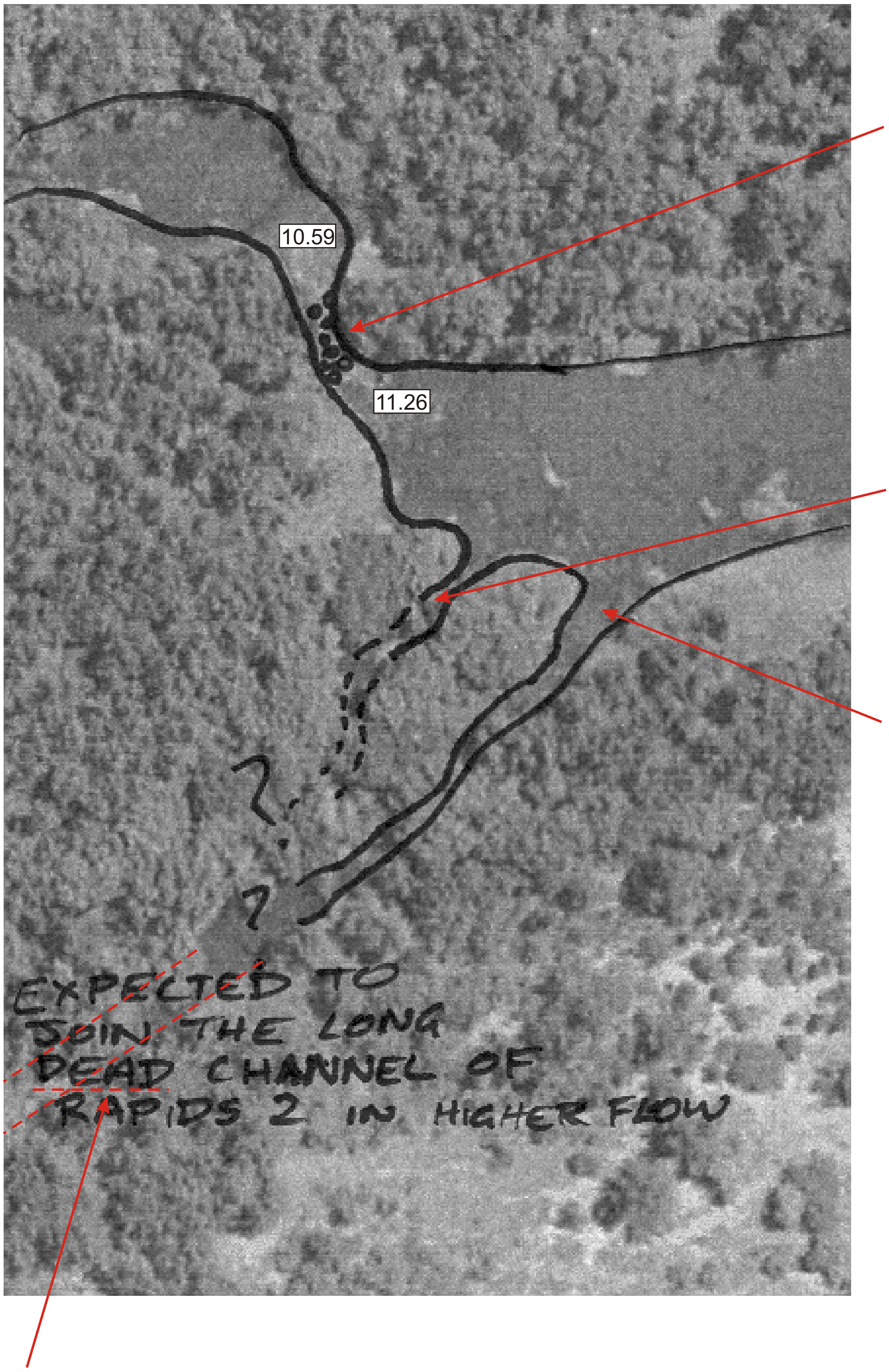
Figure
9

WRL
Report No. 2005/16

LOCATION OF RAPIDS

Figure
10

05020-10.cdr



Velocity barriers for adults and juveniles at the head of the riffle (1.75m/s @ 0.2m depth and 1.35m/s @ 0.1m depth on margins). Riffle >10m long. Thick vallisneria also potentially creating passage blocks just upstream of the head of the riffle.

Estimated that 80% of the flow was through this route.

Depth barriers for adults and juveniles-minimum thalweg depth being 0.05m.

Depth barrier for adults-minimum thalweg depth being 0.11m. Very thick vallisneria at the head of the riffle highly likely to be creating passage blocks.

Channel not dead as on the previous trip, we paddled down it without too much difficulty.

10.00 indicates water surface level

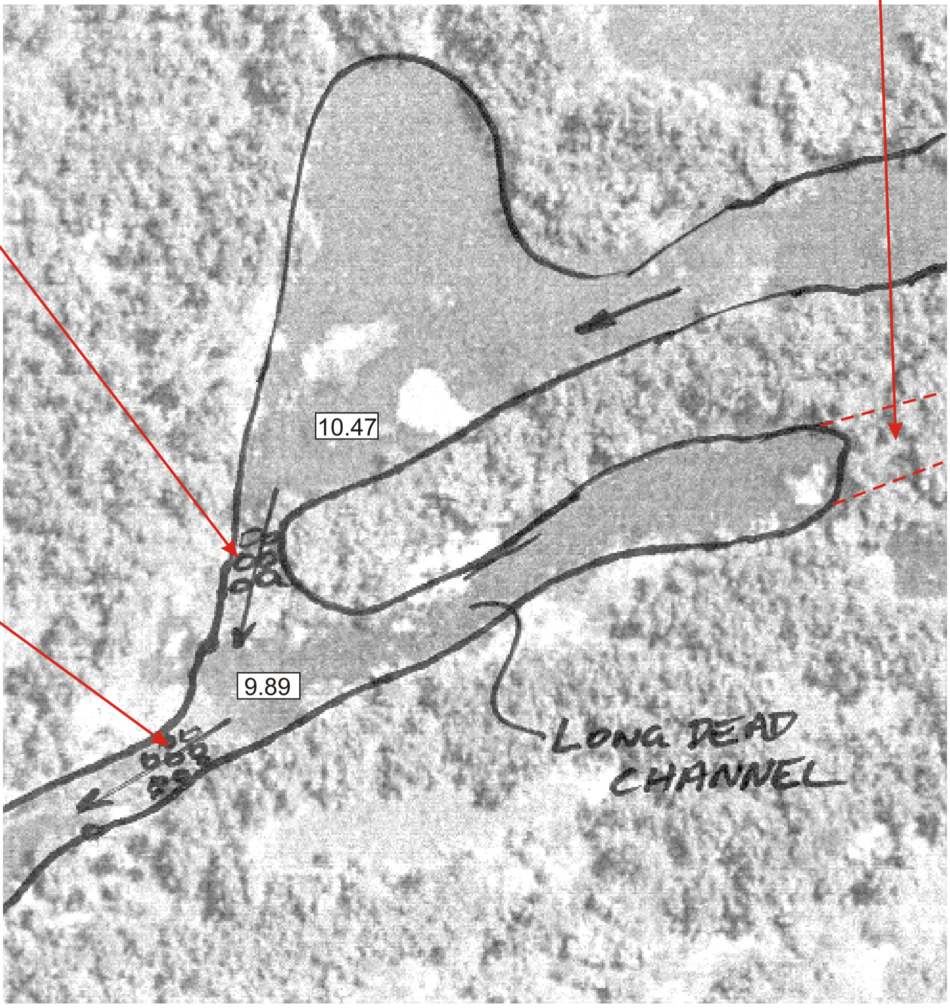
RAPIDS 1

Figure 11

Channel not dead ?

Water velocity blocks for adults and juveniles at the head of the riffle (1.75m/s @ 0.2m depth and 0.84m/s @ 0.1m depth on margins). Riffle >10m long. Thick vallisneria potentially creating passage blocks near the head of the riffle.

Water velocity blocks for adults and juveniles along the riffle (1.54m/s @ 0.2m depth and 0.85m/s @ 0.1m depth along the margins). Riffle >10m long.



