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Statistically Integrated Flow and Flood Modelling Compared to Hydrologically Integrated Quantity and Quality Model for Annual Flows in the Regulated Macquarie River in Arid Australia

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Abstract Water resource management traditionally depends on use of highly complex hydrological models designed originally to manage water for abstraction but increasingly relied on to determine ecological impacts and test ecological rehabilitation opportunities. These models are rarely independently tested. We compared a relatively simple statistical model, integrated flow and flood modelling (IFFM), with a complex hydrological model, the integrated quality and quantity model (IQQM), on the highly regulated Macquarie River of the Murray-Darling Basin, southeastern Australia. We compared annual flows (1891–2007) at three gauges to actual data and modelled output: before dams and diversions (unregulated) and after river regulation (regulated), using the goodness of fit (Nash-Sutcliffe coefficient of efficiency) and nonparametric tests. IQQM underestimated impacts of river regulation respectively on median and average flows at the Macquarie Marshes (Oxley gauge) by about 10% and 16%, compared to IFFM. IFFM model output more closely matched actual unregulated and regulated flows than IQQM which tended to underestimate unregulated flows and overestimate regulated flows at the Ramsar-listed wetland. Output was reasonably similar for the two models at the other two flow gauges. Relatively simple statistical models could more reliably estimate ecological impact at floodplains of large river systems, as well as an independent assessment tool compared to complex hydrological models. Finally, such statistical models may be valuable for predicting ecological responses to environmental flows, given their simplicity and relative ease to run.

Keywords Nonparametric tests · Integrated flow and flood modelling (IFFM) · Integrated quantity and quality model (IQQM) · Goodness of fit · Local regressions · Partial differential equations

Introduction

Dams regulate a river's flow and control its water, often for extraction downstream. Many of the world's rivers are regulated by large dams that store river flows for downstream irrigation communities (Lemly and others 2000). In Australia, much of this water on inland river systems is diverted for irrigation, affecting floodplain ecosystems (Kingsford 2000). The sharing of water and its management between different industries and the environment is traditionally managed through sophisticated hydrological models that simulate amount of water reaching a particular downstream node of a river, usually a river gauge. They attempt to track the water balance using partial differential equations and accounting for transmission losses and extractions from the river (Wheater and others 2008). Such hydrological models have often received considerable investment and development and become the primary and often the only modelling tool available for decision-making about the environment. For example, a suite of such hydrological models were used to determine impacts of diversions on the rivers of the Murray-Darling Basin, southeastern Australia (Murray-Darling Basin Authority 2010b). Also for environmental management, the linking of complex hydrological models to ecosystem responses and the rapidity with which such hydrological models can

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be run for scenarios remain significant challenges. The number of variables and often limited access to up to date data (e.g., user demand) make such models difficult to run predicatively for event management decision-making, essential for environmental management.

In the Murray-Darling Basin in southeastern Australia, where most of the water on the continent is diverted (Kingsford 2000), one of the more prominent hydrological models is a generic integrated water quantity and quality simulation model (IQQM). The model is used to manage many of the rivers in the Murray-Darling Basin from which the mean annual diversion of water is about 11,000 gigalitres (11 km^3), 95% for irrigation (CSIRO 2008a). IQQM is primarily a hydrological planning tool, intended to provide information on system performance and behaviour for different management scenarios (Black and others 1995) but its output was also used to predict the impact of plantation forestry and climate change on the Murrumbidgee River (Brown and others 2007) and Macquarie River in southeastern Australia (Herron and others 2002); to assess hydrological effects of water resource development (Thoms and Sheldon 2000; Thoms and others 2005); and ecological implications of different environmental flow releases (Kingsford and Auld 2005).

There is a real need to test outputs from complex hydrological models, using independent models, given reliance in measuring impacts of water resource development (CSIRO 2008b). For example, the Murray-Darling Basin Authority determined new sustainable diversions for all rivers in the Murray-Darling Basin (Murray-Darling Basin Authority 2010a), relying on outputs from hydrological models, including IQQM. Over or under estimation of hydrological impacts by complex hydrological models have considerable effects on policy decisions for environmental flow. Further, as flows fundamentally structure dependent aquatic ecological communities (Stachowicz 2001), it is critical to adequately predict responses in terms of ecological processes and biotic communities (Poff and Zimmerman 2010).

Independent hydrological analysis of monthly river flow data is possible using time series, but the residuals are large, limiting predictive power, even though results may be generally consistent with the integrated quantity and quality model (IQQM) (Wen 2009). Alternative simple models with fewer input variables than complex hydrological models may have more predictive power. This includes simple statistical models that track the empirical relationships between key hydrological variables. We developed the integrated flow and flood modelling (IFFM), including temporal flow models, temporal inundated area size models and spatial-temporal flood models, to simulate annual flows and spatial flooding in the Macquarie River (Ren and others 2010). These relatively simple statistical models relied primarily on the statistical relationships among data for annual flow and rainfall. The most significant environmental endpoint of this system is the internationally recognised Macquarie Marshes, listed under the Ramsar Convention, and whose ecological health is seriously affected by the regulation and diversion of river flow upstream (Kingsford and Thomas 1995; Kingsford and Johnson 1998; Kingsford 2000; Thomas and others, 2011). The Warren gauge is immediately upstream while the Oxley gauge is within and the Carinda gauge is downstream of the Macquarie Marshes (Fig. 1). The Macquarie River is a highly regulated river with two large dams, Burrendong and Windamere Dam, and a long-term annual average diversion estimated at 391.9 gigalitres (CSIRO 2008a).

