Integrated Monitoring of Environmental Flows: Assessment of predictive modelling for river flows and fish

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NON-TECHNICAL SUMMARY

River Flows in New South Wales are being restored in an effort to improve river health and sustainability under the NSW Water Reform Process. Historical development of the State's water resources has dramatically altered the natural flow regimes in many rivers. Water managers need tools to enable them to protect the ecological needs of rivers, to restore more natural flows and to rehabilitate fish communities and other components of riverine ecosystems.

This project sought to produce a mathematical model that could predict the responses of fish communities to different environmental flow strategies in 7 regulated rivers. The development of the model had 2 stages: first, to identify and describe how current river flows differ from natural hydrological conditions; second, to assess whether the hydrological changes had affected fish communities. Based on the predictions of the mathematical model, the project aimed to recommend flow regimes that were beneficial for native fish for consideration when drafting river management guidelines.

The study confirmed that the natural hydrology of the rivers has changed substantially because of the historical level of water resource development in NSW. The modelling suggests that environmental flow rules, developed as part of water management plans, have not achieved the desired objective of partially re-establishing natural flows. Rather, they have produced an alternative flow regime that is as different to natural conditions as the river flows prior to the introduction of environmental flow rules (i.e. at 1993/94 levels of development).

Our current ability to predict responses of fish to environmental flow rules is limited, partly because the environmental flow rules appear to have created a new hydrological regime which does not mimic the natural regime, and partly because of the unavailability of data collected over suitable time frames. Further monitoring of fish communities is recommended, as is the possible use of contingency flow allocations to more directly test fish responses to changed environmental flows.

1. INTRODUCTION

The New South Wales Government's Water Reform package contains a commitment to water sharing arrangements to improve environmental management and provide greater certainty for water users. The package outlines a community-based planning process to develop local flow targets in line with 12 broad River Flow Objectives (RFOs) and other interim environmental objectives for NSW waters (EPA 1997), which set out the general principles on which environmental flow and water quality management are to be based.

For regulated rivers (i.e. those in which flows are controlled by upstream reservoirs), the decision was made that environmental flow rules should enhance environmental quality while reducing diverted volumes of water by no more than an average of 10%. Indicative rules were developed by an inter-agency working group comprising representatives of the Department of Land and Water Conservation (DLWC), the Environment Protection Authority (EPA), the National Parks and Wildlife Service (NPWS), NSW Agriculture and NSW Fisheries. These indicative rules were reviewed by river management committees (RMCs) for the following rivers:

- Barwon-Darling River
- Gwydir River
- Hunter River
- Lachlan River
- Macquarie River
- Murrumbidgee River
- Namoi River

The revised rules recommended by the RMCs were approved and adopted in 1998-99. These rules may be reviewed annually by RMCs, but a major review is planned after five years.

The Integrated Monitoring of Environmental Flows (IMEF) project was established to assess the environmental responses to improved flows (DLWC 2001). Ecological responses to the environmental flows were predicted by eight response hypotheses to establish the likely ecological benefits. Freshwater fish were selected as one of the environmental indicators that were examined as a part of the monitoring program.

1.1. IMEF Objectives and Intended Outputs

The objectives of IMEF are:
- To measure changes in the hydrology, habitats, biota (including fish) and ecological processes in the major regulated river systems (and the Barwon-Darling River) following the application of environmental flow rules;
- As far as practical, to infer relationships between these changes and environmental flows, through statistical analysis and an understanding of ecosystem processes;
- To provide scientific information needed for the RFO review process.

The intended outcomes of the project are:
- An understanding of the current state and trends over time in hydrology, morphology and ecology in the major river systems;
- An evaluation of the likely contributions of environmental flows to these changes;
- An informed RFO review process.

The NSW Fisheries component of the IMEF program was designed to address four of the River Flow Objectives by testing four of the eight response hypotheses (full lists of the RFOs and hypotheses are given in DLWC 2001):

Hypothesis 2. Low-flow habitat improvement
Protecting natural low flows (RFO 2), for example by raising pumping thresholds, will promote the recovery of water plants, native fish and invertebrates, by maintaining wetted area and reducing the frequency and severity of stratification, thereby increasing dissolved oxygen levels and reducing salinity.

Hypothesis 4. Stony bed conditioning
Protecting or restoring a portion of freshes and high flows, and otherwise maintaining natural flow variability (RFOs 3 & 6), through off-allocation use restrictions and dam releases, will induce scouring of silt and sloughing of biofilms from stony substrata, resetting biofilm development and improving habitat quality for some invertebrate scrapers and their predators, and spawning conditions for gravel-spawning fishes.

Hypothesis 7. Wetland replenishment
Protecting or restoring a portion of freshes and high flows, and otherwise maintaining natural flow variability (RFOs 3, 4 & 6), through off-allocation use restrictions and dam releases will replenish anabranches and low-lying riverine wetlands, restore their biota, and promote the exchange of biota and non-living organic matter between these and the main river channels.

Hypothesis 8. Rehabilitating fish communities
Protecting or restoring a portion of freshes and high flows, and otherwise maintaining natural flow variability (RFO3 and RFO6), through off-allocation use restrictions and dam releases, will create conditions less amenable to carp recruitment, and more amenable to native fish recruitment, survival and passage past low weirs, and thereby increase the abundance and relative proportion of native fish.

This report from the NSW Fisheries component of the IMEF project evaluates a predictive model for fish responses to river flows that result from current water resources development and the environmental flows that are released under current water management plans. In particular, the predictive model presented in this report seeks to test Hypothesis 8 "Rehabilitating fish communities".

A preliminary flow/fish predictive model was evaluated by Gehrke *et al.* (2001). Based upon the limited preliminary hydrological data and the low number of sites where both fish data and hydrological information were available, Gehrke *et al.* (2001) suggested that our ability to predict responses of fish and other river health indicators to environmental flow rules was poor. Modelling suggested that the natural hydrology of the regulated rivers had changed because of the level of water resource development in New South Wales and that environmental flow rules, developed as a part of water management plans, had not achieved the desired objective to re-establish flows that are closer to the natural condition. The initial predictive model showed some relationships with two fish community indices: the proportion of native fish and proportion of carp in rivers. These results were very preliminary, however, and Gehrke *et al.* (2001) recommended two ways of improving the predictive models, namely: using a greater range of hydrological indices and including a larger number of sites where data for fish community composition and modelled flow regimes were available. The expanded data sets became available in 2002, and the revised model is re-evaluated in this report.

These analyses and modelling are based on two assumptions. First, that hydrological differences between rivers with natural and developed flow conditions can be represented as a linear combination of hydrological variables. A corollary of this assumption is the hypothesis that the environmental flow rules implemented in the major river valleys of New South Wales are effective in moving river flow regimes from their degraded, developed state in the reverse direction toward a more natural condition.

The second assumption is that relationships can be identified between the fish community and the level of water resource development in each river. This assumption gives rise to the following hypothesis, that by providing flow regimes in regulated rivers that more closely resemble the natural flows, fish communities will change to resemble their natural structure and composition

These 2 hypotheses are illustrated in Figure 1.