10.00 indicates water surface level

RAPIDS 2

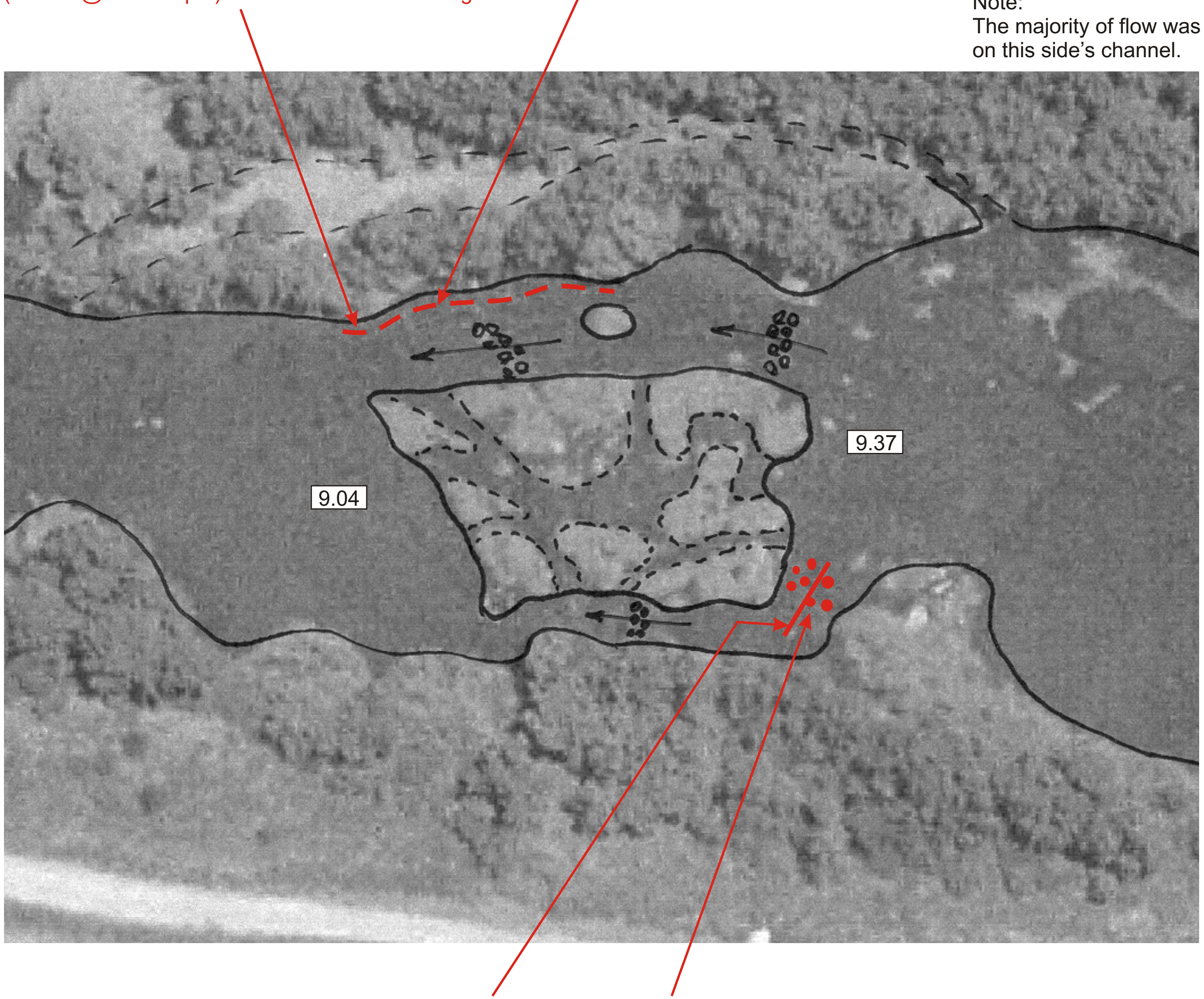
Figure 12

Depth barrier for adults (min. thalweg depth 0.1m) and water velocity barrier for adults and juveniles (1.9m/s @ 0.1m depth). Riffle/cascade >10m long.

Thalweg

Bedrock shelf

Note:
The majority of flow was on this side's channel.



Thalweg

Depth barrier for adults (min. thalweg depth 0.1m) and water velocity barrier for juveniles (0.95m/s @ 0.1m depth).

10.00 indicates water surface level

RAPIDS 3

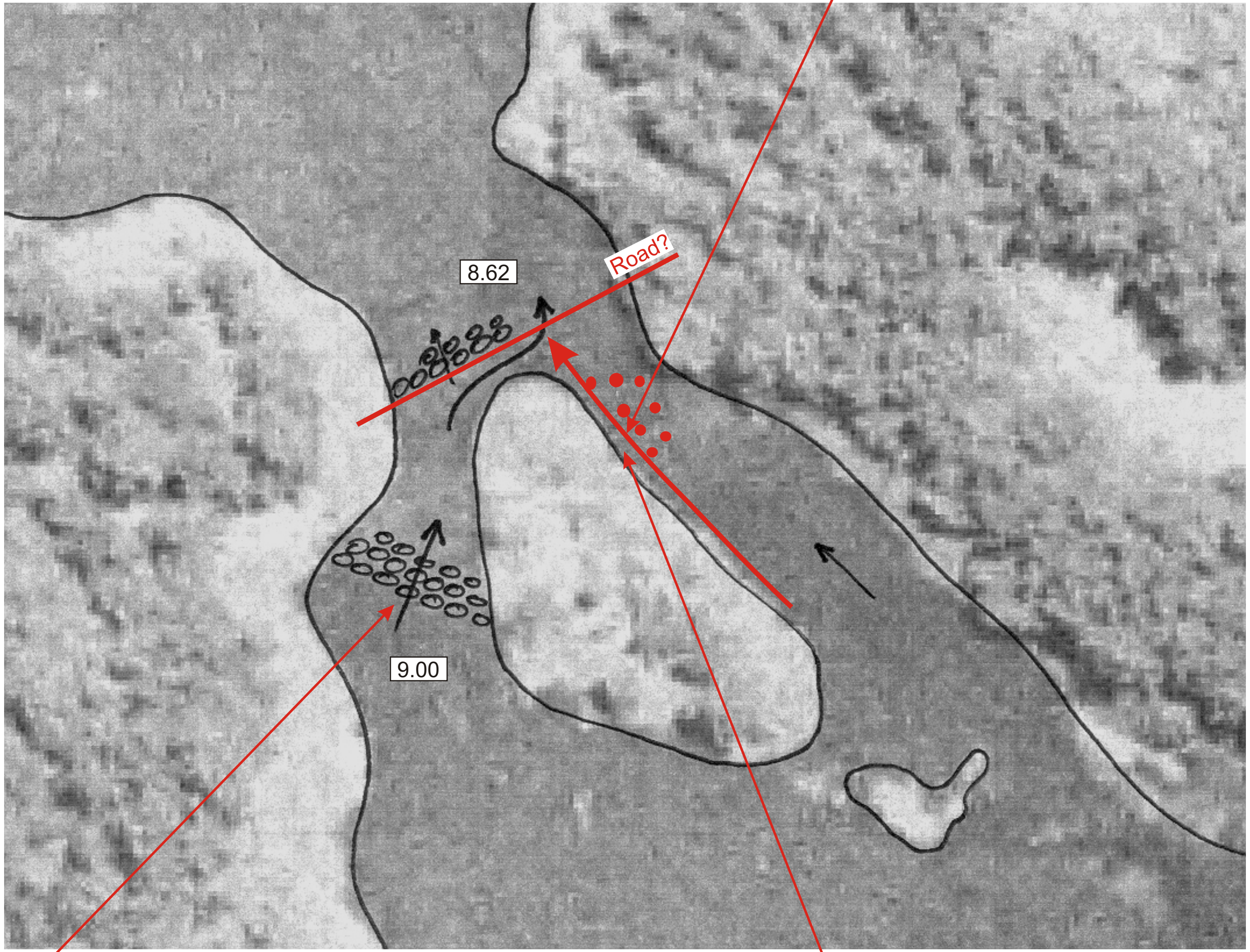
Figure 13

WRL
Report No. 2005/16

RAPIDS 4

Figure 14

05020-14.cdr



Depth barrier for adults (min. thalweg depth 0.14m). Riffle >10m long. Marginally water velocity barrier for juveniles (0.67m/s @ 0.14m depth). Highly likely that very thick vallisneria along the length of this gently sloping riffle also creates significant passage barriers.

Depth barrier for adults (min. thalweg depth 0.13m) at the head of the riffle. Water velocity barrier for juveniles (1.01m/s @ 0.13m depth). Riffle >10m long. Thick vallisneria at the head of the riffle potentially causing an additional passage barrier.

Possible passage gutter amongst thick vallisneria.

10.00 indicates water surface level

WRL

Report No. 2005/16

RAPIDS 5a AND 6

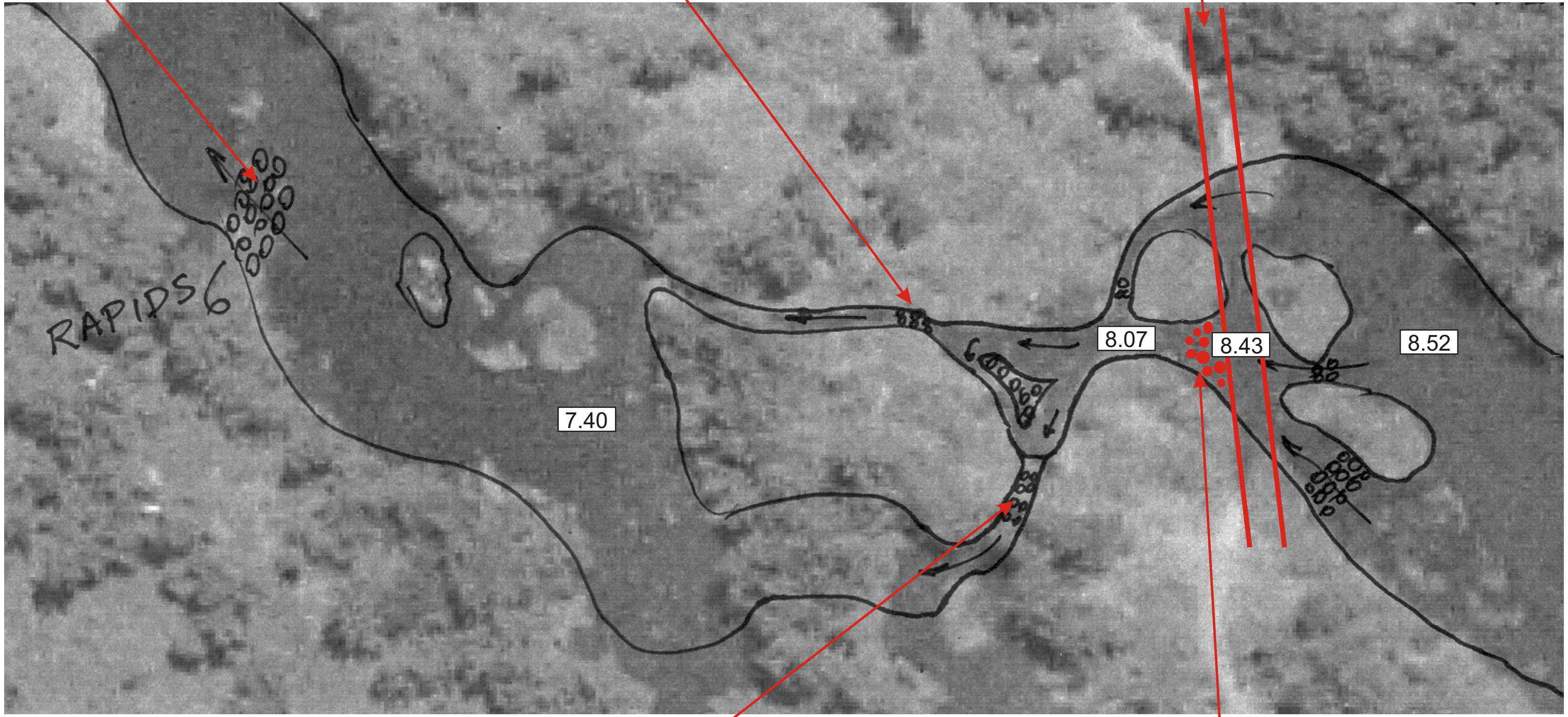
Figure 15

05020-15.cdr

Depth passage barrier for adults (0.14m min. thalweg depth). Riffle >10m long. Very thick vallisneria at top also causing a barrier.