Our main objective was to compare the outputs of our relatively simple statistical models (IFFM) to a significantly complex hydrological models (IQQM) developed for three river gauges on the Macquarie River, a large regulated river in Australia's Murray-Darling Basin, using nonparametric tests. Firstly, we assembled annual actual flow data and matching modelled flows from IFFM or IQQM for two time periods, unregulated (no large dams or diversions) and regulated (current full water resource development), at three flow gauges (Warren, Oxley and Carinda) in the first section. And then we used the Nash-Sutcliffe coefficient of efficiency as the goodness-of-fit indicator and the nonparametric tests between modelled outputs and actual data in the third section. Finally we examined the implications of potential differences in terms of ecological effects and potential impacts of water resource development of using the two models: IFFM and IQQM simulated flow and the implications for the generality of this approach to other river systems of the world in the fourth and fifth sections.

Data and Methods

Data

Actual daily flow data (NSW Natural Resources Pinneena Version 9.3 and NSW Water Information Website http://waterinfo.nsw.gov.au) were transformed to monthly and then annual data (November–October) to coincide with spring flooding in the Macquarie Marshes, when most flooding usually occurs (Kingsford and Auld 2005), while retaining an annual time frame. Burrendong Dam (1,678 gigalitres, Fig. 1) primarily regulates the Macquarie River and its building began in August 1963 and was complete by August 1967; this defined the cut point for our unregulated and regulated period: before and after 1964. For the unregulated period, annual actual flow data were available

Fig. 1 The Macquarie River within the Murray-Darling Basin of southeastern Australia and its tributaries and distributaries that flow northwest to the Macquarie Marshes (*shaded area*) within its catchment in southeastern Australia, where Burrendong and Windamere Dams are the major regulatory structures; IFFM (Integrated Flow and Flood Modelling) models were developed using rainfall stations (*circles*) and flow gauges (*triangles*)

(Fig. 2) for different periods at the three gauges [Warren (1914–1964), Oxley (1944–1964) and Carinda (1940–1964)], but for the regulated period the corresponding actual flow data were available for the three flow gauges (1965–2007). Note that regulation was not a simple one-off effect but a press impact, increasing with the building of other dams and the diversion of water from the river (Kingsford and Thomas 1995) as irrigation licences were activated.

IQQM models have been developed to simulate the major hydrological processes in river valleys, along with relevant management rules, and have been calibrated to match observed reservoir levels, diversions and flows over the calibration periods. IQQM is based on a node-link concept where the important features of a river system (e.g., reservoirs, diversion points for irrigation and town water) can be represented by one of thirteen node types with the movement and routing of water between nodes done through links (Simons and others 1996; Hameed and O'Neill 2005). Generally, IQQM runs on a daily time-step but where there is adequate representation of water quality and routing processes, the model runs on any time step down to hourly (Hameed and O'Neill 2005). The Macquarie-Castlereagh is modelled by an IQQM V7.61.1 implementation of the river system model (Vaze and others 2011). The runoff estimates for the Macquarie-Castlereagh region, particularly the high runoff producing areas in the eastern half of the region, are relatively good because there are many calibration catchments in the region from which to estimate the model parameter values (CSIRO 2008a). Modelled regulators on the Macquarie River are adjusted to manage the passage of flood flows. Unregulated flow events are shared between irrigators in proportion to their supplementary licenses to unregulated flows. The Macquarie River, downstream of Burrendong Dam, is divided into 35 supplementary access reaches, with supplementary

