Artist's Impression

Environmental Impact Statement – Appendix H3: Warragamba Dam Environmental Flows Scenario Assessment Summary

Warragamba Dam Raising

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Warragamba Dam Environmental Flows

Scenario Assessment Summary 2021

Acronyms

Acronym	
°C	degrees Celsius
DoI Water	Department of Industry, Water
e-flow	environmental flow
FMO	Flood management options
FSL	Full Supply Level – dam at 100% capacity (in metres – for Warragamba FSL is RL116.72m
The Forum	Hawkesbury-Nepean River Management Forum
HSPF	Hydrologic Simulation Program Fortran
IQQM	Integrated Quantity and Quality Model
ML	Megalitres
ML/d	Megalitres per day
ML/a	Megalitres per annum
MWCEOs	Metropolitan Water Chief Executive Officers
MWP	Metropolitan Water Plan
RAP	River Analysis Package
RL	Relative Level – refers to height above sea level in meters
TWG	Hawkesbury-Nepean Technical Working Group
WATHNET	Generalised Water Supply Headworks Simulation using Network Linear Programming
WWTP	Wastewater Treatment Plant

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1. Introduction

1.1. Background

The Hawkesbury-Nepean River is an iconic waterway that supplies more than 85 percent of Sydney's water. It underpins the economy of the region, supporting farming and commercial fishing as well as tourism, sport, and recreation. The river experiences the pressures of Sydney's development and growth, and increased urbanisation is expected to put further pressure on the water quality and ecology of the Hawkesbury-Nepean River, which is already under stress.

Warragamba Dam is the largest dam on the river and is owned and operated by WaterNSW. It stores around 80 percent of Sydney's drinking water and, when full, stores over 2,000 gigalitres. It sits on the Warragamba River, a tributary of the Hawkesbury-Nepean River, and has a 9,000 km^2 catchment that includes Lithgow and the Coxs River to the west and Goulburn and the Wollondilly River to the south.

With its location low in the catchment, Warragamba Dam has had a significant impact on downstream river flows, resulting in the river experiencing prolonged periods of reduced flows. This has exacerbated poor water quality, which in turn has led to increased aquatic weed growth and, at times, extensive algal blooms. The community's uses of the river are substantially impacted by these impacts.

In 2004 the Hawkesbury-Nepean River Management Forum (the Forum) undertook detailed investigations onto the condition of the river and made recommendations on how to improve river health. Since then, the Government has implemented an integrated suite of actions to improve river health, including the release of environmental flows (e-flows) from the upper Nepean dams. Despite these measures, significant improvement is required to meet Hawkesbury-Nepean river flow and water quality objectives that were agreed to by the NSW Government in 2001. The NSW Government's 2017 Metropolitan Water Plan (MWP - Department of Industry, Skills and Regional Development (DISRD) 2017) proposes variable environmental flows from Warragamba Dam to improve the health of the Hawkesbury-Nepean River. The Plan aims to mimic as much as possible the natural flow of the river.

Investigations over the last six years have shown:

- aquatic plants have become more abundant in recent years
- there is a history of toxic cyanobacterial (blue-green algae) blooms in the river and the risk remains high
- severe and immediate threats to aquatic ecosystems continue.

The need for active and ongoing management of the water environment is well recognised, especially as pressures continue and demands increase with Sydney's urban growth. The two future population growth areas for Sydney, the North West and South West sectors, are located largely within the Hawkesbury-Nepean catchment and the river condition is expected to deteriorate further unless additional action is taken.

Warragamba Dam is the last dam within the catchment to provide variable environmental flows releases.

1.1.1. Environmental Flows from Warragamba Dam

The release of variable e-flows from Warragamba Dam will allow the river to better meet community and values. These include boating, fishing, swimming, river amenity for picnicking and other on-bank recreational activities, agricultural production, and ecosystem health. E-flow releases will achieve this by:

- reintroducing more natural flow conditions
- improving water quality
- reducing problems caused by excessive growth of algae and aquatic weeds

- improving fish populations.

The variability in e-flow releases is estimated from daily inflows and releasing a proportion of this, which is varied each day. This mimics the natural flow variability in the river. The release volume is calculated based on a transparency/translucency rule, where:

- **Transparency** - all inflows up to a set low flow volume (a lower percentile of the natural flow regime), and
- **Translucency** - a percentage of the remaining inflow is released.