Depth passage barrier for adults (0.14m min. thalweg depth). Riffle >10m long. Water velocity barriers for adults and juveniles (1.57m/s @ 0.14m).

Road

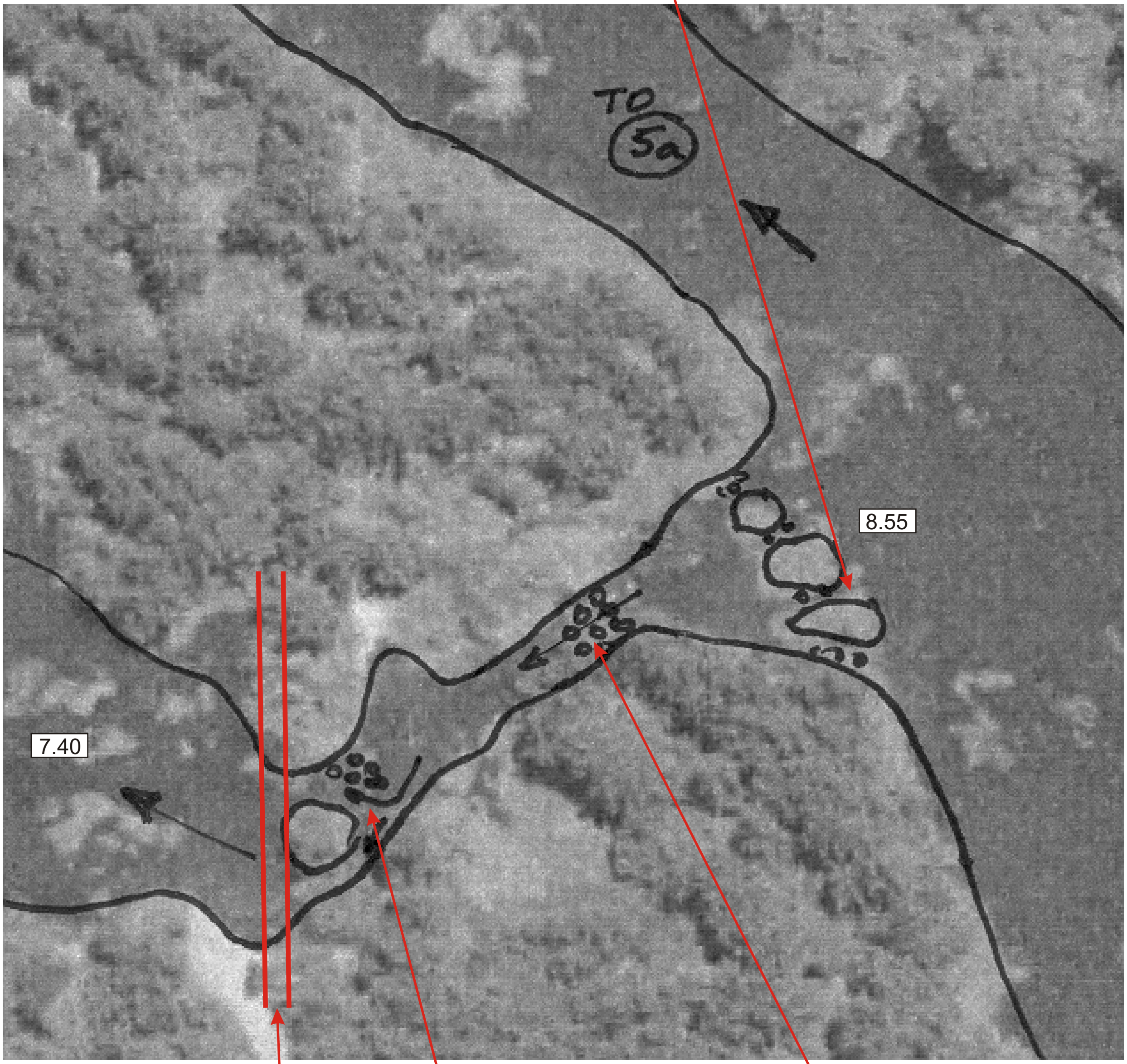


Depth passage barrier for adults (0.12m min. thalweg depth). Riffle >10m long. Water velocity barriers for adults and juveniles (1.22m/s @ 0.12m).

Depth passage barrier for adults (0.14m min. thalweg depth). Riffle complex >10m in length. Marginal water velocity barriers for adults and juveniles (1.17m/s @ 0.14m and 0.61m/s @ 0.1m on margins).

10.00 indicates water surface level

Least limiting:
Depth barrier for adults (0.13m min. thalweg depth). Marginal water velocity barrier for juveniles (0.63m/s @ 0.13m depth). Riffle >10m long.



Road

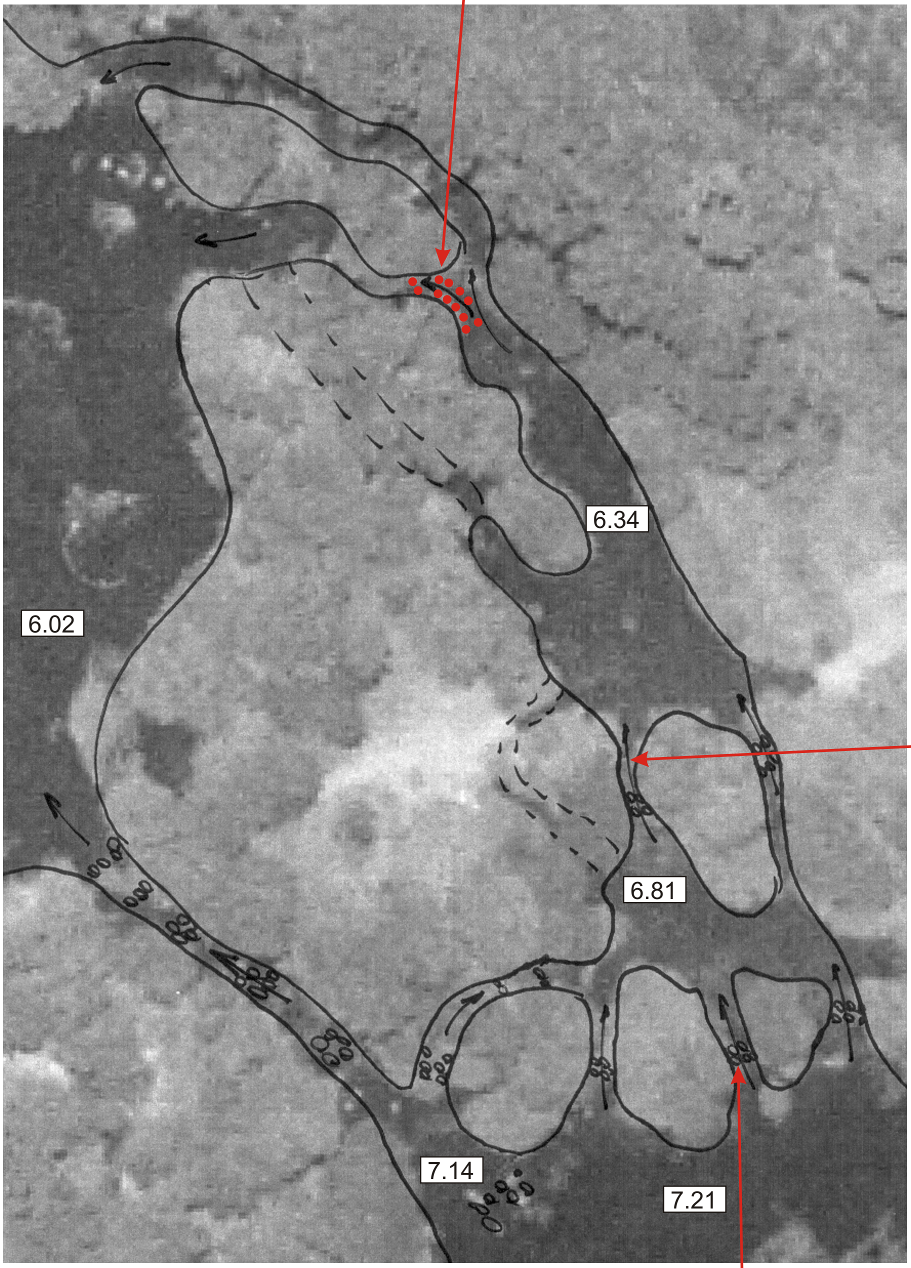
Depth barrier for adults (0.1m min. thalweg depth).

Velocity barriers for adults and juveniles (1.35m/s @ 0.2m and 1.04m/s @ 0.1m depth on margins). Riffle >10m long.

10.00	indicates water surface level

WRL Report No. 2005/16	RAPIDS 5b	Figure 16 05020-16.cdr

Best passage option:
No apparent hydraulic barriers (0.22m min. thalweg depth with water velocity 0.82m/s @ 0.1m depth on margins, the water velocity was 0.5m/s).
Riffle >10m long.



Best passage option:
Water velocity barriers for adults and juveniles (1.13m/s @ 0.2m and 1.01m/s @ 0.1m depth on margins). Riffle >10m long.

Best passage option:
Marginal depth barrier for adults (0.19m min. thalweg depth). Water velocity barriers for adults and juveniles (1.13m/s @ 0.19m and 0.85m/s @ 0.1m depth on margins). Riffle >10m long.