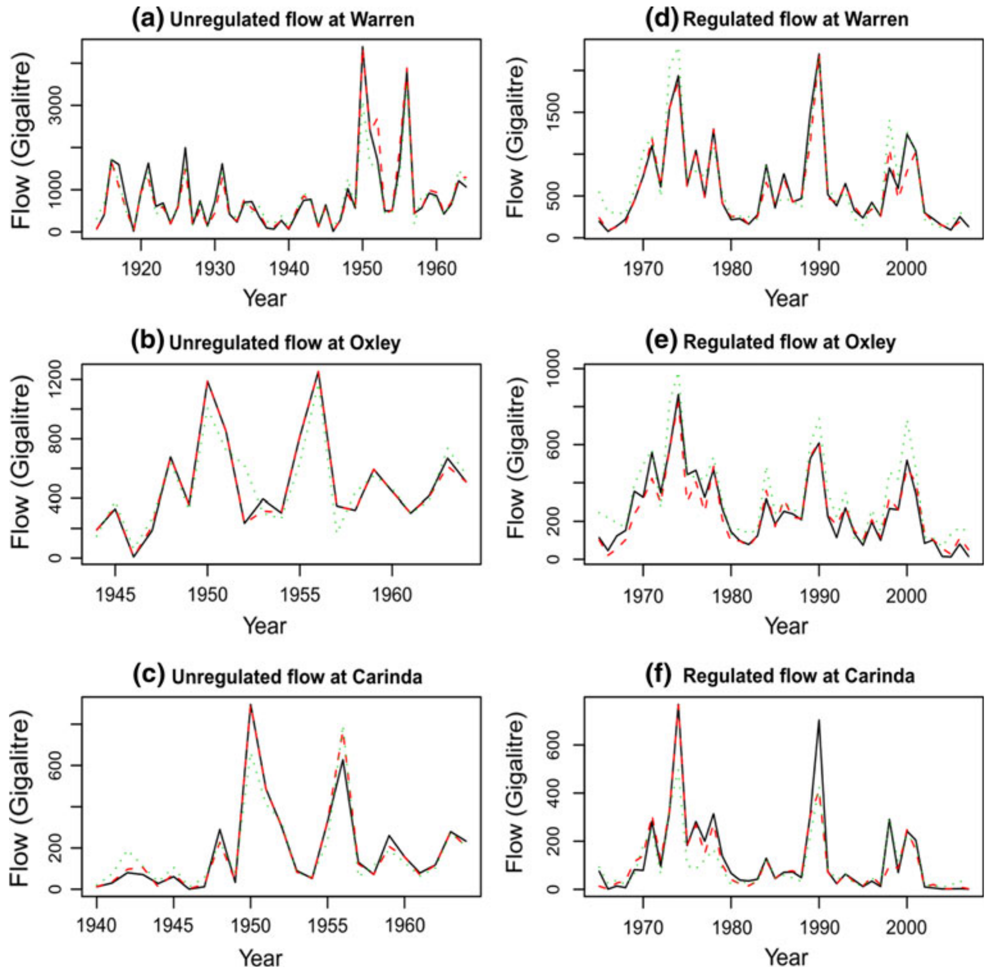

Fig. 2 Comparisons of distributions for actual (*solid line*), IFFM (*dashed line*) and IQQM (*dotted line*) at the three gauges from upstream to downstream (Warren, Oxley, Carinda) for the two periods: unregulated and regulated

access being announced simultaneously for all irrigators within a reach when flows are not regulated by the major dams (Vaze and others 2011). Modelled unregulated and regulated monthly flow from IQQM, were setup and calibrated by NSW Office of Water at the three flow gauges (1891–2007) and transformed to annual modelled flows.

Actual annual flow data were not sufficient for time series analysis, but LOESS (Cleveland 1979; Cleveland and Devlin 1988; Cleveland and others 1992) was ideal for modelling the complex hydrological processes where no theoretical models existed. We developed annual unregulated and regulated IFFM flow simulated output for the three flow gauges (1879–2007), using LOESS and leave-one-out samples without overfitting, based on annual rainfall at rainfall stations in the upper catchment and flow (Ren and others 2010). For example, the unregulated flow model at the Oxley gauge was built based on the relationship between annual flow data at the Oxley gauge and unregulated flow data at the Warren gauge before 1964; the regulated flow model at the Oxley gauge was developed using the relationship between annual flow data at the Oxley gauge and ‘regulated’ flow data at the Warren and Dubbo gauges after 1965; and then the unregulated and regulated flow models were extended to predict annual flow at the Oxley gauge for the full period (1879–2007).

For IQQM and IFFM, there were two versions of each model, unregulated and regulated. The unregulated model represented the river flowing freely without dams and diversions while the regulated model represented the current developed system with its dams and extractive use (Kingsford and Thomas 1995). Both models were subject to stochastic variability of rainfall from the catchment, forming a primary input variable for the period of record. Subsets of annual data were used for the comparison between actual data, IQQM and IFFM for matching periods of data.

Goodness-of-Fit Indicator

Judgements of the efficacy of hydrologic and water quality models usually rely on pairwise comparison of actual data and modelled predictions (Legates and McCabe 1999). The Nash-Sutcliffe coefficient of efficiency is a dimensionless indicator widely used and suited to evaluate the goodness of fit for hydrologic and water quality models (Nash and Sutcliffe 1970).

Nonparametric Tests

We used Kolmogorov-Smirnov (K-S) tests, which make no assumptions about the distribution of the data, to determine if hydrological datasets were from the same distribution (Gille 2004). The K-S test is non-parametric and distribution free (including non-stationary distribution), and applicable for correlated data (Weiss 1978). It provides valid comparison for time varying processes and inhomogeneous distributions (Brown and others 2002). Often, the K-S test may be the most appropriate nonparametric tests for overall differences between two datasets but tests for differences in median and variability are also useful. We used two separate tests for different potential distributions. The Wilcoxon and Ansari-Bradley tests respectively identify differences in medians (location) and variability (dispersion) (Lepage 1971). The Wilcoxon signed rank test (Flores 1989; Thompson and others 1999; Dewan and Rao 2005) or Wilcoxon matched pairs test is a nonparametric test for the median difference for paired data and it is more powerful than the K-S test if the spread and shape of two distributions are the same. The Ansari-Bradley, a nonparametric test, compares the difference in variability between two datasets and it is more powerful than the K-S test if the median and shape of the two distributions are the same (Pappas and DePuy 2004).

Comparison of Actual Flows and Modelled Outputs from IFFM and IQQM

First, we compared the actual flow to the corresponding modelled output from IQQM or IFFM at the Warren, Oxley and Carinda gauges for the unregulated and regulated periods. Then, we compared the modelled flow from IFFM and IQQM at the Warren, Oxley and Carinda gauges for the regulated or unregulated flow. After this, we compared modelled unregulated and regulated flow outputs from IFFM or IQQM model at the Warren, Oxley and Carinda gauges to show the effects of regulation.

Actual Annual Flows Compared to Modelled Outputs from IFFM or IQQM

We compared annual actual flows to the corresponding modelled outputs from IFFM or IQQM, separately for the unregulated and regulated periods at three flow gauges, proceeding from the most upstream gauge of Warren, then Oxley and finally Carinda on the Macquarie River (Fig. 1).