The rest of the inflows are stored for water supply.

The Metropolitan Water Chief Executive Officers' (MWCEOs') Committee, a committee comprising representatives of government agencies and the major public water utilities, agreed that a shortlist of e-flow options for Warragamba Dam would initially be assessed based on the work of the MWP and the Forum. These were:

- Base Case (business as usual)
- 80th percentile transparency and 20 percent translucency (80/20)
- 90th percentile transparency and 10 percent translucency (90/10)
- 95th percentile transparency and 20 percent translucency (95/20).

The results of the initial economic assessment identified 90/10 (particularly) and 95/20 as having a net economic benefit. Further analysis using more advanced water quality and hydro-economic models reduced the apparent net benefits of these flow regimes and resulted in later analyses focusing on alternatives that released less water from the dam. These alternative e-flow options endorsed by the MWCEOs' Committee for further investigation were:

- 90/10 half, reducing 90/10 releases by half when total water supply storage falls below 50 percent
- 90/10 scaled, reducing 90/10 releases proportionally as total storage changes by 5 percent
- 90/5
- 95/5.

The 90/10 scaled option was included in the 2017 Metropolitan Water Plan (MWP), as the economic analysis indicated a high benefit to cost ratio of 4. The NSW Government committed to further investigation of some additional e-flow options to determine whether a higher e-flow release would be possible without too great an impact on water security, or unreasonably bringing forward the requirement for augmentation (such as a new dam or expanded desalination plant). These were:

- 95/20 scaled at 5 percent
- 95/20 halved at 50 percent
- 90/10 scaled at 10 percent
- 90/10 scaled at 5 percent
- 90/20 scaled at 5 percent
- 80/10 scaled at 5 percent
- 90/10 scaled at 5 percent, plus 14m dam raised.

This report reviews the initial assessment of the four e-flow options, the analyses undertaken for the alternative e-flow options (2017 MWP e-flow options), and then compares these to the additional 2018 e-flow options.

1.1.2. Warragamba Dam – e-flows and flood mitigation options

To assess the impacts of possible flood mitigation options for Warragamba Dam, e-flow scenarios were run through WNSW's water supply system model (Wathnet), a hydrological system simulation model (IQQM) and water quality and ecological models (Table 1). These were:

- Base Case (do nothing)
- Lowering FSL by 5 m to create airspace
- Raising the dam by 14 m and keeping the FSL at the current level.

Each of these was modelled with and without the (unscaled) 90/10 e-flow option. In addition, two flood release options were modelled – 40 GL/d and 100 GL/d. The 2018 e-flow options analysis included one dam raising scenario; however, in the model this option did not have different releases based on flood management as the flood management options (FMOs) did. Based on the FMO analyses, it is expected that any dam raising will impact on river health if e-flows are not released, and that any e-flow benefit will be increased if Warragamba Dam wall is raised.

Table 1. Flood management options considered in the environmental modelling.

Option	Full supply level (m)	Dewatering Rate (GL/d)	Environmental flow
Base Case	0	0 – spills only	None
90/10	0	0 – spills only	90/10
-5-40	-5m	40	none
-5/40EF	-5m	40	90/10
-5/100	-5m	100	none
-5/100EF	-5m	100	90/10
14/40	+14m	40	none
14/40EF	+14m	40	90/10
14/100	+14m	100	none
14/100EF	+14m	100	90/10

1.1.3. The Technical Working Group

The Hawkesbury-Nepean Technical Working Group (TWG) was established under terms of reference to provide scientific, technical, economic and social advice about the Warragamba e-flows project. It comprised technical and scientific experts from a range of Government agencies and provided analysis and advice on the potential river health outcomes of environmental flow options. This was supported by expert knowledge, systematic documentation of the interaction between flows and ecosystems; and hydrological, water quality and ecological models. The methods and outcomes were peer-reviewed by a panel of experts.

1.1.4. How the environmental flows are to be released

The Department of Finance and Services investigated options to release variable e-flows from Warragamba Dam, including siphons, a new outlet, or whether the existing infrastructure could be modified to release e-flows. The best option is to modify the unused hydro power station to allow releases to be made, with a multi-level offtake to enable selection of the most appropriate water quality (given the potential issues with cold water pollution downstream of such a large dam).