10.00 indicates water surface level

WRL

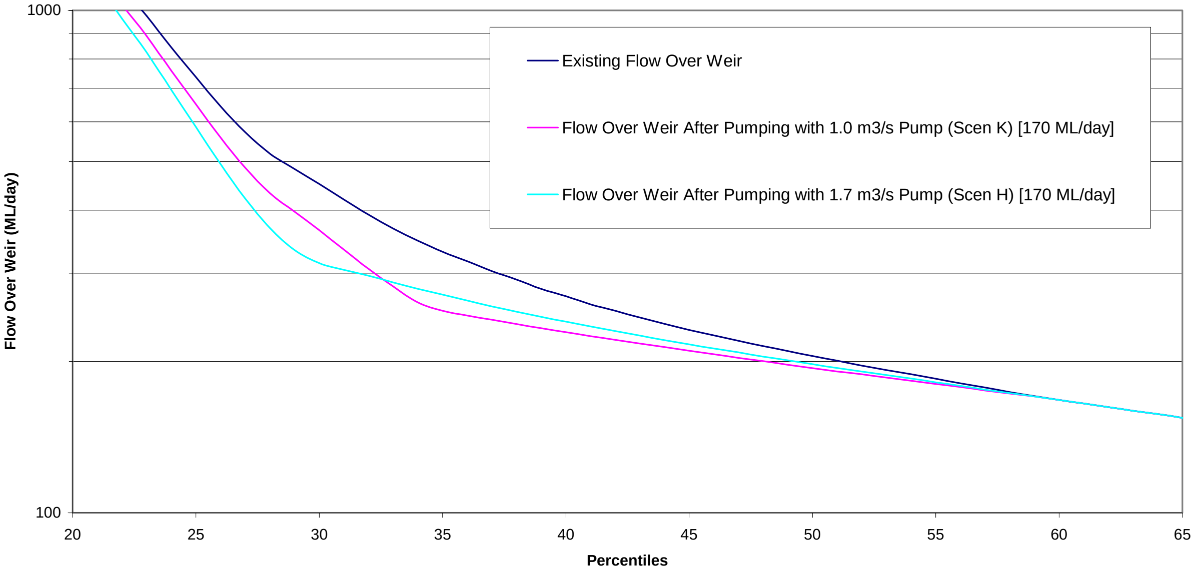
Report No. 2005/16

RAPIDS 7

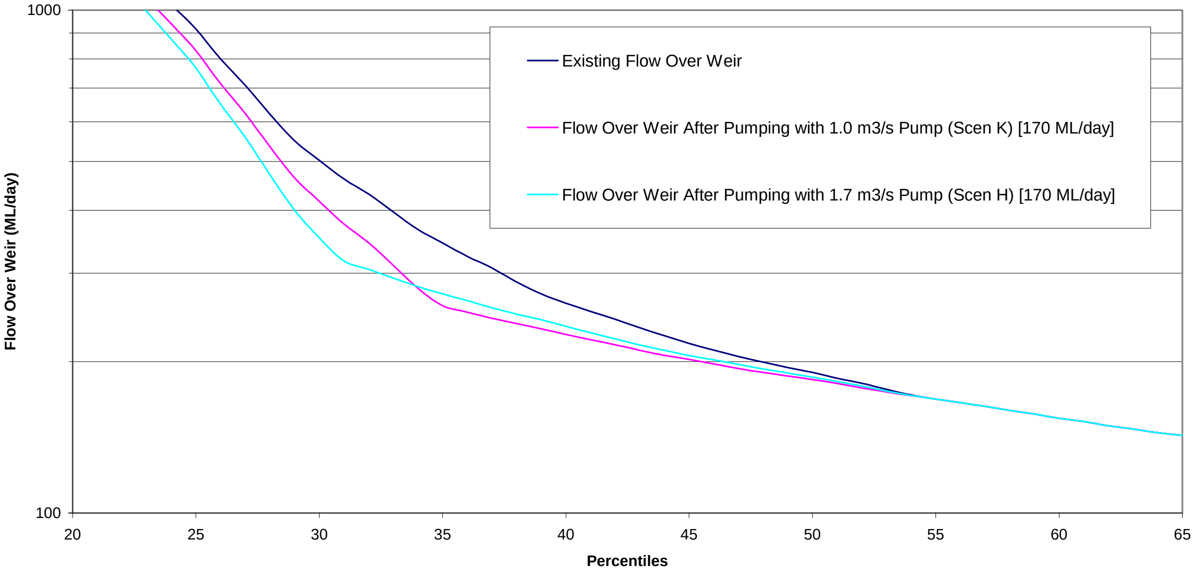
Figure 17

05020-17.cdr

Graph 1A: Comparison of River Flow After Extraction (All Data)

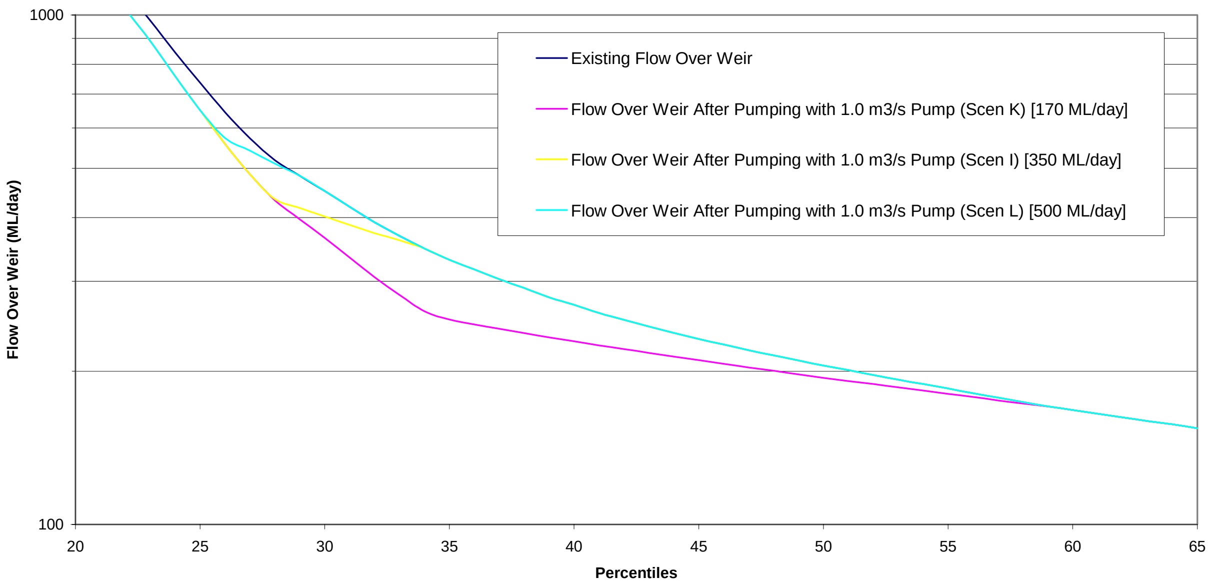


Graph 1B: Comparison of River Flow After Extraction (Sept-Oct Only)

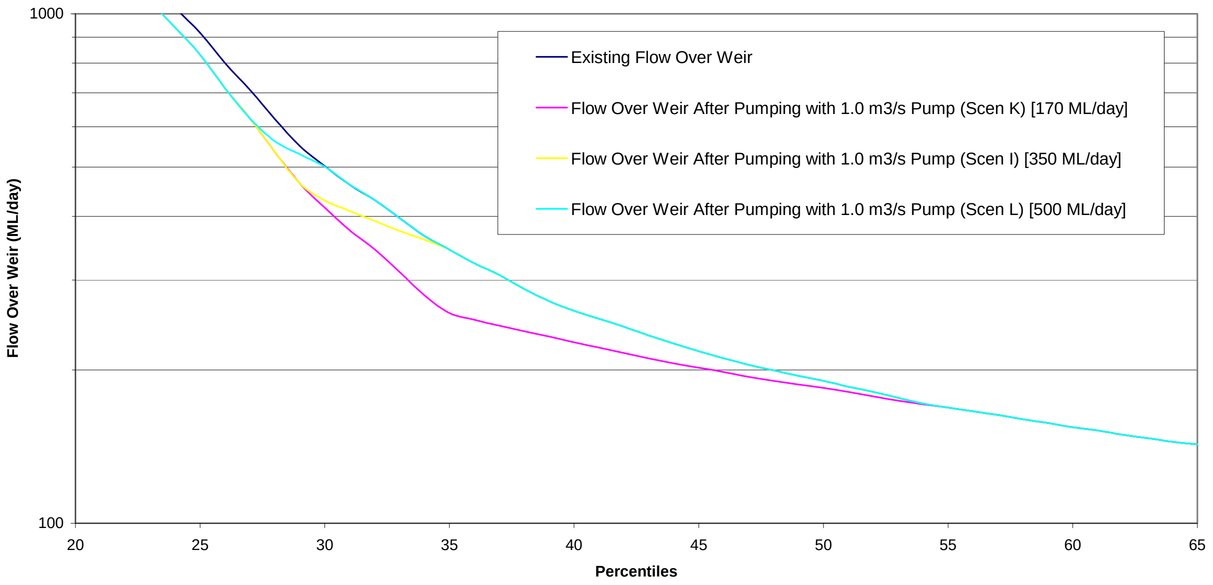


WRL Report No. 2005/16	GRAPH 1: FLOWS BEFORE AND AFTER EXTRACTION FOR SCENARIOS K AND H (ALL DATA & SEPT-OCT ONLY)	Figure 18

Graph 2A: Comparison of River Flow After Extraction (All Data)

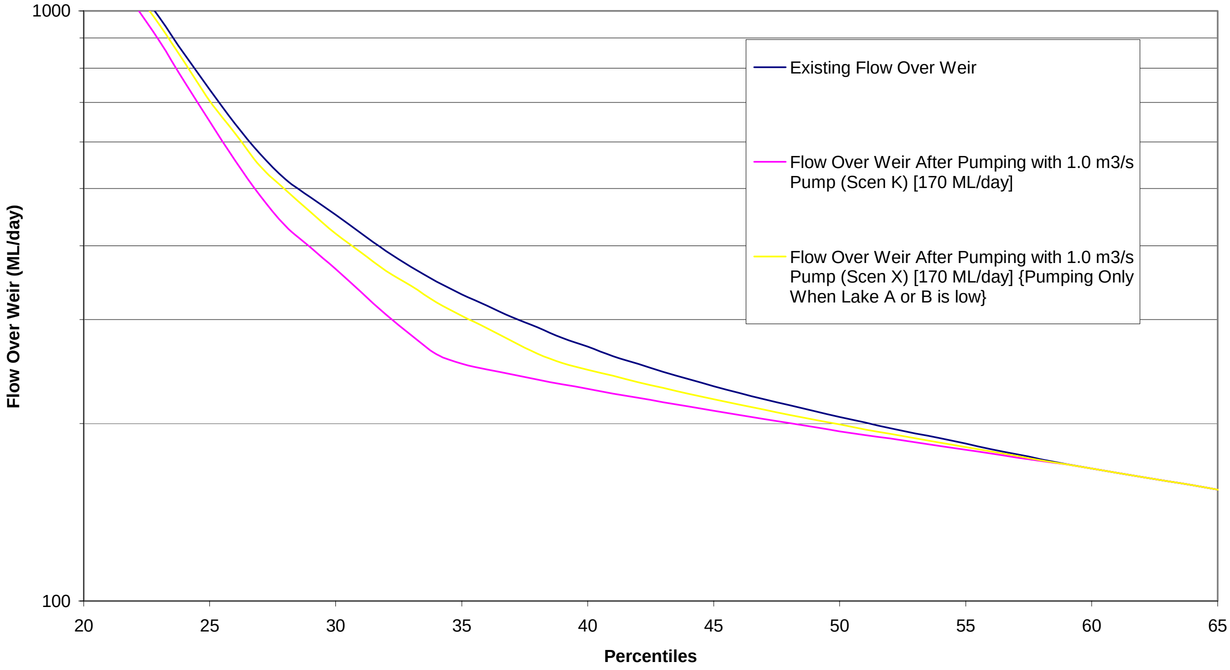


Graph 2B: Comparison of River Flow After Extraction (Sept-Oct Only)