Unregulated Period

Overall for the unregulated period, annual IFFM modelled outputs were closer to the actual flow than those generated by IQQM (Table 1; Fig. 2). For the most upstream river gauge at Warren (1914–1964), there were no significant differences between medians of actual unregulated flow and the corresponding modelled outputs from IQQM ($P = 0.6928$) or IFFM ($P = 0.6108$), using Wilcoxon test or between variability of the actual unregulated flow and the corresponding modelled outputs from IQQM ($P = 0.4196$) or IFFM ($P = 0.7364$) using Ansari-Bradley test. The goodness-of-fit between actual data and respective modelled output varied from 94.1% for IFFM to 90.2% for IQQM (Table 1), reflected in similarities among distributions of actual, IFFM and IQQM (Fig. 2a).

Similarly for the Oxley gauge, within the Macquarie Marshes (1944–1964), there were no significant differences between medians (IFFM, $P = 0.9697$; IQQM, $P = 0.4733$) or variability (IFFM, $P = 0.99$; IQQM, $P = 0.9404$) of the actual unregulated flow and the corresponding modelled outputs from IFFM or IQQM. Goodness-of-fit between actual data and modelled data for IFFM (99.5%) was better than IQQM (84.2%, Table 1). There was a close alignment between IFFM modelled and actual data whereas the IQQM model underestimated actual flows throughout, particularly low annual flows (Fig. 2b).

As with the other gauges, there were no significant differences between medians of actual unregulated flow and the corresponding modelled outputs from IQQM ($P = 0.8949$) or IFFM ($P = 0.9187$) at the Carinda gauge (1940–1964) below the Macquarie Marshes (Fig. 1). Also, there were no significant differences in variability between actual unregulated flow and corresponding modelled outputs from IFFM ($P = 0.6509$) but the variability of actual

Table 1 Pairwise comparison of actual flows and modelled outputs from IFFM and IQQM for the unregulated or regulated periods for three flow gauges, from upstream to downstream: Warren, Oxley and Carinda

Gauges	Period	Goodness-of-fit[a]	
		IFFM (%)	IQQM (%)
Unregulated			
Warren	1914–1964	94.1	90.2
Oxley	1944–1964	99.5	84.2
Carinda	1940–1964	97.4	87.8
Regulated			
Warren	1965–2007	95.5	86.5
Oxley	1965–2007	92.9	70.6
Carinda	1965–2007	88	78.4

[a] Goodness-of-fit indicator was Nash-Sutcliffe coefficient of efficiency

unregulated flow was less than the modelled outputs from IQQM ($P = 0.0976$). Comparisons of goodness-of-fit with actual data showed IFFM (97.4%) performed considerably better than IQQM (87.8%, Table 1). IFFM was better than IQQM, compared to the actual flow, for the unregulated period (Fig. 2c).

Regulated Period

Overall, annual IFFM modelled outputs were closer to actual flow than those generated by IQQM for the regulated period (Table 1; Fig. 2). For the Warren flow gauge (1965–2007), there were no significant differences between variability of the actual regulated flow and the corresponding modelled outputs from IQQM ($P = 0.5078$) or IFFM ($P = 0.8068$). Also, there was no significant difference between the medians of actual regulated flow and the corresponding modelled outputs from IFFM ($P = 0.3392$) but median actual regulated flow was significantly less than the corresponding modelled outputs from IQQM ($P = 0.0498$). Goodness-of-fit analysis showed that IFFM (95.5%) performed considerably better than IQQM (86.5%), compared to actual data (Table 1). This was apparent in the cumulative probability distributions for the regulated period where IQQM tended to underestimate large floods, compared to IFFM (Fig. 2d).

At the Oxley gauge, there were no significant differences in variability of the actual regulated flow and the corresponding modelled outputs from IQQM ($P = 0.3943$) or IFFM ($P = 0.5674$) or between medians of actual regulated flow and the corresponding modelled outputs from IFFM ($P = 0.5014$). Contrastingly, modelled median from IQQM was significantly greater than the corresponding median actual regulated flow ($P < 0.0001$). There was also considerable difference in the goodness-of-fit of actual data to IFFM (92.9%) compared to IQQM (70.6%, Table 1). The distributions showed that IFFM was better at predicting actual flow than IQQM, which overestimated actual flows (Fig. 2e).

Similarly at the Carinda gauge, there were no significant differences between medians of actual regulated flow and the corresponding modelled outputs from IQQM ($P = 0.2274$) or IFFM ($P = 0.7562$). There was also no significant difference between the variability of the actual regulated flow and IFFM modelled flow ($P = 0.8534$) but the variability of actual regulated flow was less than modelled flow from IQQM ($P = 0.0966$). Goodness-of-fit between modelled data and actual flow was poorer than at other gauges (Table 1), with IFFM (88%) performing better than IQQM (78.4%). The distributions of flow showed IFFM with reasonably close matching of actual flow, better than IQQM which underestimated actual flow (Fig. 2f).

Comparison Between IFFM and IQQM Models

We then compared distributions of IFFM and IQQM models (unregulated and regulated), including medians and variability, for the three flow gauges for the full modelled period 1891–2007 (Fig. 1), using nonparametric tests. We also calculated a modelled flow index as the proportion of IQQM modelled flow compared to IFFM modelled flow for three flow sizes: low, medium and high.