Investigations indicated that using the existing ‘hole’ in the wall, with a multi-level offtake upstream, the release volumes that could be achieved were between ~0 ML/d to 6,700 ML/d at Full Supply Level (FSL). This would be able to release water for approximately 98 percent of the time. The maximum e-flow would be required when inflows are around 67,000 ML/d. The TWG considered that at this inflow rate, the entire catchment would likely be wet and close to low to moderate flood levels. The TWG agreed that during high flow events, e-flows would likely exacerbate any downstream flooding, and that the benefits of e-flows would be equally met by tributary inflows from unregulated catchments. Subsequent analysis has indicated that a maximum release capacity of 3,000 ML/d will achieve all the identified ecological benefits downstream.

Preliminary work indicated that a multi-level offtake that extends from Reduced Level (RL - height above sea level in meters) 117.72m (1m above FSL) to RL 84.72m (20.6 percent of storage capacity) will allow e-flows to be released at least 98 percent of the time. The infrastructure design will allow for water to be selected from different depths to minimise the impact on downstream water quality. For example, selecting offtake levels with suitable temperature and no cyanobacteria.

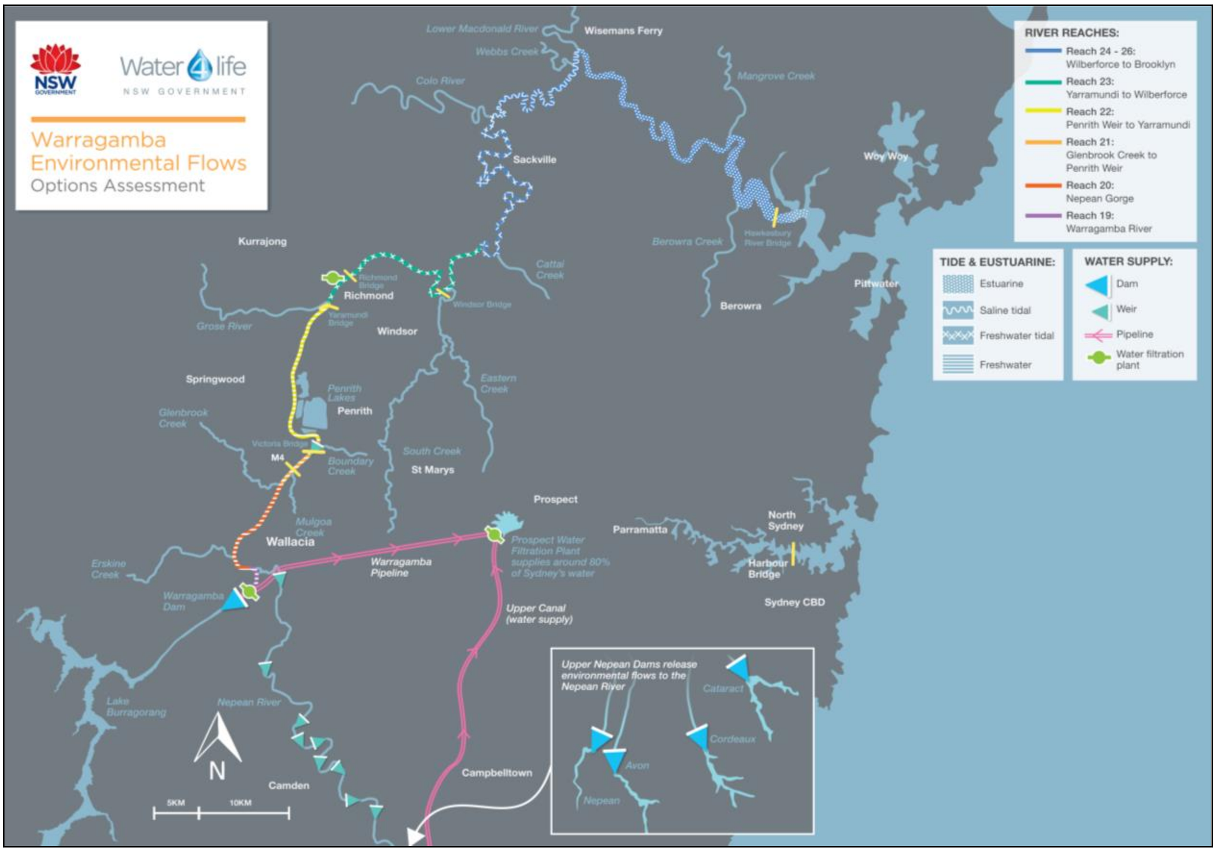
1.1.5. River reaches and sites considered for the e-flow options assessment