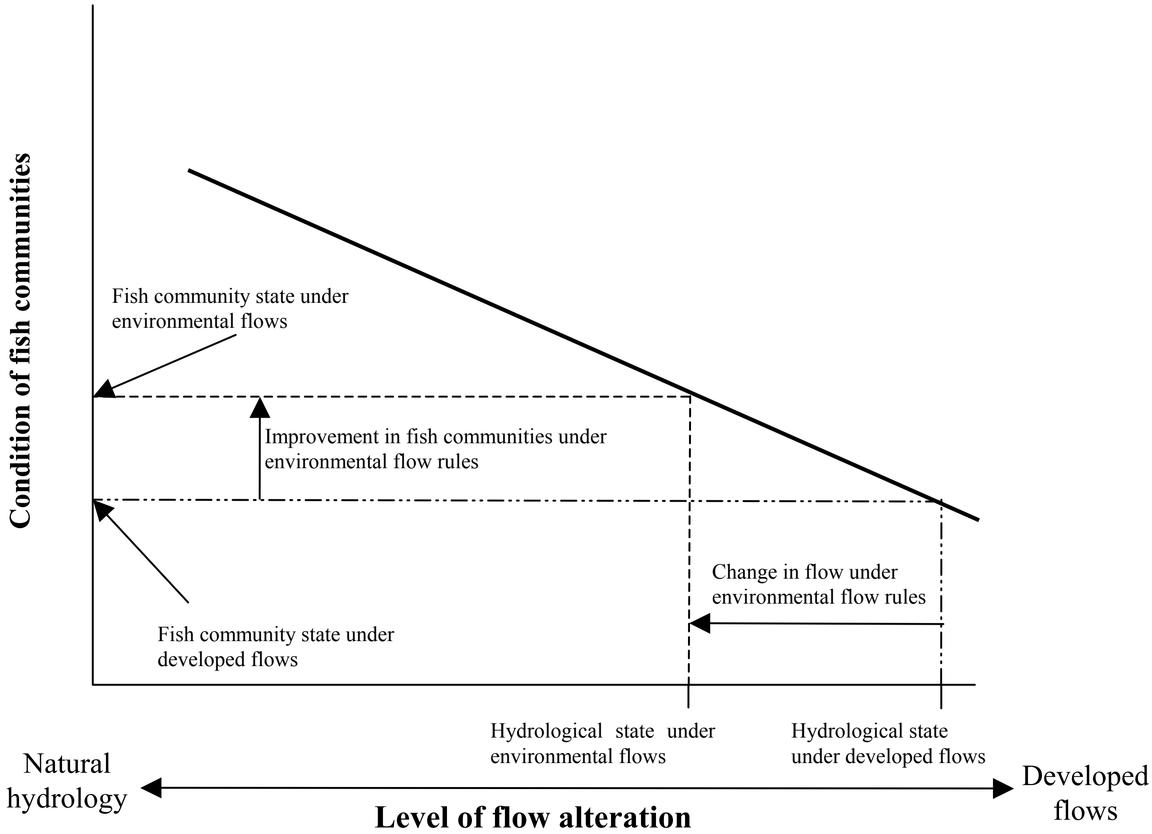

Figure 1. Diagrammatic representation of anticipated ecological responses to environmental flow rules.

2. METHODS

2.1. Hydrology Data and Indices

Hydrological data were supplied by the Department of Land and Water Conservation (DLWC). The hydrological information used was based upon currently available data from 60 gauging stations on the Barwon-Darling, Gwydir, Lachlan, Namoi, Macquarie, Murrumbidgee and Hunter rivers (Table 1). Flows at each site were modelled using the Integrated Quantity and Quality Model (IQQM). This model is a sophisticated daily flow simulation tool developed by DLWC for use in planning and evaluation of water resource management policies. River systems to be analysed are represented in the model by a series of nodes connected by links. Inflows, storages, outflows and other point processes are modelled by the nodes. Flow and water quantity routing processes are modelled by the links between nodes.

Models were based on 70 years of daily flows for all rivers, from 1925 to 1995. Three river management scenarios were modelled for the gauging stations:
1. natural flows over the flow record;
2. daily discharge at sites assuming 1993/1994 levels of development of water resources (i.e., pre environmental flows);
3. flows with water reform environmental flow rules (as set by River Management Committees) in place and water resources development.

There is very little information available about the pre-European settlement condition of rivers. An IQQM “natural conditions” scenario represents a calibrated developed condition model, which has then had the effects of major dams and irrigation development removed.

The IQQM scenarios for the “1993/94 level of development” represented conditions as defined under the MDBC Cap on Diversions. That is, the irrigation development, irrigation infrastructure plus operation and management rules that were in operation at the 1993/94 water year. As the Hunter system is outside the Murray-Darling Basin, a 1993/94 development model scenario has never been built. Consequently, a hypothetical scenario was used which includes 1999/2000 conditions for development, infrastructure and management but excludes environmental flow rules.

For all systems except the Barwon-Darling, the “environmental flow rules set by River Management Committees” scenario included both:
- the flow rules recommended by Committees to the Minister for Land & Water Conservation in mid-December 2001 as part of the draft Water Sharing Plans, and
- 1999/2000 development, operational and management conditions.

The Barwon-Darling environmental flow rules (EFR) scenario includes:
- flow rules recommended by the Committee for implementation in 2001/02 and,
- 2000/01 development on the Barwon-Darling itself and 1998/99 or 1999/2000 development on tributaries, and
- 2000/01 operational and management conditions.

It is important to note that data provided for the environmental flow rule scenario represent flow rules together with either the 1999/2000 or 2000/2001 level of development. Inferences about the hydrologic effects of the flow rules *per se* would be best made by comparing scenarios for the 1993/94 level of development with and without flow rules. Such comparisons would be unconfounded by underlying increases in consumptive water usage which is thought to have occurred since 1993/94 to some extent in all valleys but most certainly in the Barwon-Darling. However, due to other priorities, DLWC was not in a position to develop paired-modelled scenarios in which presence or absence of flow rules was the sole variant.

Thirty-six hydrological variables were calculated for each modelled flow data set (Table 2). The flow variables were chosen to represent aspects of hydrographs that are likely to be important for fish ecology (see Puckridge *et al.* 1998). Twenty-eight of the variables were a subset of hydrological indices used by Growns and Marsh (2000) to characterise differences in flow between regulated and unregulated rivers in eastern Australia. These hydrological variables described aspects of the daily flow record, the types of high and low daily flows, rises and falls between daily flows and aspects of monthly flows.

Eight additional flow variables were calculated to describe medium flows for each of the flow scenarios over the 70 years of data available. These variables were calculated in the following manner and are similar to the calculation of the mean inter-annual variation and mean monthly variation used by Growns and Marsh (2000). Growns and Marsh (2000) calculated the mean inter-annual variation as the mean of the 90^{th}-10^{th} flow values divided by the median flow for that year for twenty years. Similarly, mean monthly variation was calculated as the 90^{th}-10^{th} flow values divided by the median flow for each month.

The following variables were calculated from daily flows for inter-annual and inter-monthly data for each site over the 70 year flow record.

1. (15^{th} percentile flow - median flow)/median flow;
2. (30^{th} percentile flow - median flow)/median flow;
3. (median flow - 70^{th} percentile flow)/median flow;
4. (median flow - 90^{th} percentile flow)/median flow.

A diagrammatic representation of how these variables were calculated is presented in Appendix A.

Table 1. Fish sampling sites and the related gauging stations in each river system used for IQQM modelled flow data.

River System	Fisheries Site No.	Fisheries site name	River Reach	DLWC Flow Gauge No.	DLWC Flow Gauge Name
Barwon-Darling	100	Yetman	upper	416050	Barwon R @ Presbury Weir
	101	Little Weir	upper	416050	Barwon R @ Presbury Weir
	102	Old Pokataroo	upper	422003	Barwon R @ Collarenebri
	103	Bundabarina	upper	422003	Barwon R @ Collarenebri
	104	Gowrie	mid river	422025	Barwon R @ Tara (u/s Namoi Junction)
	105	Old Booroma	mid river	422026	Barwon R @ Boorooma (u/s Macquarie Junction)
	106	Wolkara Station	mid river	422028	Barwon R @ Beemery (u/s Culgoa Junction)
	107	Stony Point pump hole	mid river	425003	Darling R @ Bourke Town
	108	Jandra	mid river	425003	Darling R @ Bourke Town
	016	East Toorale	end of system	425004	Darling R @ Louth
	110	Curranyalpa	end of system	425009	Darling R @ Dunlop
	089	Billilla	end of system	425002	Darling R @ Wilcannia Total Flow
Gwydir	112	Keera	upper	418026	Gwydir R d/s Copeton Dam
	009	Benbraggie	upper	418012	Gwydir R @ Pinegrove
	007	Coulton	mid river	418013	Gwydir R @ Gravesend Road Bridge
	115	Gum Flat	mid river	418001	Gwydir R @ Pallamallawa
	018	Moree	end of system	418002	Mehi R @ Moree
	160	Norwood	end of system	418057	Gingham Watercourse @ d/s Diversion Regulator
	161	Brageen Crossing	end of system	418053	Gwydir R @ Brageen Crossing
	162	Wondoona Lagoon	end of system	418066	Gwydir R @ Millewa
	163	Gin Holes	end of system	418066	Gwydir R @ Millewa
	164	Big Leather Watercourse	end of system	418031	Gwydir R @ Collymongle
	165	Second Lagoon	end of system	418031	Gwydir R @ Collymongle
	117	Barwon/Meehi confluence	end of system	418055	Mehi R @ near Collarenebri
Hunter	153	Segenhoe Stud	upper	210015	Hunter R @ Glenbawn
	154	Aberdeen	upper	210002	Hunter R @ Muswellbrook Bridge
	054	Muswellbrook	mid river	210002	Hunter R @ Muswellbrook Bridge
	156	Bureen	mid river	210083	Hunter R @ Liddell
	157	Barellan	mid river	210083	Hunter R @ Liddell
	158	Recluse	end of system	210001	Hunter R @ Singleton
	047	Elderslie	end of system	210064	Hunter R @ Greta
Lachlan	133	Darby Falls Bridge	upper	412067	Lachlan R @ Wyangala
	134	Merriganowry	upper	412002	Lachlan R @ Cowra
	135	Moxey Farms	upper	412057	Lachlan R @ Nanami
	136	Timaroo	mid river	412004	Lachlan R @ Forbes (Cottons Weir)
Lachlan	095	Kirkup Park	mid river	412036	Lachlan R @ Jemalong Weir
	138	Euabalong Bridge	mid river	412001	Lachlan R @ Euabalong
	139	Gunniguldrie	end of system	412048	Lachlan R @ Lake Brewster Weir
	036	Wheelba	end of system	412078	Lachlan R @ Whealbah
	141	Erin Station	end of system	412045	Lachlan R @ Corrong
	142	Geramy	end of system	412026	Lachlan R @ Oxley