Unregulated Comparison

At the Warren gauge, there were no significant differences (Fig. 3) between unregulated modelled flows from IQQM and IFFM ($P = 0.5716$), using two-sided K-S test. The lowest flows were lower and the highest flows higher from IFFM, compared to IQQM (Table 2), and this was reflected in the proportional index of medians for low and high flows (Table 3). This difference in distribution was reflected in near parity between overall medians (IQQM/IFFM = 102%) but median high flows from IQQM about 12% less than from IFFM and low flows about 35% higher from IQQM than from IFFM (Table 3). At the Oxley gauge, median unregulated flows from the IFFM model was less ($P = 0.0517$) than the corresponding IQQM model, using one-sided Wilcoxon test (Fig. 4), mostly because median high flows were about 16.3% higher from the IFFM model compared to the IQQM model (Table 3). At the Carinda gauge, unregulated median flows from IQQM modelled outputs were also significantly less than the corresponding IFFM flow ($P = 0.0328$, Fig. 5), using one-sided K-S test. This was reflected in near parity between overall medians (IQQM/IFFM = 105%) but, median high flows from IQQM were about 25% less than from IFFM while median low flows were about 112% higher from IQQM than from IFFM (Table 3).

Regulated Comparison

At the Warren gauge, there were no significant differences between the regulated modelled outputs from IQQM and IFFM ($P = 0.6815$), using two-sided K-S test (Fig. 3). The highest flows from IFFM were less than the corresponding IQQM (Table 2) and median low flows were about 29% higher from IQQM than from IFFM (Table 3). Similarly at the Oxley gauge, regulated IFFM modelled median was significantly less than the corresponding IQQM modelled median flow ($P < 0.0001$), using one-sided Wilcoxon test (Fig. 4; Tables 2, 3). Further, the regulated modelled outputs from IFFM were significantly less than the corresponding IQQM at the Carinda gauge ($P = 0.0457$), using one-sided K-S test. Median high flows for IQQM were about 26% less than those for IFFM while median low flows were about 49% higher for IQQM than for IFFM (Table 3).

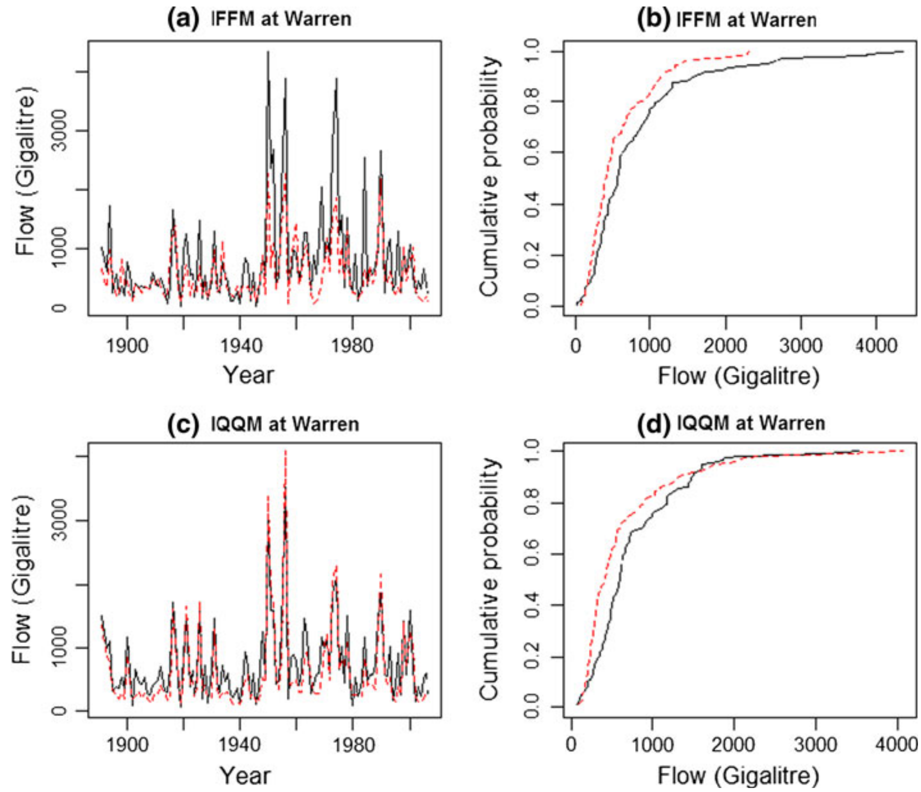

Fig. 3 Comparisons of annual flow between the unregulated (*solid line*) and regulated (*dashed line*) outputs from IFFM (**a**) and IQQM (**c**) models at the Warren gauge with the corresponding cumulative distributions of IFFM (**b**) and IQQM (**d**) for the period 1891–2007

Table 2 Quantiles (gigalitres/year) of unregulated and regulated modelled flow from IFFM and IQQM for three flow gauges (Warren, Oxley and Carinda) on the river

Flow gauges	Cumulative probabilities	Quantiles			
		IFFM		IQQM	
		Unregulated	Regulated	Unregulated	Regulated
Warren	0.05	124.93	133.11	140.31	136.59
	0.25	348.59	254.95	392.26	245.15
	0.5	564.43	410.2	586.21	411.39
	0.75	994.96	725.9	998.17	731.74
	0.95	2578.15	1412.24	1623.72	1784.49
Oxley	0.05	112.54	50.47	110.63	85.47
	0.25	240.36	113.29	258.37	146.23
	0.5	350.2	193.21	348.59	228.41
	0.75	510.62	314.2	523.16	418.56
	0.95	957.75	540.79	730.91	732.8
Carinda	0.05	7.07	8.99	22.09	11.03
	0.25	40.06	23.77	59.69	21.2
	0.5	90.05	53.9	100.29	44.75
	0.75	206.45	123.92	189.05	105.11
	0.95	493.57	307.76	351.32	345.37