The Hawkesbury-Nepean River can be divided into reaches based on river geomorphology. The Forum identified 26 distinct reaches, nine of which are downstream of Warragamba Dam. These are (Figure 1):

- Reach 19 — Warragamba River from the dam to the junction with the Nepean River
- Reach 20 — Nepean River from its confluence with the Warragamba River to Glenbrook Creek
- Reach 21 — Nepean River from Glenbrook Creek to Penrith Weir
- Reach 22 — Nepean River from Penrith Weir to the Grose River junction
- Reach 23 — Hawkesbury River from the Grose River to Wilberforce
- Reach 24 — Hawkesbury River from Wilberforce to the Colo River
- Reach 25 — Hawkesbury River from the Colo River to Wisemans Ferry
- Reach 26 — Hawkesbury River from Wisemans Ferry to Brooklyn.

These are described in more detail in the separate Context Baseline report.

Figure 1. River reaches considered in the e-flows assessment



1.1.6. What was excluded from the analysis

Some physical and ecological processes would likely improve following the commencement of e-flows from Warragamba Dam and were excluded from the analyses. These are:

i. **Geomorphology** was excluded as e-flows impacts will be within the natural variability of the river and contained within the banks. Releases will be managed to limit rapid changes in water levels (beyond natural) and can be modified if unacceptable geomorphic impacts are observed.

ii. **Cyanobacteria** were not considered directly, nor as part of the water quality assessment, due to difficulties in cyanobacterial modelling. The Algae baseline report provides detailed information on cyanobacteria in the river. In recent years, there has been a notable decrease in cyanobacterial blooms (extent, persistence and frequency). In addition, there has been a shift from blooms dominated by the potentially toxic *Microcystis aeruginosa* to blooms dominated by genera such as *Aphanocapsa* that are not known to be toxic. This may be due to changes in nutrients being discharged to the river, however, the reasons for this have not been well researched. Predictions of blooms is difficult. While most conventional wisdom says that blooms occur during low flows and warm weather, recent observations indicate that blooms will also occur in autumn. The last major cyanobacterial bloom on the Nepean River occurred in March 2012, three weeks after the dam spilled for the first time in 14 years, and while the flow rate was still high.

iii. **Macroinvertebrates** were not considered in the e-flows analysis as there is a paucity of data from the Hawkesbury-Nepean River downstream of Warragamba Dam. However, it is likely that macroinvertebrate populations will improve with the introduction of environmental flows. This will be included in the monitoring program.

iv. **Vertebrates** other than fish were not considered further in the analyses due to the paucity of available data. Reptiles such as turtles and water dragons, mammals, and birds that rely on the river are likely to benefit from more natural flows.

v. **Estuarine processes** and commercial fishing are likely to benefit from e-flows. For example, prawn numbers may improve following the introduction of e-flows, as prawns spend at least part of their time in estuarine areas. However, quantification of this change is difficult to estimate, given the available information.

1.1.7. Fish in the Hawkesbury-Nepean

Thirty-six species of fish have been recorded in the Hawkesbury-Nepean River, from Warragamba Dam to Wisemans Ferry (Reaches 19 to 25). There are some migratory species that move between the sea and freshwater during different life cycle stages and can be affected by reduced river flows. Water temperature and flow are known to be triggers for migration and spawning in some species. With less flow in rivers due to upstream dams and water extraction, the impact of natural (such as bars and riffles) and artificial (such as dams and weirs) barriers on fish migration opportunities is exacerbated by reduced flows.