River System	Fisheries Site No.	Fisheries site name	River Reach	DLWC Flow Gauge No.	DLWC Flow Gauge Name
Macquarie	101	Dripstone	upper	421040	Macquarie R @ d/s Burrendong Dam
	126	Wellington	upper	421003	Macquarie R @ Wellington
	127	Dickygundi	mid river	421127	Macquarie R @ Baroona
	128	Wambool	mid river	421031	Macquarie R @ Gin Gin
	129	Marebone	end of system	421090	Macquarie R @ d/s Marebone Weir
	130	Old Oxley	end of system	421022	Macquarie R @ Oxley Station
	020	Brewon	end of system	421012	Macquarie R @ Carinda
	132	Binghi Bridge	end of system	421012	Macquarie R @ Carinda
Murrumbidgee	143	Glendale	upper	410008	Murrumbidgee R @ Burrinjuck Dam
	144	Wantabadgery	upper	410004	Murrumbidgee R @ Gundagai
	145	Colhagens Beach	upper	410001	Murrumbidgee R @ Wagga Wagga
	146	Buckingbong Station	mid river	410005	Murrumbidgee R @ Narrandera
	147	Lamonts Beach	mid river	410036	Murrumbidgee R @ d/s Yanco Weir
	148	Whitton Punt	mid river	410082	Murrumbidgee R @ Gogeldrie Weir
	090	Cookoothama	mid river	410021	Murrumbidgee R @ Darlington Point
	150	Moatfield Reserve	end of system	410040	Murrumbidgee R @ Maude Weir
	038	Willow Isles	end of system	410003	Murrumbidgee R @ Balranald
Namoi	118	Kibah	upper	419007 + 419006	(Namoi R @ Keepit) + (Peel R @ Carrol Gap)
	119	5 Mile	upper	419001	Namoi R @ Gunnedah
	006	Boggabri	mid river	419012	Namoi R @ Boggabri
	121	Broadwater	mid river	419002	Namoi R @ Narrabri
	122	Yarral	mid river	419039	Namoi R @ Mollee
	123	Wilgamere	end of system	419059	Namoi R @ d/s Gunidgera Weir
	124	Yarradool	end of system	419021	Namoi R @ Bugilbone (Riverview)

Table 2. Description of hydrological indices calculated for each daily flow record.

General analysis type	Type of index	Description	Index code
Daily flow summary	Long Term Values	Minimum flow for entire period (70 years)	Ltv1
		Maximum flow for entire period	Ltv2
		Mean daily flow	Ltv6
		Median daily flow	median
		Base flow index as calculated by Growns and Marsh (2000)*	Bfi1
		Base flow index as calculated by Growns and Growns (2001)*	Bfi2
High flow event analysis	Number of 'above threshold' flows	Mean of the annual number of flows greater than twice the mean daily flow	Hf6b
		Variation (CV) of annual number of flows greater than twice the mean daily flow	Hf6d
	Magnitude of 'above threshold' flow	Mean of annual high flows greater than twice the mean daily flow	Hf12b
		CV of annual high flows greater than twice the mean daily flow	Hf12d
	Duration of 'above threshold' flow	Mean of annual duration of events greater than twice the mean daily flow	Hf18b
		CV of annual duration of events greater than twice the mean daily flow	Hf18d
Low flow Spell analysis	Number of 'below threshold' flows	Mean of the annual number of flows less than 10% of the mean daily flow	Lf6b
		CV of the annual number of flows less than 10% of the mean daily flow	Lf6d
	Magnitude of 'below threshold' flows	Mean of annual flow below less than 10% of the mean daily flow	Lf8b
		CV of annual flow below less than 10% of the mean daily flow	Lf8d
	Duration of 'below threshold' flows	Mean of annual duration of events less than 10% of the mean daily flow	Lf12b
		CV of annual duration of events less than 10% of the mean daily flow	Lf12d

General analysis type	Type of index	Description	Index code
Moving average	Maximum annual moving average	Mean annual maximum 30 day flow	Ma2b
		CV of annual maximum 30 day flow	Ma2d
	Minimum annual moving average	Mean annual minimum 30 day flow	Ma5b
		CV of annual minimum 30 day flow	Ma5d
Rise and fall hydrograph	Number of rises and falls	Mean total number of rising limbs per year	Rf1b
		CV of total number of rising limbs per year	Rf1d
		Mean total number of falling limbs per year	Rf3b
		CV of falling limbs per year	Rf3d
Monthly flow	Inter-month variability	Mean variability of inter-annual monthly variability	Mf13b
	Inter-annual, monthly variability	Mean of annual values of inter-month variability	Mf14b
Medium flow	Inter-annual variability	Partial series median -85th percentile flows of mean annual flows	Newmf1a
		Partial series median - 70th percentile flows of mean annual flows	Newmf2a
		Partial series 30th percentile - median flows of mean monthly flows	Newmf3a
		Partial series 10th percentile - median flows of mean monthly flows	Newmf4a
	Inter month variability	Partial series median -85th percentile flows of mean annual flows	Newmf1b
		Partial series median - 70th percentile flows of mean annual flows	Newmf2b
		Partial series 30th percentile - median flows of mean monthly flows	Newmf3b
		Partial series 10th percentile - median flows of mean monthly flows	Newmf4b

* - *Details of these calculations are given in Appendix B*

2.2. Fish Data and Indicators

The fish data used for this report were the three IMEF fish sampling events in 1999/2000, 2000/2001 and 2001/2002. Site descriptions and locations can be found in Growns *et al.* (2001). The basic fish data for all sampling occasions will be described elsewhere (Growns & Rodgers, in prep.). Nine fish indicators were calculated for each site, representing broad fish community composition, recreationally important fish species and the dominant pest species in the rivers:

1. Total number of fish (catch per unit effort);
2. Total number of native species;
3. Total number of alien species;
4. Proportion of native fish collected (the proportion of alien fish collected is derived as the complement of the proportion of native fish) from all sampling occasions;
5. Proportion of Murray cod (*Maccullochella peelii peelii*) individuals from all sampling occasions;
6. Proportion of golden perch (*Macquaria ambigua*) individuals from all sampling occasions;
7. Proportion of carp (*Cyprinus carpio*) individuals from all sampling occasions;
8. Number of Murray cod individuals from all sampling occasions;
9. Number of golden perch individuals from all sampling occasions;
10. Number of carp individuals from all sampling occasions.

2.3. Model Description and Data Analyses

Differences in the hydrological variables between the three flow management scenarios were tested using the non-parametric Kruskal-Wallis test. A non-parametric test was chosen because of the large deviations from normality shown by a large proportion of the hydrological variables.

Canonical discriminant analysis (CDA) was used to show relationships among the modelled scenarios for all sites and separately for upper, mid river and end-of system sites. The separate analyses for different river reaches were done because environmental flow rules target different ecological features in particular river reaches. CDA is a method that finds linear combinations of variables that maximally separate known groups in the data set. The method is related to principal components analysis (PCA) and canonical correlation (SAS 1990). Unlike PCA, which summarises total variation among variables, CDA in this application summarises variation between different river management scenarios by creating canonical variables that are linear combinations of the hydrological indices. CDA cannot be used with missing values and the original data set was culled to remove hydrological variables or sites with missing values.

To test the validity of the predictive model, indices describing aspects of fish communities were correlated with the canonical variables describing the differences between the different flow management scenarios. For each site a range of fish variables were calculated and each correlated with the scores of sites with developed flows along the first and second canonical variates.