Effects of Regulation

A key aspect in determining the values of different models is identification of hydrological impact which can often then be used as a surrogate or ecological effects of water resource development. To determine how the different models estimated the effects of river regulation, we compared between regulated and unregulated models from IFFM or IQQM (1891–2007), using the K-S test. We also developed a regulation index: the proportion of regulated

Table 3 The medians of annual flow index (overall, low, medium, high) used to compare IFFM and IQQM modelled outputs (gigalitres/year) within unregulated and regulated periods for the three flow gauges

Index	Level	Warren		Oxley		Carinda	
		Flow	Index (%)	Flow	Index (%)	Flow	Index (%)
Unregulated							
IQQM/IFFM	Overall		102.06		95.53		105.02
	Low	<395	135.11	<262	116.74	<49	211.87
	Medium	[395,824]	100.31	[262,437]	101.04	[49,140]	103.11
	High	>824	87.75	>437	83.76	>140	74.91
Regulated							
IQQM/IFFM	Overall		102.19		126.29		89.72
	Low	<305	128.82	<140	161.27	<35	148.95
	Medium	[305,548]	95.75	[140,267]	121.99	[35,99]	64.83
	High	>548	98.02	>267	120	>99	73.97

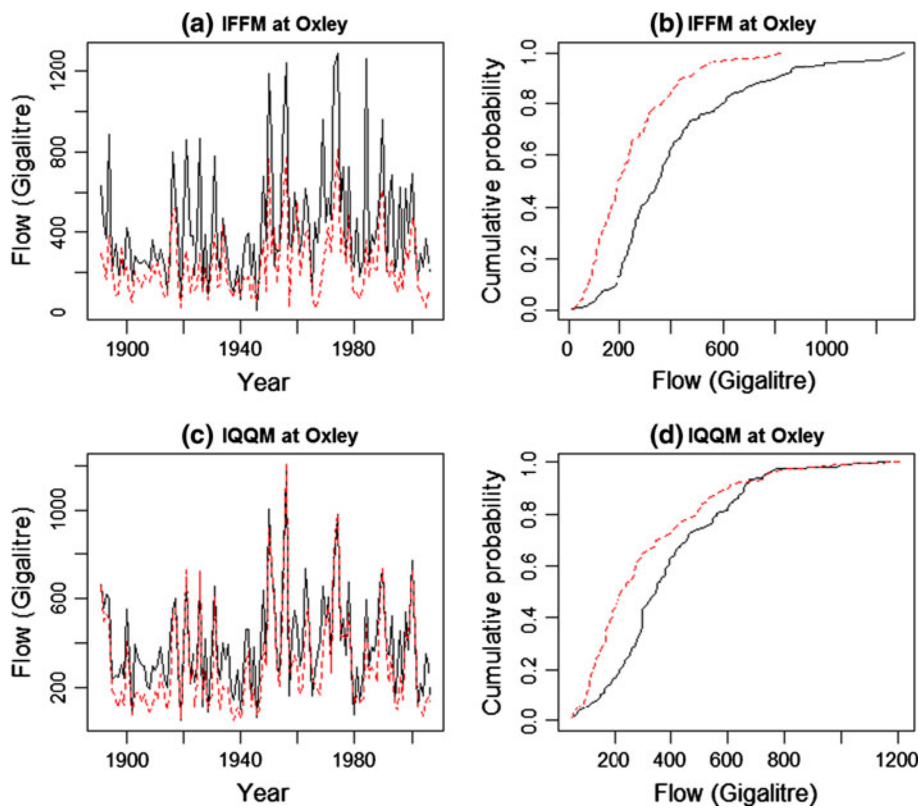

Fig. 4 Comparisons of annual flow between the unregulated (*solid line*) and regulated (*dashed line*) outputs from IFFM (**a**) and IQQM (**c**) models at the Oxley gauge with the corresponding cumulative distributions of IFFM (**b**) and IQQM (**d**) for the period 1891–2007

flow compared to unregulated flow for three flow sizes: low, medium and high (Table 4).

As a result of the differences between the models, there were differences in the hydrological impacts of river regulation (Table 4). At the Warren gauge, regulated IFFM flows were significantly lower ($P = 0.0031$) than corresponding unregulated flows (Fig. 3a): overall median regulated flow was about 80% of median unregulated flow (Table 4). Comparison of cumulative unregulated and regulated flow distributions (Fig. 3b) showed five quantile differences. The 95% quantile of regulated flows was about 55% of corresponding unregulated flow (Table 2). This difference was also apparent from IQQM modelling where regulated annual flow was significantly ($P = 0.0005$) different to unregulated flows (Fig. 3c): regulated flows were about 74% of unregulated flows at the Warren gauge (Table 4).