Due to the paucity of information on species' ecology for most fish recorded in the Hawkesbury-Nepean River, the TWG chose to focus on Australian bass (*Macquaria novemaculeata*) and freshwater mullet (*Trachystoma petardi*) as indicator species. Australian bass are large predatory fish at the top of the food chain, requiring a complex array of habitat, ecological and food requirements to ensure a healthy population. They move from the freshwater section of the river to the estuary to breed. Freshwater mullet are large and mainly herbivorous fish that migrate downstream to spawn in the estuary or sea in summer. Peak spawning occurs in February. Both species have known triggers for movement and spawning that can be modelled and are important in recreational fishing.

The most significant natural barrier to fish movement in the Hawkesbury-Nepean River downstream of Warragamba Dam is a rock bar known informally as Bishop's Bench, in Reach 22 near Russell St, Emu Plains (Figure 2). This was confirmed by a reconnaissance trip which was carried out by canoe in September 2011 to determine the character of the natural barriers in the river. Seventeen (17) other barriers were also identified. A detailed survey of the Bishop's Bench was undertaken and a River 2-D model developed to determine flows at which an adult fish, such as an Australian bass or Freshwater mullet, would be able to migrate upstream over the barrier. With an effective fishway at Penrith Weir, it was assumed that if fish could move over Bishop's Bench, they would be able to cross the smaller barriers in the rest of the river, thus the whole of the river from below Warragamba Weir to the estuary would be connected.

Figure 2. Nepean River at Emu Plains – view across Bishops Bench from the left bank.

1.1.8. Macrophytes in the Hawkesbury-Nepean River

While some growth of aquatic macrophytes is a normal and healthy component of a river's ecosystem, 'over growth' can be negative. Overgrowth is a symptom of high nutrients and altered flow regimes. Aquatic plants, especially weed species, have caused serious problems in the past in the Hawkesbury-Nepean River. They are generally described as floating or submerged. Floating weeds can be unsightly, can impede boating and swimming, impact on ecological processes and be costly to manage (Figure 3). In 2004, a salvinia bloom (*Salvinia molesta*) covered 88 km of the Hawkesbury-Nepean River and was estimated to have economic impacts that ran into the millions of dollars. This included the cost to manage the weed (for example, physical removal and disposal) and the loss of revenue from tourism.

Floating macrophytes (weeds) are responsive to small flow events and will be pushed downstream or up onto the banks at relatively low flows. The TWG considered that e-flows would be likely to provide a benefit in the reduction of floating weeds.

Submerged weeds such as egeria (*Egeria densa*) grow extremely well in the Hawkesbury-Nepean River and at times require expensive management such as physical removal, particularly in well-used recreation areas. Egeria can completely block river channels making any form of recreation dangerous and difficult, if not impossible (Figure 4). Submerged weeds have been shown to be less responsive to low and moderate flows as they are rooted in the sediment. Under low and moderate flows some plant material may be removed, but often roots and stems remain intact. The likely effect of e-flows on submerged weeds (primarily egeria) was investigated by the TWG. Sydney Water's water quality model included an egeria model component based on observations and velocity estimations for different flows. The TWG also commissioned the CSIRO to undertake a remote-sensing project to determine the impact of the 2012 dam spill on submerged weed species. The 2012 spill had a peak flow of 133,000 ML/d (at Penrith), with a total of over 600,000 ML over 21 days.

Sydney Water's egeria model indicated that for the different e-flows there was little difference over much of the model period (10 years), and that it was only observable after high flows (beyond the scope of the e-flows) that removed most or all the submerged weed cover.

Based on these two analyses, and observations of smaller flows over the period of the e-flow options assessment, the TWG concluded that flows much larger than those that will be released by e-flows alone are needed to have any measurable impact on the submerged aquatic weeds in the Hawkesbury-Nepean River, and no further analysis of e-flows effects on submerged weeds was undertaken.

Figure 3. Nepean River near the Warragamba River junction. This *Salvinia molesta* bloom extended for several hundred metres behind a weed boom. February 2011.

Figure 4. Submerged weeds - Nepean River near the Warragamba River junction. Thick beds of *Egeria densa* almost completely blocked the channel, with *Salvinia molesta* caught in the surface fronds. March 2009.

2. Methods

2.1. Hydrological models

Three flow models were used in the e-flows analysis: HSPF, Wathnet and IQQM.