3. RESULTS

3.1. Differences in hydrological variables between management scenarios

Fifteen hydrological variables were significantly different between the three management scenarios (Table 3). The median inter-annual and inter-monthly variability of flows in the range of the median and 85th and 70th percentile flows, the number of flows greater than twice the mean and peak magnitude flows, the number of falling hydrograph limbs, the variability of the number of rising limbs and one measure of baseflow were larger under natural conditions than under either developed flows or environmental flow rules. The number of rising limbs of the hydrograph, the variability of the number, size and duration of high flows and the variability of the maximum annual moving average was decreased under natural conditions. The values for all these variables were similar between developed flows or environmental flow rules.

The differences between the significantly different variables between flow types suggests that:

1. natural flows have greater inter-monthly variability in the range of 85th percentile to median flows compared with developed flows and environmental flow rules;
2. the number and size of floods is greater under natural conditions, but the variability of the duration, magnitude and number of high flows has increased under developed and environmental flow rules;
3. under natural conditions, flows are more often decreasing than increasing, but the variability in rising water flows is greater;
4. the volume of water at base flows is greater under natural flows compared with developed flows or environmental flow rules;
5. The variation of the annual maximum 30-day average flows has increased under developed flows and environmental flow rules compared with natural conditions.

3.2. Canonical Discriminant Analysis - all sites

Hydrological conditions at each site under the modelled natural daily flow scenario clearly separated from the hydrology at the same sites under either developed or environmental flow rule scenarios along the first canonical variable (Table 3, Figure 2). The developed and environmental-flow-rule water management scenarios generally separate along the second canonical axis. The first axis explained 97% of the variance between the three flow types indicating that the natural flows are different from the flows that exist under either developed or environmental flow rule scenarios. The second axis only explained 3% of the total variation suggesting that river flows under the environmental flow rules are not different from flows under developed conditions. There is no clear separation among the different catchments along either the first or second canonical variates (Figure 2).

Fourteen hydrological variables had loadings greater than ± 0.25 on the first canonical axis, compared to only three variable on axis 2 (Table 3). The reduction in the number of important variables in the second axis is consistent with the small amount of variation explained by this axis. The fourteen variables with large loadings on the first axis were those that were significantly different between management scenarios. In comparison, the three variables separating the developed flows from the environmental flow rules were not significantly different between these management scenarios (Kruskal-Wallis test, $p > 0.05$). This suggests that there are no significant changes in the hydrological variables that are likely to be important for fish ecology between the developed flow and environmental flow rule scenarios.

Table 3. Median values in each group and loadings of each hydrological variable on the two canonical variables. A full description of hydrological variables is given in Table 2. Numbers in bold indicate loadings on vectors whose absolute value is greater than 0.25. Asterisks indicate variables significantly different between flow management scenarios.

Hydrological variable	Median values			Canonical variate	
	Developed	Env. Flow	Natural	1	2
Ltv1	0	0	0	-0.19	0.07
Ltv2	182741	190150	178296	0.05	-0.02
Ltv6	2284	2312	2504	0.10	-0.02
Median	596	671	467	-0.05	0.04
Bfi1***	0.99997	0.99996	0.99998	**0.36**	**-0.36**
Bfi2	4.4	4.0	2.7	-0.14	-0.03
Hf6b***	2.7	2.8	3.5	**0.26**	0.14
Hf6d***	112	107	88	**-0.40**	-0.07
Hf12b*	28799	28890	40342	**0.25**	-0.06
Hf12d***	127	124	97	**-0.35**	0.02
Hf18b	40	41	43	0.13	0.11
Hf18d***	121	113	97	**-0.38**	-0.05
Lf6b	2.4	2.8	2.9	-0.13	-0.12
Lf6d	93	93	90	-0.14	-0.11
Lf8b	139	155	190	0.03	0.06
Lf8d	181	201	250	0.12	-0.01
Lf12b	95	80	108	0.08	-0.20
Lf12d	62	66	77	0.02	0.13
Ma2b	9784	9606	12533	0.14	-0.06
Ma2d***	107	107	88	**-0.32**	-0.05
Ma5b	86	93	132	-0.03	0.02
Ma5d***	156	179	130	**0.31**	0.01
Rf1b***	149	146	107	**-0.72**	0.08
Rf1d***	11	11	17	**0.38**	-0.06
Rf3b***	197	198	233	**0.65**	0.03
Rf3d	9.1	8.8	9.2	-0.07	-0.06
Mf13b	6.9	5.7	8.6	-0.01	-0.06
Mf14b	6.6	6.4	8.7	-0.12	**-0.31**
Newmf1a***	0.68	0.68	0.77	**-0.33**	-0.12
Newmf2a***	0.48	0.47	0.55	**-0.33**	-0.02
Newmf3a	1.3	1.2	1.4	0.03	-0.02
Newmf4a	6.2	5.0	7.9	0.01	0.06
Newmf1b***	0.65	0.66	0.83	**0.50**	-0.15
Newmf2b***	0.44	0.45	0.57	**0.40**	-0.17
Newmf3b	1.0	1.3	1.3	0.06	0.04
Newmf4b	5.8	5.8	7.8	0.13	**0.31**

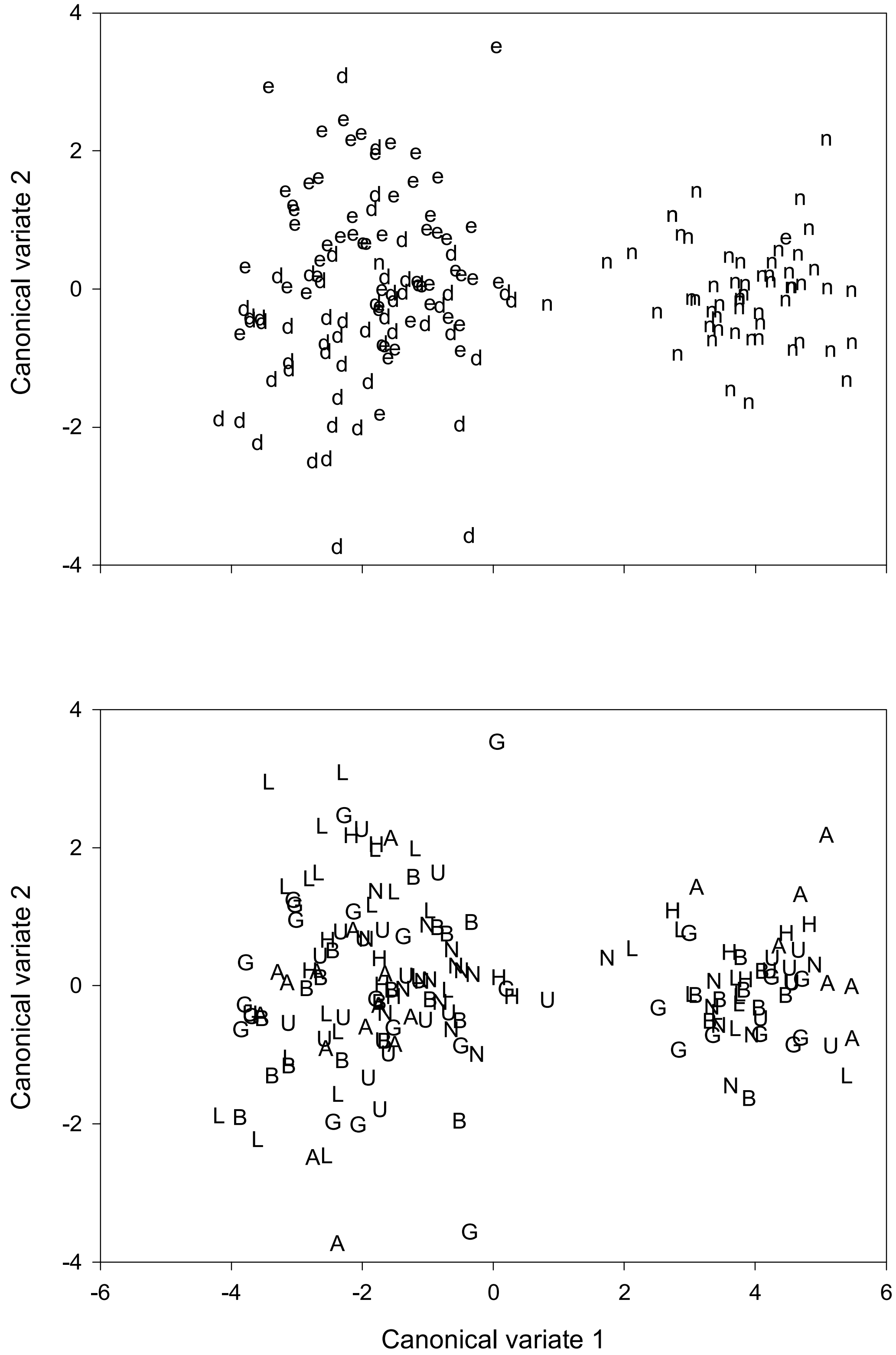

Figure 2. Scatterplot of the flow management scenarios along the first and second canonical variates. The top diagram shows sites recorded with either developed flows (d), environmental flow rules (e) or natural flows (n). The bottom diagram is coded with the rivers Barwon-Darling (B), Gwydir (G), Macquarie (A), Namoi (N), Lachlan (L), Murrumbidgee (U) and Hunter (H).