At the Oxley gauge, regulated IFFM flows were also significantly lower ($P < 0.0001$) than the corresponding unregulated flows (Fig. 4a): overall median regulated flows were about 61.5% of unregulated flows (Table 4). There was also a significant difference ($P < 0.0001$) between

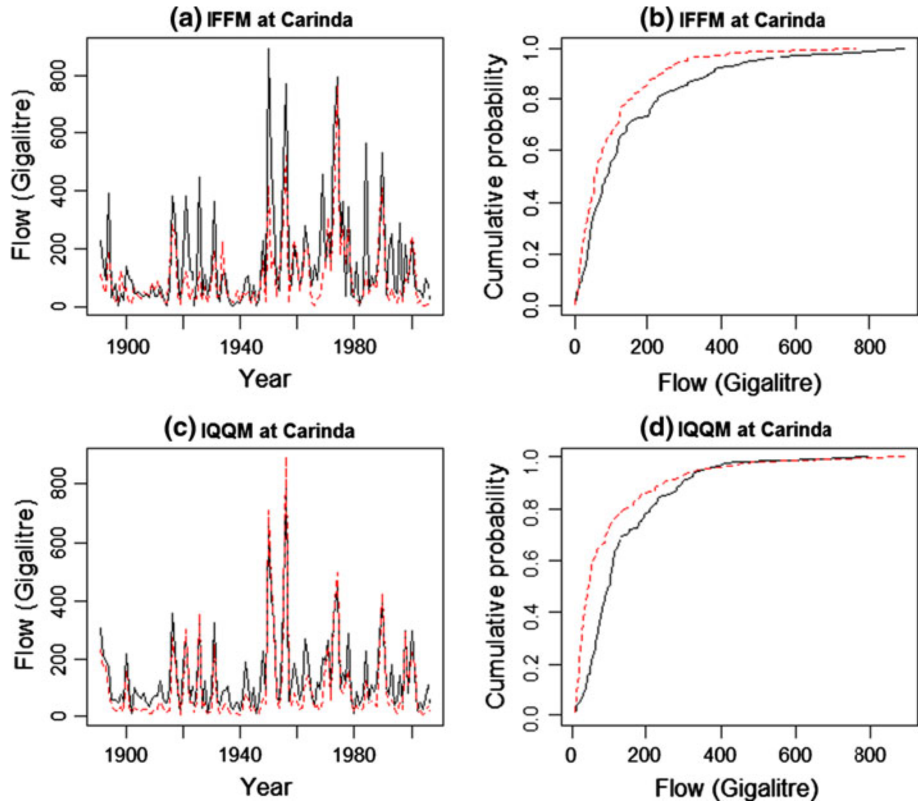

Fig. 5 Comparisons of annual flow between the unregulated (*solid line*) and regulated (*dashed line*) outputs from IFFM (**a**) and IQQM (**c**) models at the Carinda gauge with the corresponding cumulative distributions of IFFM (**b**) and IQQM (**d**) for the period 1891–2007

Table 4 The medians of annual flow index (overall, low, medium, high) used to compare unregulated and regulated modelled outputs (gigalitres/year) within IFFM and IQQM for the three flow gauges

Index	Level	Warren		Oxley		Carinda	
		Flow	Index (%)	Flow	Index (%)	Flow	Index (%)
IFFM							
Regulated/unregulated	Overall		79.52		61.48		73.36
	Low	<451	109.65	<288	70.79	<68	140.58
	Medium	[451,888]	68.78	[288,454]	52.85	[68,147]	50.39
	High	>888	59.56	>454	55.63	>147	54.81
IQQM							
Regulated/unregulated	Overall		74.38		77.08		51.28
	Low	<489	75.61	<302	68.77	<78	43.6
	Medium	[489,873]	54.83	[302,457]	62.61	[78,148]	40.77
	High	>873	87.55	>457	91.63	>148	77.93

regulated and unregulated flows, using IQQM modelled data (Fig. 4c) but this difference was lower than for IFFM: regulated flows were about 77% of unregulated flows (Table 4).

Such patterns were also reflected at the Carinda gauge, except that the difference between regulated and unregulated flows was higher for IQQM (51%), compared to IFFM (73%, Table 4). Regulated IFFM and IQQM flows were respectively significantly lower ($P = 0.0328$, $P < 0.0001$) than the corresponding unregulated flows (Fig. 5a, c).

Discussion

Many of the world's wetlands are in serious ecological decline as a result of water resource development regulating and diverting water upstream (Lemly and others 2000; Kingsford and others 2006). There is a need for analytical tools that help determine the extent of ecological degradation but also allow for testing environmental flow management scenarios as governments increase environmental flows (Poff and Zimmerman 2010). Measurement of ecological impacts on highly regulated rivers is primarily done using hydrological indices from complex hydrological models, developed initially for determining different options for extractive use of water. Such models were not initially designed to test for environmental impacts. The degree of hydrological change, as a surrogate for ecological change, becomes the primary assessment process for ecological degradation (CSIRO 2008a). For example, hydrological analyses were the primary basis for proposing cuts of 27–37% in irrigation diversions in favour of environmental flows for the Murray-Darling Basin (Murray-Darling Basin Authority 2010a). Such modelling is critically important for major water sharing decisions between the environment and extractive use but efficacy of such modelling is seldom tested. We have previously shown that inundation extent and patterns in the Macquarie Marshes were primarily dependent on volumes of annual flows in the Macquarie River (Ren and others 2010) with inundation areas contracting considerably with reduced flooding (Thomas and others 2011), affecting dependent biota (Kingsford and Thomas 1995; Kingsford and Johnson 1998).

We showed that relatively simple statistical models (IFFM, Ren and others 2010) more closely matched actual data than the complex hydrological model (IQQM) primarily used to determine changes in flows in the Macquarie River system, part of the Murray-Darling Basin. IFFM was better at predicting the actual distribution of annual flow data at the three gauges tested. This was particularly important in determining the level of ecological degradation in the system, particularly the Macquarie Marshes. In 2009, the Australian Government notified the Ramsar Bureau that there was a likelihood of detrimental ecological change to the Macquarie Marshes. The degree of change, based primarily on hydrology remains contentious.