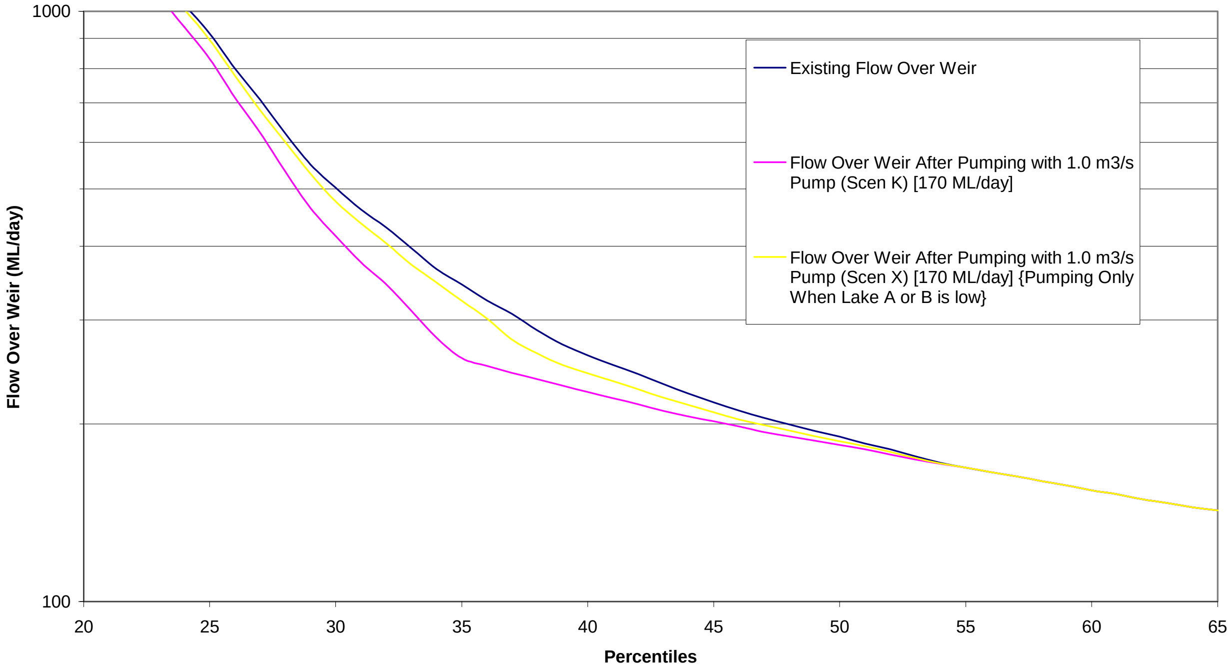


GRAPH 2: FLOWS BEFORE AND AFTER EXTRACTION FOR SCENARIOS K, I AND L (ALL DATA & SEPT-OCT ONLY)

Graph 3A: Comparison of River Flow After Extraction (All Data)



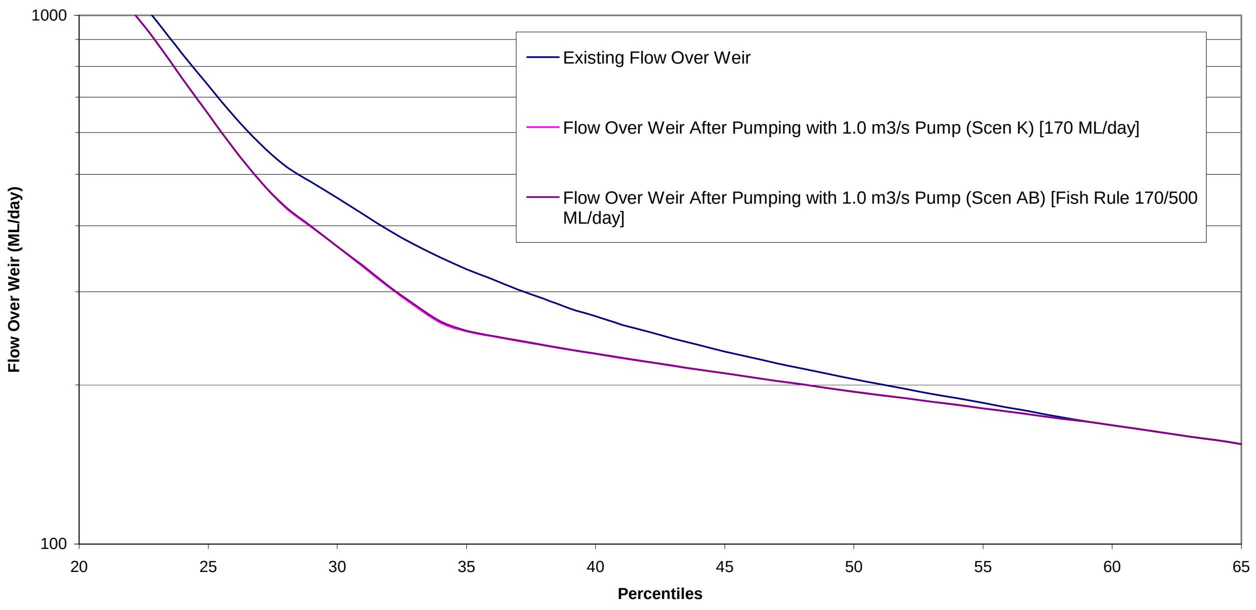
Graph 3B: Comparison of River Flow After Extraction (Sept-Oct Only)



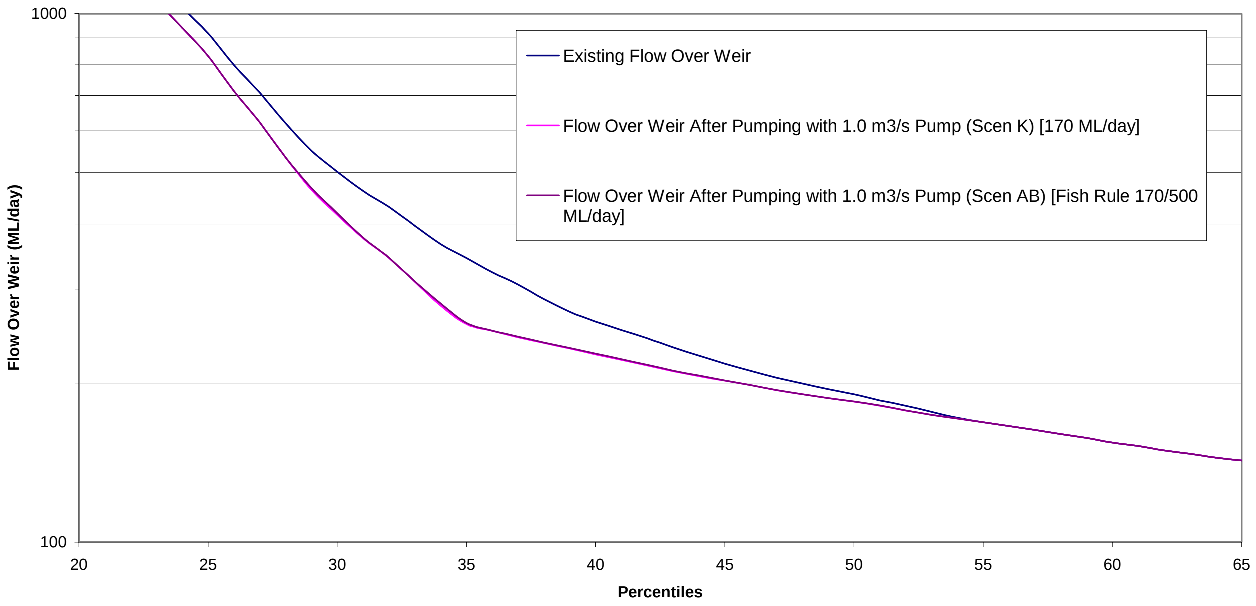
GRAPH 3: FLOWS BEFORE AND AFTER EXTRACTION FOR SCENARIOS K AND X (ALL DATA & SEPT-OCT ONLY)

Figure
20

Graph 4A: Comparison of River Flow After Extraction (All Data)



Graph 4B: Comparison of River Flow After Extraction (Sept-Oct Only)



WRL Report No. 2005/16	GRAPH 4: FLOWS BEFORE AND AFTER EXTRACTION FOR SCENARIOS K AND AB (ALL DATA & SEPT-OCT ONLY)	Figure 21

Appendix A
Weir and Culvert Flow Calculation Method

Weir Flow

Flow over a weir was calculated using Equation 1.

$$Q = B\sqrt{g\left(\frac{2}{3}HW\right)^3} \qquad 1$$

Where,

Q = flow (m^3/s)
g = gravity (m/s^2)
B = width (m)
HW = water level above weir height (m)

Culvert Flow

Flow through the culverts was calculated using Equation 2 and 3. For more information on the development of the culvert dimensions refer to WRL Technical Report 2004/13.