3.3. Canonical Discriminant Analysis - by river sections

Hydrological conditions at each site under the modelled natural daily flow scenario clearly separated from the same sites in each river section under either developed or environmental-flow-rule scenarios along the first canonical variable (Figure 3). The separation between developed flow and environmental flow scenarios appeared to decline from the upper sections to the end-of system sites, possibly indicating that the influence of environmental flows is strongest in the upper and middle river sections.

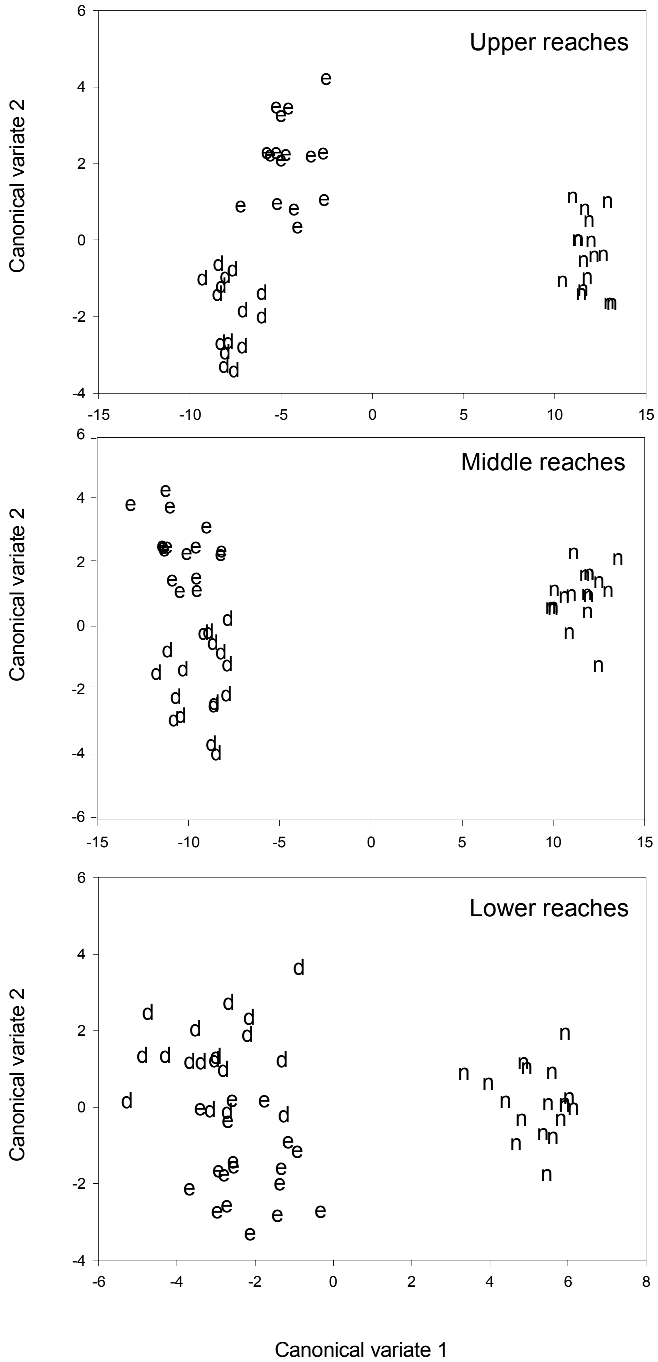

Figure 3. Scatterplot of the flow management scenarios along the first and second canonical variates for different river sections. Developed flows (d), environmental flow rules (e) and natural flows (n).

The first canonical axis explained greater than 95% of the variation for each river section (Table 4). The number of daily rises and falls (Rf1b and Rf3b) were the two hydrological variables that had the greatest weighting on the first canonical variate for all river reaches (Table 4). The median values of these variables suggest that the number of daily rises in flow has increased under developed flows and environmental flow rules (Table 5). This suggests that the main influence of water resources development has been to alter the daily rate of change in flows from natural conditions along the rivers.

Six other hydrological variables also contributed strongly to the first canonical variate in all river reaches including the inter-monthly variability of flows in the range of 85th percentile and median flows (Newmf1b and Newmf2b), the inter-annual variability of the number, peak magnitude and duration of flows greater than two times the mean flow (Hf6d, Hf12d and Hf18d) and the inter-annual variability in the number of rising hydrological limbs (Rf1d) (Table 4).

The median values for inter-monthly variability of flows between the 85th percentile and median flows were greater under natural conditions compared with developed or environmental flow rules (Table 5) in all river sections. Similarly, the median inter-annual variability in the number of rising limbs of the hydrograph was greater under natural conditions compared with either developed flows or environmental flow rules. In contrast, the median inter-annual variability of the number, peak magnitude and duration of high flows were less under natural conditions compared with the other management scenarios in all river sections.

Three hydrological variables, including the number and magnitude of high flows (Hf6b and Hf12b) and one measure of the base flow index (Bfi1), were important in separating the natural from developed flows and environmental flow rules only in the mid and upper river reaches (Table 4). In contrast, the inter-annual variability of flows between the 85th percentile and median flows (Newmf1a and Newmf1b) and the variability of 30-day average flow (Ma2d) were important only in the mid-river and end-of-system sites.

Overall, the number of important hydrological variables describing the differences between natural flows and developed and environmental flow rules increased from the upper river reaches to the lower river reaches (Table 4). This suggests that the changes resulting from water resource development are more complex in the lower river reaches than at upper sites.

Table 4. Loadings of each hydrological variable on the two canonical variables in each river reach. A full description of hydrological variables is given in Table 2. Numbers in bold indicate loadings on vectors whose absolute value is greater than 0.25. Asterisks indicate variables significantly different between flow management scenarios: *- $p < 0.10$, **- $p < 0.01$, *** - $p < 0.001$. Percentages in parentheses indicate the percentage variance explained for that canonical variate.

Hydrological var.	**Upper reaches**			**Mid-river**			**End-of-system**		
	Prob.	**Canonical variate**		**Prob.**	**Canonical variate**		**Prob.**	**Canonical variate**	
		1 (95%)	**2 (5%)**		**1 (95%)**	**2 (5%)**		**1 (96%)**	**2 (4%)**
Ltv1		-0.25	0.07		0.21	0.01		-0.11	-0.12
Ltv2		0.08	-0.05		-0.08	-0.02		0.02	-0.01
Ltv6		-0.02	-0.02		-0.12	-0.01		0.20	0.02
Median		-0.17	0.01	*	0.07	0.08		0.22	0.04
Bfi1	***	**0.54**	-0.28	***	**-0.46**	-0.24		0.05	-0.06
Bfi2		-0.21	0.07		0.15	0.02		-0.05	0.13
Hf6b	*	**0.40**	-0.06	*	**-0.35**	-0.01		0.16	-0.11
Hf6d	**	**-0.40**	0.09	**	**0.35**	0.02	**	**-0.42**	0.09
Hf12b	*	**0.38**	-0.11	*	**-0.39**	-0.03		0.08	0.01
Hf12d	***	**-0.45**	0.11	*	**0.40**	-0.02		**-0.28**	0.02
Hf18b		-0.07	0.04		-0.24	-0.04		0.18	-0.10
Hf18d	*	**-0.34**	-0.01	***	**0.43**	0.04	**	**-0.40**	0.08
Lf6b		0.06	-0.07		0.12	-0.05		**-0.35**	0.08
Lf6d		-0.20	0.10		0.14	-0.06		-0.04	0.14
Lf8b	*	-0.12	0.07		-0.05	0.01		**0.37**	0.03
Lf8d		0.15	0.09	**	**-0.40**	0.09		-0.07	0.01
Lf12b		0.17	-0.13		-0.22	-0.07		-0.23	0.02
Lf12d		-0.09	0.20		0.08	-0.01		**0.39**	0.20
Ma2b		0.14	-0.08		-0.16	-0.04		0.11	0.01
Ma2d		-0.20	0.11	***	**0.37**	0.01		**-0.35**	0.05
Ma5b		-0.17	0.02		0.07	0.02		0.33	0.03
Ma5d		0.20	-0.06	**	**-0.49**	0.04		0.17	0.10
Rf1b	***	**-0.78**	0.11	***	**0.80**	0.02	**	**-0.47**	-0.06
Rf1d	*	**0.38**	-0.12	***	**-0.53**	-0.03	**	**0.27**	-0.01
Rf3b	***	**0.71**	-0.05	***	**-0.82**	0.00	**	**0.48**	0.08
Rf3d		-0.21	-0.03		-0.10	-0.14		0.05	-0.03
Mf13b		-0.12	-0.04		-0.21	-0.03		-0.04	-0.11
Mf14b		0.03	-0.13		0.01	-0.11		**-0.27**	0.22
Newmf1a		-0.24	0.08	*	**0.42**	0.02		**-0.27**	0.11
Newmf2a		-0.24	0.09	**	**0.45**	0.03		**-0.25**	0.09
Newmf3a		0.14	-0.02	*	**0.30**	0.05		-0.13	0.14
Newmf4a		0.12	0.04		0.21	0.03		0.05	0.11
Newmf1b	*	**-0.37**	0.03	***	**0.54**	-0.04	**	**-0.43**	0.08
Newmf2b		**-0.30**	0.00	**	**0.52**	-0.03	*	**-0.29**	0.10
Newmf3b		-0.17	-0.08		0.20	0.08		**0.35**	-0.06
Newmf4b		-0.02	0.13		-0.02	0.12		**0.28**	-0.22
Number of important variables		12	1		17	0		17	0