1. WaterNSW uses HSPF (Hydrologic Simulation Program Fortran) to model daily tributary inflows to the SCA's storages.
2. WaterNSW uses the HSPF outputs to model dam behaviour and water supply in Wathnet (Generalised Water Supply Headworks Simulation using Network Linear Programming). Wathnet determines how much water will be available for use under varying climatic sequences, population growth models and environmental flow scenarios, and how dam operations and water use will affect the releases from the dams. Wathnet was used to estimate daily releases for each of the e-flow options.
3. These releases were provided to the Department of Industry Water (DoI Water) for inclusion in IQQM (Integrated Quantity and Quality Model), which is used to model river flows, extractions, tributary inputs (from HSPF) to compare the changes in hydrology in the river due to the e-flow options with the Base Case. IQQM does not model tidal exchange, and so can only be used to model the cumulative effects of freshwater inflows, including environmental flows, in the tidal reaches of the Hawkesbury River. DoI Water also modelled a pre-development (no dams, no extraction, no unnatural inflows) flow scenario to aid in analyses.

Outputs were provided for five sites downstream of Warragamba Dam, for the model period 1909 – 2003, and analysed using the RAP (River Analysis Package). RAP was developed by the eWater Cooperative Research Centre to undertake hydrological analyses. It produces a series of metrics based on the flow time series data (or modelled outputs) that have been used to compare the e-flows scenarios. Flow classes were established by the NSW Office of Water to describe the river health benefits of different parts of the hydrograph (Table 2).

Table 2. Flow Classes and their ecological relevance

Flow Class	River Flow Objective	Ecological Relevance
Very low flows <95th percentile	1. Protect water levels in rivers during dry periods	Pool and riffle connectivity Protection of low flow habitat during summer
Low flows 95th – 80th percentile	2. Protect low flows	Provision of variable flows throughout the year Protection of low flow habitat
Moderate flows 80th – 30th percentile	4. Mimic natural flows 7. Maintain rates of rise and fall within natural bounds	Protect and restore a number of moderate flows Barrier inundation, riffle scour, habitat resetting Floating macrophyte removal, minimise pool stratification Reduce risk of cyanobacterial blooms
Freshes 30th – 10th percentile	3. Protect/restore freshes 6. Mimic natural flow variability 9. Minimise impact of instream structures	Freshes transport sediment, nutrients, carbon, increase dissolved oxygen, minimise pool stratification Barrier inundation, riffle scour, habitat resetting Reduce risk of cyanobacterial blooms Maintain / rehabilitate estuarine processes
Floods >10th percentile	9. Restore natural flood variability	Remove instream macrophytes Support healthy riparian zones

The Pre-Development modelled flows were used to determine the percentiles, which formed the basis for the e-flows scenarios and for the hydrological assessments (Table 3).

Table 3. Pre-development flows and flow classes for the Hawkesbury-Nepean and Warragamba rivers. Values in ML/d.

Site	95th %ile (Very low)	80th %ile (Low)	30th %ile (Moderate)	10th %ile (Fresh)
Warragamba River	69	190	1,132	3,397
Penrith Weir	216	391	2,137	7,402
Yarramundi	227	412	2,221	7,665
North Richmond / Windsor	249	449	2,353	8,156
Wilberforce / Sackville	270	486	2,484	8,647

Note – the pre-development 90th percentile for the Warragamba River is 110 ML/d. All e-flows releases use the Warragamba pre-development release percentiles as the transparent volume. The transparency options are:

- 95th percentile, all inflows up to 69 ML/d are released
- 90th percentile, all inflows up to 110 ML/d are released
- 80th percentile, all inflows up to 190 ML/d are released.

A more detailed explanation of transparency and translucency e-flows rules are provided in the MWP 2017.

2.2. Water quality models

Sydney Water has developed a three-dimensional hydrodynamic-water quality model for the Hawkesbury-Nepean River, from the upper Nepean storages to Brooklyn, and including South Creek. The model used a 'representative' 10-year weather/flow period (1986 – 1994), and then used the current (2011) wastewater treatment and population settings to model differing water management settings over time. The four original e-flows scenarios were modelled (Base Case, 90/10, 95/20 and 80/20). Outputs were compared against existing water quality guidelines. The TWG concluded that for some parameters, particularly those parameters used to assess suitability for recreation, the model did not perform well enough to be able to distinguish different e-flows scenarios. In addition, Sydney Water was unable to model additional e-flows scenarios, and so the water quality model had limited application in the e-flows assessment. Sydney Water's water quality model is not a predictive model, and the model's developers have advised that its Base Case predictions cannot be compared with the actual (current) measured condition of the river. This means that the model can only be used to assess relative change between scenarios rather than improvement over the current situation.