Culverts in Outlet Control

$$Q = B \times H\sqrt{\frac{2gZ}{1 + k_e + k_f}} \qquad 2$$

Where,

Z = difference between the upstream and downstream lake levels (m)
K_e = loss factor to account for energy losses at the culvert entrance
K_f = loss factor to account for energy losses associated with culvert friction
B = width of culvert (m)
H = height of culvert (m)

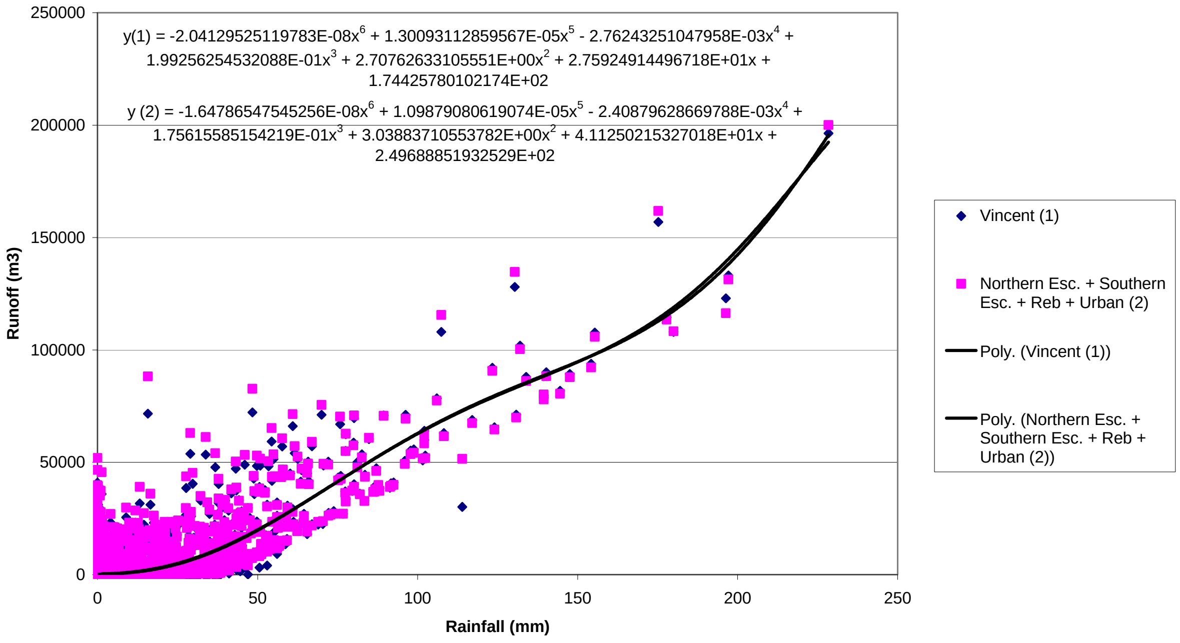
Culverts in Inlet Control

$$Q = C_b B\sqrt{g\left(\frac{2}{3}HW\right)^3} \qquad 3$$

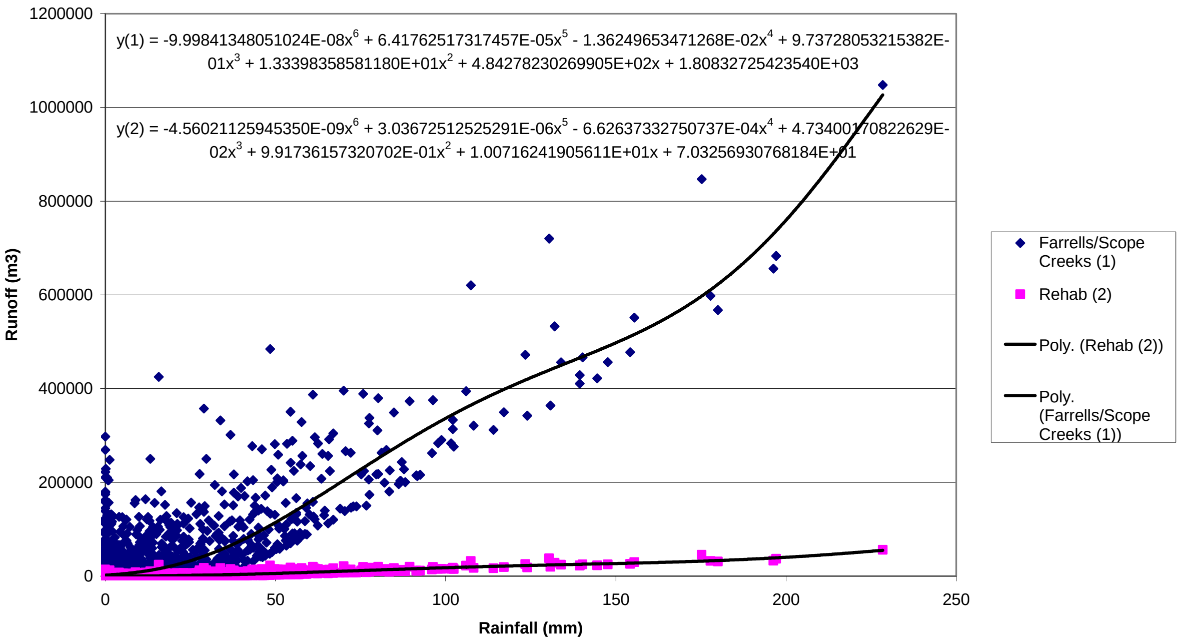
Where,

C_b = coefficient for flow contraction inside the culvert entrance
HW = water level above the culvert invert (m)