Table 5. Median values of each hydrological variable in each river section under modelled water resources development (Dev.), environmental flow rules (EFR) and natural flows (Nat.). A full description of hydrological variables is given in Table 2. Shaded cells indicate significant differences between that hydrological variable between the different flow management scenarios, see Table 4.

	Upper sections			Mid-river			End-of-system		
Flow type	Dev.	EFR	Nat.	Dev.	EFR	Nat.	Dev.	EFR	Nat.
Ltv1	1	1	0	0	0	0	0	0	0
Ltv2	267894	267534	319236	262263	255184	242686	43393	42717	61537
Ltv6	2187	2189	2581	3307	3371	3674	1104	1269	2020
Median	864	784	487	867	1048	560	259	303	449
Bfi1	0.99988	0.99986	0.99998	0.99997	0.99996	0.99998	0.99998	0.99998	0.99998
Bfi2	4.51	4.10	1.70	4.73	4.55	3.14	5.07	3.84	3.67
Hf6b	2.70	2.65	3.60	2.87	2.89	3.54	1.96	2.39	3.12
Hf6d	125	122	97	106	101	88	114	106	86
Hf12b	31201	28738	59317	39299	38639	47282	10865	10469	16599
Hf12d	140	141	100	124	124	99	110	107	78
Hf18b	41	42	40	40	40	46	47	53	52
Hf18d	116	113	101	121	121	97	126	109	98
Lf6b	1.77	2.06	3.24	2.33	3.08	3.73	5.06	3.79	2.26
Lf6d	110	109	98	98	93	83	66	75	103
Lf8b	104	183	140	291	284	298	82	60	224
Lf8d	209	214	216	167	180	258	192	222	247
Lf12b	93	74	130	85	68	113	130	123	89
Lf12d	68	66	62	84	81	74	57	64	84
Ma5b	162	206	88	266	263	167	95	92	133
Ma5d	106	104	140	81	94	132	88	102	132
Ma2b	9098	8801	11717	12119	11933	15726	3942	5285	7996
Ma2d	104	105	89	116	115	87	111	95	78
Rf1b	155	155	96	156	154	108	149	143	122
Rf1d	11.66	10.93	18.52	10.36	9.98	15.58	12.92	12.37	17.52
Rf3b	187	197	242	202	205	241	201	195	220
Rf3d	10.45	9.91	9.77	7.58	7.22	8.14	9.03	9.49	9.42
Mf13b	6.35	5.26	8.94	5.79	5.09	9.00	7.02	6.73	8.36
Mf14b	6.14	5.45	8.93	6.33	5.29	8.97	10.33	10.49	8.34
Newmf1a	0.71	0.70	0.78	0.69	0.67	0.77	0.68	0.68	0.76
Newmf2a	0.48	0.50	0.57	0.48	0.45	0.55	0.47	0.46	0.55
Newmf3a	1.53	1.17	1.45	1.15	1.02	1.43	1.34	1.43	1.44
Newmf4a	5.54	4.49	8.11	5.02	4.35	8.17	6.42	6.11	7.54
Newmf1b	0.68	0.67	0.85	0.62	0.63	0.82	0.69	0.71	0.83
Newmf2b	0.45	0.45	0.57	0.42	0.41	0.57	0.48	0.49	0.59
Newmf3b	0.94	1.15	1.31	0.91	0.98	1.34	1.48	1.50	1.27
Newmf4b	5.43	4.60	8.01	5.67	4.58	8.04	9.55	9.81	7.46

3.4. Correlations between canonical discriminant analysis and fish community data

The total number of native fish species was significantly positively correlated with the first canonical variate (Table 6). The first canonical variate was associated with the separation of natural and developed flow regimes (Figure 2). This suggests that the number of native species generally decreases as the hydrological regime at sites become more developed (Figure 4). The proportion and number of Murray cod was also significantly related to the first canonical variate of CDA of Murray-Darling Basin sites only (Table 6). However, there is a large amount of variation about these trends, making it difficult to predict accurately the changes that might occur if the natural flow regime was restored (Figure 4).

The only fish variable that was associated with the second canonical variate was the number of alien fish species (Table 6). The second canonical variate was associated with the separation of developed flows from environmental flow rules (Figure 2). Although weak, the negative correlation suggests that the implementation of environmental flow rules may help reduce the number of alien species.

Table 6. Spearman rank correlations between the first and second canonical variates of all sites and a range of fish variables.

	Canonical variate	
Fish variable	**1**	**2**
Total number of fish	0.00	-0.02
Number of native species	0.43***	0.22
Number of alien species	-0.19	-0.35**
Proportion of native fish	-0.05	0.19
Proportion of Murray cod[1]	0.33*	0.25
Proportion of golden perch[1]	0.20	0.03
Proportion of carp	0.04	-0.12
Number of Murray cod[1]	0.34*	0.17
Number of golden perch[1]	0.28	-0.02
Number of carp	0.01	-0.23

** - $p < 0.05$, ** - $p < 0.01$, *** - $p < 0.001$.*

[1] - analyses conducted using CDA on Murray-Darling Basin (MDB) sites only.