There has been a long protracted process of identifying the ecological impacts of water resource development on the Macquarie Marshes (Kingsford and Thomas 1995; Kingsford and Johnson 1998; Kingsford 2000). There is considerable change in the floodplain ecology of the Macquarie Marshes (Thomas and others 2011) because flooding is closely linked to river flows which have declined with river regulation (Kingsford and Thomas 1995; Ren and others 2010). When we compared actual data (either unregulated or regulated period) for each of the flow gauges analysed, annual IFFM modelled outputs were closer to the actual flow than those generated by IQQM (Table 1; Fig. 2). The IQQM model underestimated unregulated and overestimated regulated flows within the Macquarie Marshes (Oxley gauge). Hydrological and ecological impacts to the Macquarie Marshes, based on IQQM modelling (CSIRO 2008b), were likely underestimated. Given the reasonably close match between IFFM modelled outputs and actual data, IFFM may provide a more realistic assessment of ecological impact.

Overall, there was about a 10% underestimate of the impacts of river regulation on the Macquarie Marshes (Oxley gauge) based on our IFFM model which estimated a 44.83% reduction in median annual flow compared to a 34.48% from the IQQM model (Table 2). This was because IQQM models underestimated unregulated flows and overestimated regulated flows when compared to actual flows. The statutory water sharing plan estimates that 73% of the long-term average annual flow remains for basic ecosystem health, using IQQM estimates (CSIRO 2008a), between Oxley and Marebone gauges; Marebone gauge lies between the Oxley and Warren gauge. Contrastingly, our IFFM modelling showed that 57% of the long-term average annual flows reached the Macquarie Marshes, a difference of about 16%, after building of dams and diversion of water. One of the challenges may be in the modelling of flows in the highly complex anastomosing stream system of the Macquarie Marshes. The Oxley gauge lies on one of the branches of the system and some flows in IQQM may be inadvertently diverted down one of the other branches in the modelling. Impacts of river regulation on the Macquarie Marshes are likely to be exacerbated with climate change. Flows to the Macquarie Marshes are estimated to decrease by a further nine percent by 2030 but for as much as 28% under an extreme dry scenario using IQQM modelling (Herron and others 2002; CSIRO 2008b).

Given that IFFM more closely modelled actual flows, it is also probably more useful in predicting environmental responses, particularly as it is already linked to an inundation model (Ren and others 2010). One of the major challenges for regulated river systems is transparent management of environmental flows. The Australian Government is currently spending $AU3.1 billion on buying water from extractive use to return to the rivers of the Murray-Darling Basin (Wong 2008). Flow models will be critical for measuring the hydrological and subsequent ecological responses. Such flow models when linked to inundation patterns (Ren and others 2010) can potentially allow objective assessment of different flow delivery and likely ecological outcomes. Already the amount of environmental flow available in the Macquarie River, as an environmental flow, has increased by 62.5% from 160,000 ML to about 260,000 ML as a result of the purchase of irrigation licences by the NSW State and the Australian Governments. Models with good predictive power will be essential for measuring hydrological and ecological impacts and assessing the benefits of flow delivery.

Conclusions

Environmental management increasingly requires modelling to determine effects of different policy or management decisions on ecosystems. Such models need to cater for stochastic variation of climate and adequately measure anthropogenic impacts. In rivers, critical analyses usually involve an assessment of the effects of changes to river flows as a result of the building of dams and extraction of water upstream of major ecosystems. Many of the large wetland ecosystems lie in lowland parts of rivers, often downstream of dams and extraction of river flows. Increasingly, there is realisation that such ecosystems are declining in ecological health, affected primarily by river regulation. Determining the level of impact is a key question which can then define how much of a policy response is required, such as returning environmental flows. Also management of flows for restoration is highly dependent on modelling that allows managers to trial various trial releases of environmental flows that reflect the ecological variability of flows. Traditionally, highly complex hydrological models were developed and used initially for managing rivers to provide water for use (e.g., irrigation) but increasingly these models are being applied to measuring ecological impacts.

We showed that one traditional model underestimated the median and average annual flow impacts of river regulation by about 10% and 16% to a Ramsar-listed wetland of high conservation importance in the Murray-Darling Basin of southeastern Australia. This has considerable implications for environmental flow management as the Murray-Darling Basin Authority estimated that 14–18% cut in diversions was required to increase environmental flows, largely based on the estimates from IQQM (Murray-Darling Basin Authority 2010a). Given the significant underestimation in impact identified, then the estimate of amount of water required for environmental flows to the Macquarie Marshes should be increased. If there is some generality for other rivers in this result, then this may require further readjustments in favour of the environment for other rivers. These include the Gwydir wetlands, Narran Lakes system and Cumbung Swamp (CSIRO 2008b).

On many of the world's rivers there is heavy reliance on using complex hydrological models (Doll and others 2003), but these may be underestimating hydrological and ecological impacts to downstream wetland systems. We advocate that alternative independent models, potential simple statistical ones, should be developed for all rivers to allow for measurement of ecological impacts. These would at least allow an independent testing of output from complex hydrological models. They would also potentially be more flexible and easier to run, with more predictive capacity, because of the relatively few variables incorporated which would be easier to link to ecological response models. There are considerable opportunities to use more statistical modelling in the management of the world's rivers as a predictive tool, method for assessment of impacts of river regulation on ecosystems and as test of the efficacy of complex hydrological models.

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