Appendix B
Catchment Runoff Regression Analysis

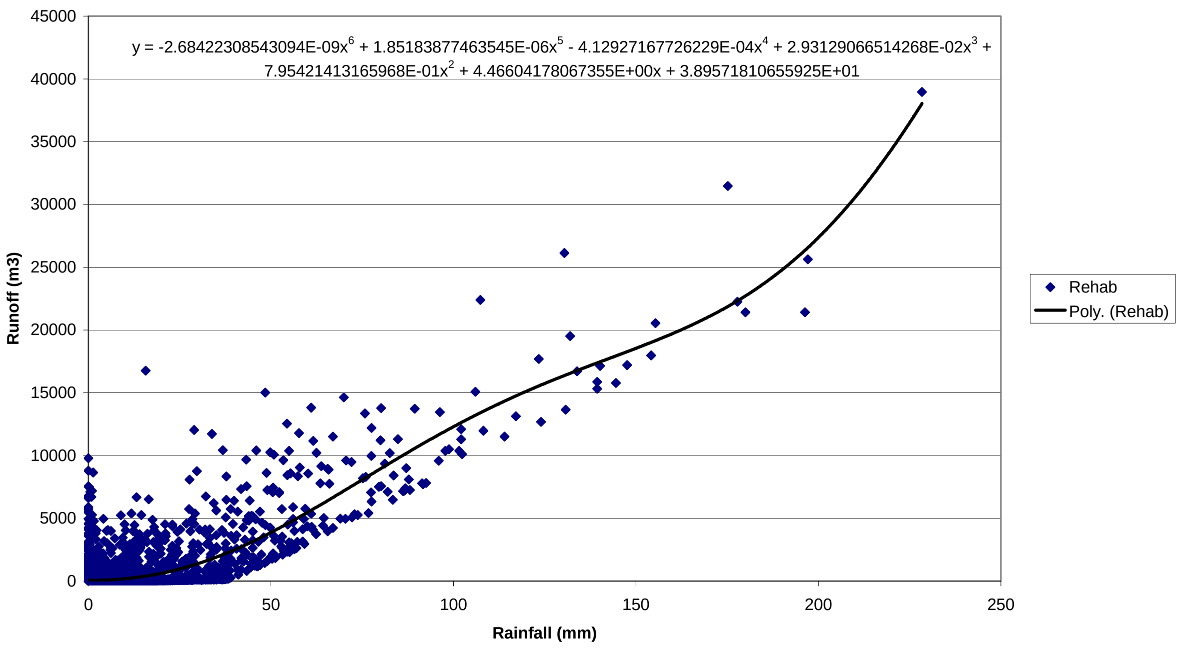


Cranebrook Lakes Catchment Runoff Regression Analysis

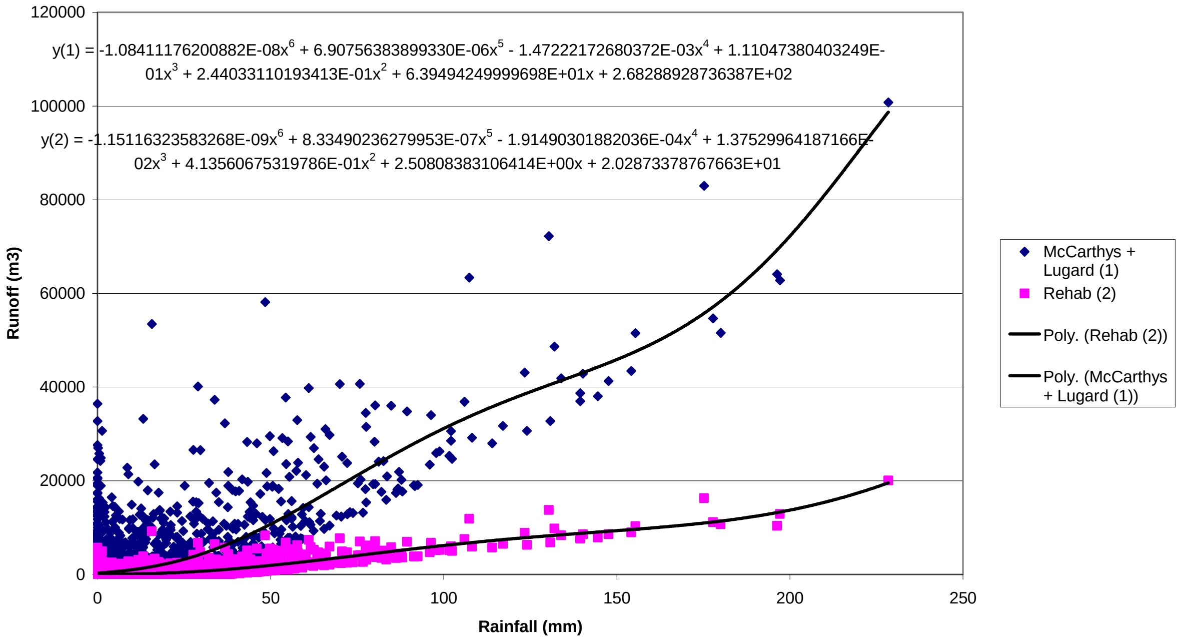


North Basin Catchment Runoff Regression Analysis

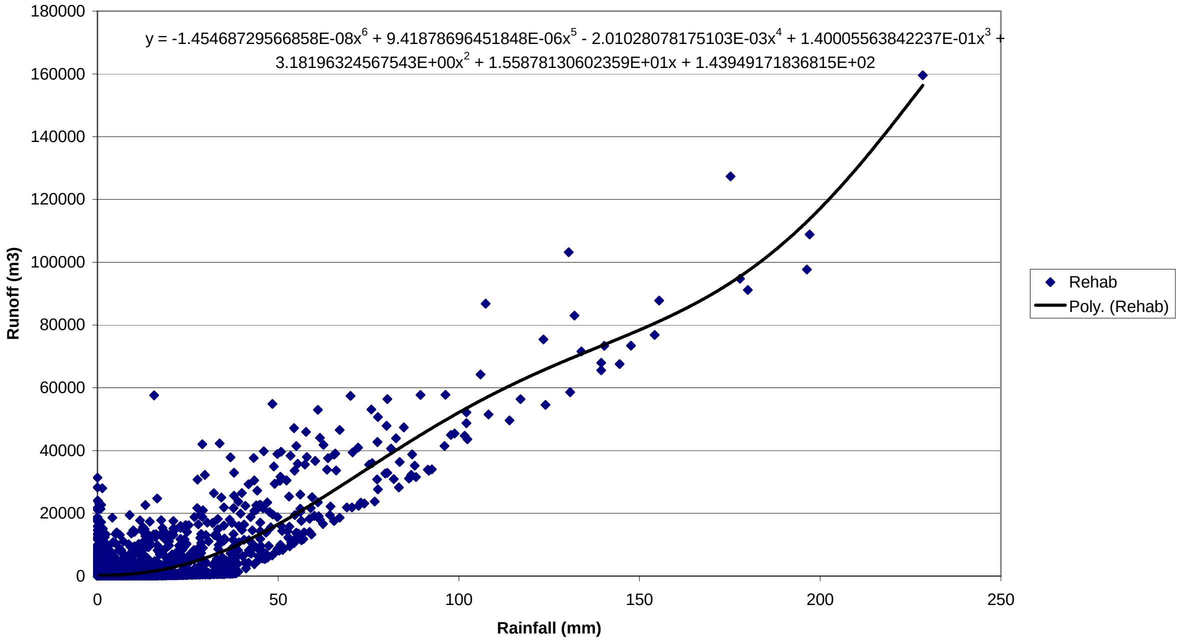
Middle Basin Catchment Runoff Regression Analysis



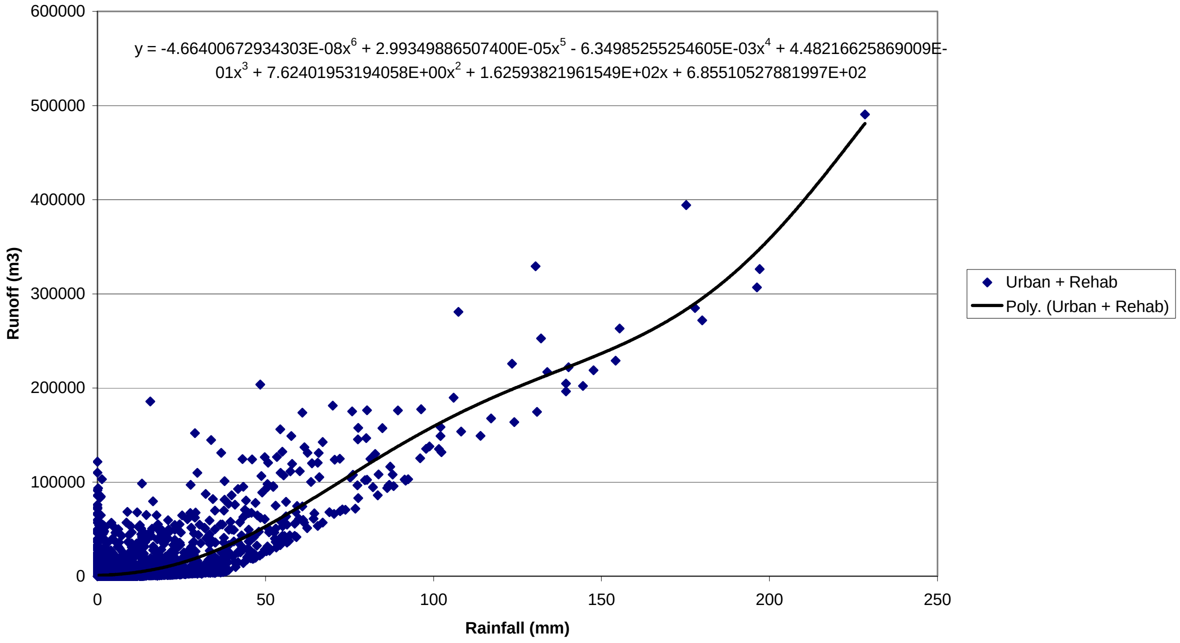
Final Basin Catchment Runoff Regression Analysis

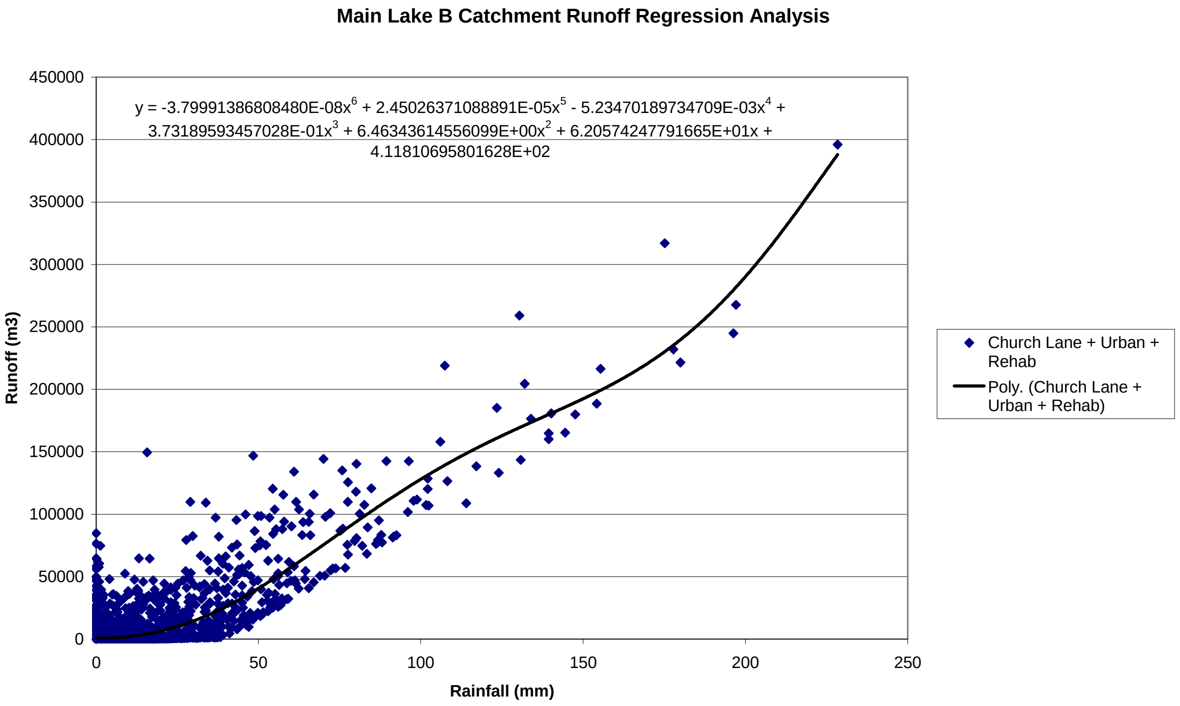


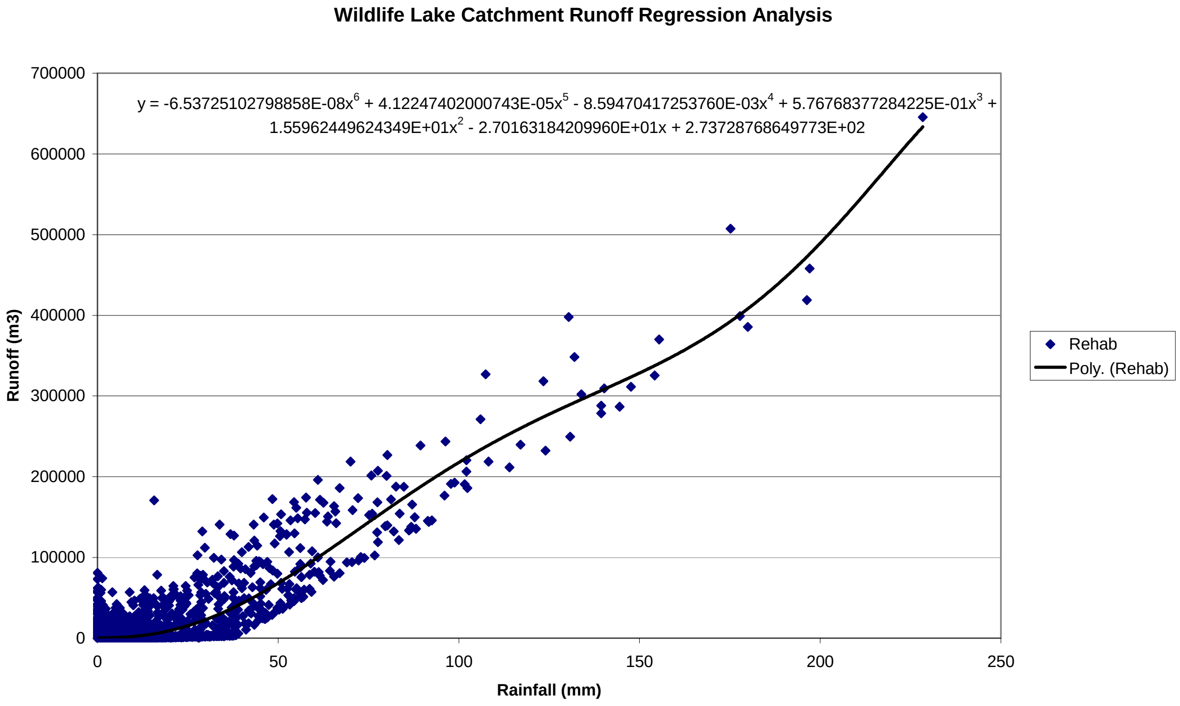
Regatta Lake Catchment Runoff Regression Analysis



Main Lake A Catchment Runoff Regression Analysis




Main Lake B Catchment Runoff Regression Analysis


Wildlife Lake Catchment Runoff Regression Analysis

Appendix C
Comparison of Water Balance Model Results with Other Studies

Water balance studies of the Penrith Lakes Scheme have been conducted by the Department of Environment and Planning (1984), ERM Australia (2001), Keogh (2003, 2004, 2004a) and the Independent Expert Panel (2005).