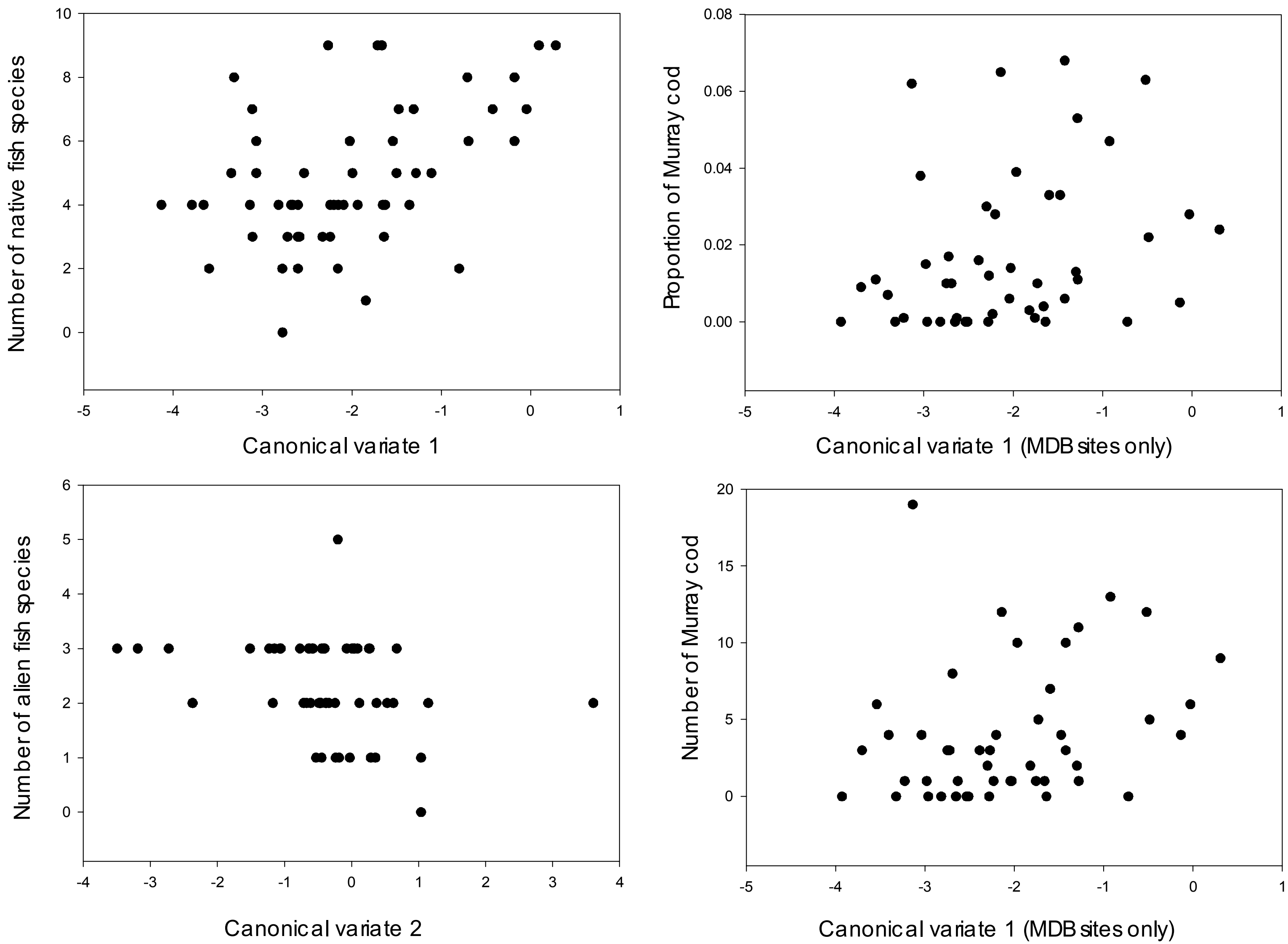

Figure 4. Scatterplots of significant correlations between fish data and canonical variates.

4. DISCUSSION

4.1. Differences between flow management scenarios

The modelled natural daily flow regimes in the Barwon-Darling, Gwydir, Namoi, Lachlan, Macquarie, Murrumbidgee and Hunter rivers were different from the flows modelled with water resource development and under environmental flow rules. In contrast, the difference between flows modelled with just water resource development and developed flows with environmental flows rules imposed was small.

Separate analyses on upper, middle and end-of system reaches suggested that the influence of environmental flow rules decreased in a downstream direction and that the effects of water resources development were more complex in end-of-system reaches compared with upper river reaches. In addition, the modelled environmental flow regimes did not align in a linear sequence between natural and developed flows, for either all sites combined or the separate reach analyses, suggesting that the environmental flow rules may have created a new, artificial hydrological regime throughout the rivers rather than restoring elements of the natural flow regime.

The largest differences between the significantly different hydrological variables, important for fish ecology, were mainly between the natural flow regime and the two water development scenarios, developed flows and environmental flow rules. The differences among flow management scenarios suggested that:

1. natural flows have greater inter-monthly variability in the range of 85th percentile to median flows compared with developed flows and environmental flow rules;
2. the number and size of floods is greatest under natural conditions, but the variability in the duration, magnitude and number of high flows has increased under developed and environmental flow rules;
3. under natural conditions, flows are more often decreasing than increasing, and the variability of rising water flows is greatest under natural conditions;
4. the volume of water at base flows is greater under natural flows compared with developed flows or environmental flow rules;
5. the variation of the annual maximum 30-day average flows has increased under developed flows and environmental flow rules compared with natural conditions.

In comparison, the differences in median values of hydrological variables between the developed flows and environmental flow rules, were slight and were not significantly different. Overall, this suggests that the environmental flows put in place in the water management plans will not be of value in conserving or rehabilitating riverine fish communities.

4.2. Predictive models

We developed a model of the response of fish communities to changed flow regimes that was based on forming a linear combination of hydrological variables between natural flows and a flow regime under water resources development. In our model, the environmental flow rules implemented in the major river valleys of New South Wales were found to be ineffective in moving river flow regimes from their degraded, developed state back towards a more natural condition. The modelled environmental flow rules appear to form a new hydrological regime that is similar to the developed flows but does not resemble the natural flow regime. The number of native fish species, and the number and proportion of Murray cod at sites was significantly (but only weakly) correlated with the continuum from developed to natural flows. The weak relationship suggests that many other environmental factors other than flow *per se* influence fish community structure.

Another approach to developing a predictive model to test the response of fish communities to environmental flow rules would be to establish if there is a relationship between the recruitment of different fish species and antecedent flows. This type of predictive model was attempted using data on fish community composition collected during the NSW Rivers Survey and the first round of IMEF fish sampling (Growns *et al.* 2001). However, due to the lack of consistent information across all sites and years, and the small numbers of young-of-year fish collected, there were no strong relationships found between river hydrology and fish recruitment. When the daily flow records are available the predictive modelling approach suggested here could be evaluated with the complete three years of IMEF fish data and then tested with any subsequent years' data.

The length of each hydrological data set used in this study was approximately 70 years of daily flows. However, the present-day fish communities in the rivers are unlikely to have been directly influenced by the hydrology in the rivers over this length of time. The calculation of the hydrological indices over the length of time likely to influence the fish community may improve the power of the predictive model. In addition, freshwater fish species have a range of lifespans. Thus, river flow patterns of different duration may influence different fish species differently. For example, a flood event twenty years in the past is unlikely to have had a long-term influence on Australian smelt which may live for only two to three years (McDowall, 1996). However, the effects of that flood may still be apparent in the population structure of Murray cod which may live for more than 50 years (McDowall, 1996). The predictive model may be improved either by using a shorter antecedent flow period or by calculating indices that are related to the average life span of the fish that occur at a particular site.

The relationships between flows, flooding and recruitment of certain species of fish could be explored by using the contingency flow allocations that exist in the Barwon-Darling, Lachlan, Macquarie and Murrumbidgee Valley flow rules using an adaptive management framework. Fish populations and species thought to be reliant on increased flows for breeding could be sampled on a frequent basis throughout winter in each of the river valleys during one year to evaluate when fish are ready to spawn. If conditions, such as temperature and climatic conditions, were suitable, the environmental contingency allocations could be released and the response of the fish measured. Such measurements could be made on an annual basis, and each year the timing of the contingency flow release could be altered based on different environmental or fish breeding conditions.

The predictive model evaluated in this report was based on riverine fish community data collected at 60 sites over three years to test Hypothesis 8 of the IMEF program. NSW Fisheries also collected fish community data to test Hypothesis 7 (Wetland Replenishment). The aim of the latter sampling was to determine the effects of flooding on permanently inundated wetlands in the Gwydir (10 sites), Namoi (5 sites) and Lachlan (5 sites) valleys by sampling before and after floods in the wetlands. Annual sampling was not possible in all wetlands and no large floods occurred in the wetlands over the 3 years sampled for IMEF. Thus, fish data collected to test Hypothesis 7 are unlikely to be useful in developing a predictive model or to test the effects of flooding on inundated wetlands, given the lack of success in developing a predictive model for the riverine fish communities (even with three years of data at sixty sites) and of the limited wetland/fish data set. We therefore recommend that the fish component of the “Wetland Replenishment” hypothesis of the IMEF program be reviewed because further fish sampling, at least at the present level of resources, is unlikely to generate sufficient data of the right sort to allow fruitful predictive modelling.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

- The natural hydrology of the rivers has changed substantially over the past 70 years because of the level of water resource development in New South Wales.
- Current modelling suggests that environmental flow rules, developed as a part of water management plans, have not achieved the desired objective of river flow regimes to re-establish flows that more closely approximate the natural condition. Rather, the environmental flow rules appear to have produced an alternative flow regime that is as different to natural conditions as the river flows at 1993/94 levels of development.

- The differences among flow management scenarios suggested that:
    1. natural flows have greater inter-monthly variability in the range of 85th percentile to median flows compared with developed flows and environmental flow rules;
    2. the number and size of floods is greater under natural conditions, but the variability of the duration, magnitude and number of high flows has increased under developed and environmental flow rules;
    3. under natural conditions, flows are more often decreasing than increasing and the variability of rising water flows is greater;
    4. the volume of water at base flows is greater under natural flows compared with developed flows or environmental flow rules;
    5. The variation of the annual maximum 30-day average flows has increased under developed flows and environmental flow rules compared with natural conditions.