A water quality model based on the effects of dilution was developed by the TWG, using water quality measured at several sites between 2005 and 2013, measured river flows, changes in flow expected from the e-flow options, and the measured water quality in Warragamba Dam. The model estimates (daily) water quality by simulating the mixing of a volume of dam release water with river water at sites downstream (Equation 1).

The analyses were undertaken daily from 1 July 2005 to 30 June 2013. The TWG considered this to be a climatically representative period. The data from 2003 and 2004 were discarded due to extreme dry weather conditions over those two years of the Millennium Drought. Table 4 shows an excerpt from the model, which illustrates how the measured daily flows, flow increase factors and water quality results are used to model water quality under the different e-flow options.

Equation 1. Water quality dilution model equation.

$$\text{Predicted water quality} = \frac{\left(\text{Base Case (measured) water quality} \times \text{Base Case (measured) flow}\right) + \left(\text{Predicted flow increase} \times \text{Water quality from dam release}\right)}{\text{(Total) daily flow under environmental flow scenario}}$$

Where

- *Base Case (measured) water quality* was sourced from water quality monitoring undertaken at the assessment sites by Sydney Water and the SCA.
- *Base Case (measured) flow* was sourced from river flow monitoring undertaken at or near the assessment sites by the SCA. Flows at sites within the tidal pool were estimated by summing the volumetric inputs upstream of that location.
- *Predicted flow increase* was calculated on flow-dependant factors determined for each environmental flow option as a function of flow, from the 1909-2003 IQQM flow model (discussed in Section 2.1.2) for the five assessment sites being used in the Abilities analysis.
- *Water quality of dam release* was determined from water quality monitoring of the Warragamba storage.
- *(Total) daily flow under environmental flow scenario* is the sum of the Base Case (measured) daily flow and the predicted (daily) flow increase – for each site and environmental flow option.

Table 4. Excerpt from the dilution model, illustrating flow data and water quality predictions.

FLOW INCREASE FACTORS FRM IQQM												
	Flow %ile	Flow	Base Case	95/20	90/10	80/20						
	100	20.2	1	1.07	1.08	1.08						
	95	124.2	1	1.58	1.70	1.72						
	90	154.6	1	1.54	1.68	1.81						
	80	200.1	1	1.49	1.59	1.89						
	70	239.6	1	1.50	1.54	1.87						
	60	286.9	1	1.51	1.51	1.83	NTU	Guideline value =		10.0	mg/L	
	50	344.1	1	1.53	1.47	1.79		Base case	Base case	95/20	90/10	80/20
	40	436.5	1	1.52	1.42	1.72		lookup				
	30	716.9	1	1.33	1.23	1.44	Complying days		110	113	113	113
	20	2282.3	1	0.98	0.96	0.98	Total result days		117	117	117	117
	10	5469.2	1	1.00	1.00	0.99	% time complying		94%	97%	97%	97%
	5	9766.4	1	1.04	1.00	1.02						
	1	52158.4	1	0.97	0.97	0.94						
DAILY FLOWS												
21/03/2006			119	128	128	128		#N/A	#N/A	#N/A	#N/A	#N/A
22/03/2006			118	127	128	128		#N/A	#N/A	#N/A	#N/A	#N/A
23/03/2006			117	125	126	126		2.00	2.00	1.86	1.85	1.85
24/03/2006			117	126	126	126		#N/A	#N/A	#N/A	#N/A	#N/A
25/03/2006			134	211	227	230		#N/A	#N/A	#N/A	#N/A	#N/A
26/03/2006			153	242	261	263		#N/A	#N/A	#N/A	#N/A	#N/A
27/03/2006			154	244	263	266		#N/A	#N/A	#N/A	#N/A	#N/A
28/03/2006			146	230	248	251		#N/A	#N/A	#N/A	#N/A	#N/A
29/03/2006			139	219	236	239		#N/A	#N/A	#N/A	#N/A	#N/A
30/03/2006			137	216	232	235		#N/A	#N/A	#N/A	#N/A	#N/A
31/03/2006			134	212	229	231		#N/A	#N/A	#N/A	#N/A	#N/A
1/04/2006			132	208	224	226		#N/A	#N/A	#N/A	#N/A	#N/A
2/04/2006			130	205	221	223		#N/A	#N/A	#N/A	#N/A	#N/A
3/04/2006			127	200	216	218		#N/A	#N/A	#N/A	#N/A	#N/A
4/04/2006			124	133	134	134		#N/A	#N/A	#N/A	#N/A	#N/A
5/04/2006			118	127	127	127		#N/A	#N/A	#N/A	#N/A	#N/A
6/04/2006			112	121	121	121		#N/A	#N/A	#N/A	#N/A	#N/A
7/04/2006			111	119	120	120		#N/A	#N/A	#N/A	#N/A	#N/A
8/04/2006			108	116	116	116		#N/A	#N/A	#N/A	#N/A	#N/A
9/04/2006			106	114	114	114		#N/A	#N/A	#N/A	#N/A	#N/A
10/04/2006			105	113	113	113		0.50	0.50	0.47	0.46	0.46