Department of Environment and Planning (1984) completed a basic assessment of the water balance required for the lakes during which the basic design and concept for the lakes was established. A mean depth of 5 m was used for the recreation lakes, and 2 m depth for the wildlife lakes. From this study, the Nepean and Grose Rivers were selected as the best options for alternative water sources. Using this water balance, the optimum lakes area of 725 ha was determined, storing about 33 000 ML of water and requiring an average of 3 500 ML/year to maintain. The current lake design holds a total of 29 500 ML. The WRL modelling found that when water was extracted to maintain operating levels the median value pumped was between 2, 580 ML (Scenario Y) and 3, 600 ML (Scenario Z).

ERM Australia's (2001) water balance model assumed seepage of 1 ML/day, a lake surface area of 839 ha and volume of 41 950 ML, far higher than the current design volume of 29 500 ML at operating levels, and for this reason is difficult to compare with the WRL model.

Keogh (2003) conducted a dynamic budget model of water, sediment and nutrients for the lakes as they operated at the time of his study using a daily time step and including the inputs of stormwater, rain, spill from upstream lakes into downstream lakes, transfers through culverts and via pumping, changes in storage and evaporation. Keogh with UWS (Keogh 2004a) expanded the capacity of Keogh's original model to include all of the proposed lakes in the Penrith Lakes Scheme and test a range of supplementary water options. These included pumping from Penrith Weir to the Regatta Centre to address the total Lakes Scheme water deficit, pumping from Penrith Weir to Main Lake A to address the total Lake Scheme water deficit, or pumping whenever flow is available to maximise flushing of the lakes. Four separate pump sizes and five upper pumping limits were also tested giving a total of 60 simulations assessing both the water balance and water quality over 30 years.

The Expert Panel for Environmental Flows for the Hawkesbury Nepean, Shoalhaven and Woronora Catchments reviewed the work of Keogh and UWS (Independent Expert Panel, 2004) and rated the work as best practice. To provide independent verification of the work, they established a spreadsheet water balance model using historical climate data from 1915 – 1996 and the ultimate operational setup of the lakes. The model did not include groundwater or seepage losses.

Results of WRL's modelling have therefore been compared to the findings of Keogh's extended model and the Independent Expert Panel as the most significant of the studies previously conducted. Scenarios modelled by WRL were chosen to supplement and confirm the work conducted by Keogh (2004a) based on current lake configurations. All scenarios pumped water from the Nepean River to Main Lake A with the option to pump from Main Lake A to the Regatta Lake, and therefore only Keogh's simulations run on this basis could be compared (labelled Deficit 2 in his report). Rather than concentrating on upper pumping limits, WRL's work has emphasised the impacts of lower pumping limits for the purpose of conserving environmental flows. Modelling included 1.7 m^3/s and 2.0 m^3/s pumps as Keogh's work did, but also included a lower rate pump of 1.0 m^3/s, and enabled these pumps to operate as either fixed or variable rate pumps. Scenarios included the variation of pumping all flow available or pumping when lake levels were below the desired operating level.

Table 1 compares drawdowns predicted by Keogh and WRL for 1.7 m^3/s fixed rate pumping with a lower pumping limit of 170 ML/day, pumping only when necessary to maintain operating levels. Drawdowns predicted by Keogh are consistently less than those predicted by WRL. This may be due to the simulation only being run for 30 years, and it may be that Keogh has used a variable rate pump (however this is not specified). Differences have also been found in the stage volume relationships devised for the lakes.

Table 1
Comparison of WRL (Scenario Z) and Keogh Results for 1.7 m^3/s Fixed Pump, Cease-to-Pump 170 ML/day Pumping to Maintain Operating Levels

Percentile	Lake	Drawdown (m)	
		WRL	Keogh
95th Percentile	Regatta	0.40	0.28
	Main Lake A	0.91	0.26
	Main Lake B	1.26	0.47
	Wildlife Lake	0.83	0.20
90th Percentile	Regatta	0.25	0.17
	Main Lake A	0.69	0.16
	Main Lake B	0.82	0.33
	Wildlife Lake	0.60	0.03
50th Percentile	Regatta	0.01	-0.08
	Main Lake A	0.04	-0.13
	Main Lake B	0.06	-0.10
	Wildlife Lake	-0.02	-0.10

Results of the Independent Expert Panel have been compared with WRL for a fixed rate 1.0 m^3/s pump operating to correct deficits in lake levels with a cease-to pump rate of 170 ML/day (Scenario X) at Penrith Weir in Table 2.

Table 2
Comparison of Independent Expert Panel and WRL Results

Percentile	Lake	Drawdown (m)	
		WRL	Independent Expert Panel
95th Percentile	Regatta	0.36	0.28
	Main Lake A	0.97	0.47
	Main Lake B	1.35	0.74
	Wildlife Lake	0.83	0.82

Drawdowns predicted by the Independent Expert Panel are less than those predicted by WRL for all but the Wildlife Lake. As WRL drawdowns include groundwater losses they are expected to be greater than those predicted by the Independent Expert Panel. Other differences may be due to the way water pumped from the Nepean River was shared between lakes and the culvert/weir flow relationships.

Both Keogh and the Independent Expert Panel investigated upper pumping limits and found that the upper pumping limit for maintenance of water quality and lake levels was 5000 ML/day from the river. No hydrological benefit was gained from pumping when the flow rate was higher than 5000 ML/day and these higher flows are of poorer water quality. This upper limit was included in all of the scenarios modelled by WRL. Pumping whenever flow was available was also not recommended as the benefit to the water levels was not thought to be worth the cost.

The Independent Expert Panel (2004) found that a pump capacity of 0.5 m^3/s was sufficient to maintain lake water levels and that little benefit was gained by a larger pump. Regardless, their recommendations advised a pump size between 0.5 – 2.0 m^3/s, in keeping with Keogh's recommendation of 2.0 m^3/s. Keogh's (2004a) key recommendation was that a 2.0 m^3/s pump operating when the flow rate at Penrith Weir is between 170 and 5000 ML/day, and pumping to Main Lake A should be installed to maintain the water balance in the lakes most efficiently. WRL have found that adequate water levels can be maintained with a 1.0 m^3/s pump with a cease-to pump rule of 350 ML/day and that this can be done by pumping to Main Lake A. While WRL did not model a 0.5 m^3/s pump, the need for a 1.0 m^3/s may be explained by groundwater losses which were not modelled by the Panel. The smallest pump modelled by Keogh was 1.7 m^3/s.

Appendix D
Water Quality Samples Taken from Penrith Weir Pool

Samples Taken from Penrith Weir Pool by Sydney Catchment Authority
1984-May 2005

Analytes	**No. Samples**	**Maximum**	**Minimum**	**Median**	**95th percentile**
Algal Total Count (cells/mL)	72*	16965	1939	2452	14829
Alkalinity (mgCaCO3/L)	52	116	15.5	42.8	78.3
Aluminium Filtered (mg/L)	52	0.1	0.01	0.016	0.053
Aluminium Total (mg/L)	62	3.07	0.01	0.028	0.485
Biochemical Oxygen Demand (mg/L)	136	3650	0	39.5	287
Calcium Filtered (mg/L)	33	15.2	3.5	9.0	14.3
Chlorophyll-a (ug/L)	855	35.98	0	3.4	11.8
Clostridium perfringens (CFU/100mL)	51	32	0	0	10
Coliforms Thermotolerant (cfu/100mL)	608	17000	0	118	903
Conductivity Field (mS/cm)	409	0.765	0.09	0.27	0.45
Dissolved Organic Carbon (mg/L)	51	8.2	0.3	4	6.06
Dissolved Oxygen (%Sat)	838	159	34	95	119
Dissolved Oxygen (mg/L)	841	13.6	3	8.8	11.4
E. coli (orgs/100mL)	52	2400	0	34	288
Enterococci	216	2600	0	63	348
Iron Filtered (mg/L)	52	0.317	0.015	0.052	0.214
Iron Total (mg/L)	52	1.09	0.033	0.114	0.637
Lorenzine (ug/L)	157	16	0.1	3.2	8.6
Magnesium Filtered (mg/L)	33	11.1	3.13	6.76	10.55
Manganese Filtered (mg/L)	52	0.233	0.001	0.003	0.037
Manganese Total (mg/L)	52	0.483	0.008	0.019	0.094
Nitrogen Ammoniacal (mg/L)	865	0.28	0	0.01	0.08
Nitrogen Oxidised (mg/L)	886	1.8	0	0.12	0.48
Nitrogen TKN (mg/L)	528	1.6	0	0.31	0.7
Nitrogen Total (mg/L)	448	1.65	0	0.37	0.79
pH (Field)	122	9.6	6.19	7.75	9.3
Phaeophytin (ug/L)	167	13.1	0.1	1.2	3.5
Phosphorus Filterable (mg/L)	798	0.27	0.001	0.005	0.016
Phosphorus Total (mg/L)	908	0.44	0	0.013	0.054
Potassium Filtered (mg/L)	33	6.84	1.52	2.81	5.14
Secchi Depth	59	0	0	0	0
Silicate Reactive (SiO2 mg/L)	818	5.5	0.1	2.6	4.5
Sodium Filtered (mg/L)	33	81.6	14.1	34.7	80.7
Sulphate (mg/L)	52	14	1	7	11.55
Suspended Solids (mg/L)	574	259	0	2	23.05
Temperature (Deg C)	850	33.7	8	19.3	26.6
Total Organic Carbon (mg/L)	51	11.2	0.6	4	6.6
True Colour at 400nm	52	26	4	8	18.1
Turbidity Field (NTU)	122	30.7	0.7	1.9	7.2
UV Absorbing constituents (organic)	52	0.189	0.056	0.079	0.144

*values only given for 4 samples, other samples only “Done”