- Our current ability to predict responses of fish and other river health indicators to environmental flow rules is limited, partly because the environmental flow rules appear to have created a new hydrological regime which does not mimic the natural regime, and partly because of the unavailability of data collected over suitable time frames.

- Separate analyses on upper, middle and end-of system reaches suggested that the influence of environmental flow rules decreased in a downstream direction and that the effects of water resources development were more complex in end-of-system reaches compared with upper river reaches.

5.2. Recommendations

- Sampling of the 60 IMEF sites should be continued to develop the ability to predict the response of fish to flow regimes and therefore improve environmental flow rules.
- The relationships between the fish data, collected during the NSW Rivers Survey data and the 3 years IMEF, and antecedent flow regimes should be further examined.
- The use of contingency flows in the Hunter, Lachlan, Macquarie and Murrumbidgee Valleys should be assessed for suitability for enhancing the breeding and recruitment of native fish
- Fish sampling in wetlands should be reviewed.

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APPENDIX A. CALCULATION OF INTER-MONTHLY AND INTER-ANNUAL VARIABILITY

Inter-monthly variability

Variability was calculated as the difference between various percentiles and the median based on a average monthly flow duration curve.

The inter-monthly variability variables were calculated as follows;
1. For each month January to December the flow at various percentile exceedences was calculated across all 70 years data, giving a total of 12 values for each percentile.
2. The average of all twelve months was calculated for each percentile (Figure 5).

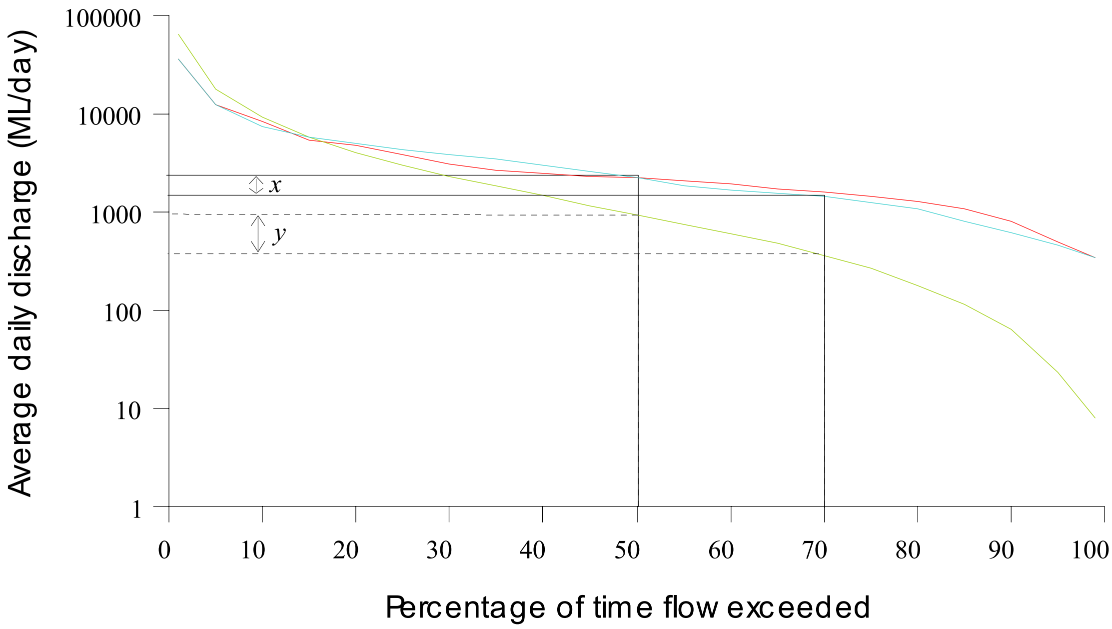

Figure 5. Average daily flow duration for all months for one site in the Macquarie River for modelled natural flows (green line), developed flows (blue line) and under environmental flow rules (red line).

For example, the inter-monthly variability (Newmf3b) for developed flows is calculated as the value *x* in (Figure 5) when divided by the median value (50^{th} percentile) for developed flows, and the inter-monthly variability (Newmf3b) for natural flows is calculated as the value *y* when divided by the median of natural flows.

Inter-annual variability

Variability was calculated as the difference between various percentiles and the median based on a average yearly flow duration curve.

The inter-annual variability variables were calculated as follows;

1. For each year from 1925 to 1995 the flow at various percentile exceedences was calculated, giving a total of 70 values for each percentile.
2. The average of all 70 years was calculated for each percentile (Figure 6).

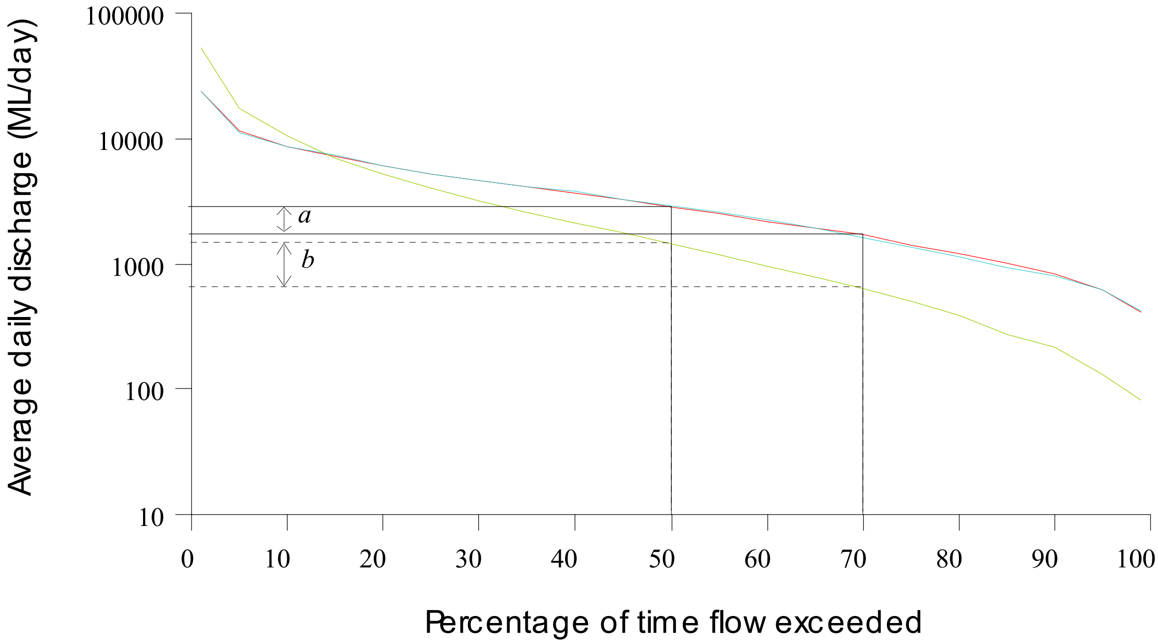

Figure 6. Average daily flow duration for all years for one site in the Macquarie River for modelled natural flows (green line), developed flows (blue line) and under environmental flow rules (red line).

For example, the inter-monthly variability (Newmf3a) for developed flows is calculated as the value *a* in (Figure 6) when divided by the median value (50th percentile) for developed flows, and the inter-monthly variability (Newmf3a) for natural flows is calculated as the value *b* when divided by the median of natural flows.

APPENDIX B. CALCULATIONS OF BASE FLOW INDICES

Growns and Marsh (2000)

The following description is based upon Growns and Marsh (2000). The base flow index was calculated using the Lyne and Hollick method described by Nathan and Weinmann (1993). A digital filter is applied three times to smooth the data, one forward pass, one backward, and then forward again as described by Grayson *et al*. (1996). The equation used was:

$$q_f(i) = \alpha\, q_f(i-1) + [q(i) - q(i-1)]\frac{1+\alpha}{2}$$

where,

$q_f(i)$ is the filtered quick flow response for the ith sampling instant;
$q(i)$ is the original stream flow for the ith sampling instant; and
α is the filter parameter for which the value of 0.925 is recommended for daily data.

After each pass a new array of base flow values is calculated. After the three passes, the base flow array elements are added to give the total base flow for the entire period, and the original flow is also added to give a total flow for the entire period. The baseflow index is baseflow/total flow.

Growns and Growns (2001)

This baseflow index was modified from Gordon *et al.* (1992) and calculated as:

Baseflow index = lowest daily discharge/mean daily discharge x 100.

An index value near 100 indicates that flow remains relatively constant over time whereas a value near zero is indicative of an intermittent stream.

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