2.3. Fish Migration Models

2.3.1. Fish Eco Modeller

Eco Modeller was used to develop four fish migration models that would generate potential migration scores under each environmental flow scenario, allowing comparison between the scenarios.

The question posed was *Which environmental flow option would provide the greatest opportunities for the passage of Australian bass and Freshwater mullet over the major natural barrier in the river known as Bishops Bench, and how does this compare to the Base Case?*

Each model included a flow trigger that would induce fish to move either up or downstream, a depth at which the barrier becomes impassable to large-bodied fish, score based on the number of days the flow trigger is met or exceeded, and the time of year (when mullet and bass are known to move up or downstream). Input parameters are summarised in Table 5.

Once the models were built, they could be run with any of the e-flow options. The only input required was the modelled flow at either Penrith Weir (for downstream models) or Yarramundi (for the upstream models).

The output is a single number per scenario – the mean daily potential migration score - which can then be compared to the equivalent score for the Base Case, to determine the percent improvement in migration opportunities for each of the e-flow options.

Table 5. Information input to the fish migration Eco Modeller models.

Site	Bass upstream	Bass downstream	Mullet upstream	Mullet downstream
Flow reference site	Yarramundi	Penrith	Yarramundi	Penrith
Commence to move flow ML/d	500	1,040	500	1,040
Cease to move flow ML/d	500	390	500	390
Timing	1/9 – 30/11	20/5 – 30/9	1/2 – 30/4	15/11 – 15/2
Duration score				
Day 1	0.3	0.3	0.3	0.3
Day 2	0.5	0.5	0.5	0.6
Day 3	0.7	0.7	0.7	1.0
Day 4	1.0	1.0	1.0	1.0

2.3.2. Time to catch an Australian bass

Time to catch an Australian bass was determined from information provided from the Bass Catch data (http://www.basssydney.com/index.php/bass-catch). These data were used to determine that the average time taken for an average fisher to catch an Australian bass is 90 minutes. This assumes equal skill across all fishers, that fish do not respond differently to different lures or baits, and that fish are equally distributed along the river. Another major assumption is that if the number of migration opportunities are increased, then the number of fish will also increase.

With 90 minutes as the Base Case, percent improvement in migration opportunities under each scenario was used to determine the reduction in time to catch a bass. That is, the time to catch a bass is the inverse of the improvement. Therefore, if migration opportunities have improved by 40 percent, then the time to catch a bass is:

$$1 / (1+0.4) \times 90 = 64.3 \text{ minutes.}$$

This method was developed for the economic analysis, where a value that was understood by the community, one that the community was willing to pay for, and that was independent of other values (such as weed cover or water quality) was required.

2.4. Floating macrophyte model

2.4.1. Development of the Eco Modeller floating macrophyte model

The TWG focused on the assessment of the benefits that e-flows might provide in reducing the cover of floating weeds. Information on weed cover was gathered from Nearmap images and photographic records. Images were assessed for percent cover of floating weeds at sites between Warragamba Weir and South Creek. Cover was the only attribute assessed, as it was difficult to discern genera from most of the photographs and Nearmap images. Attempts were made to account for external factors that might affect weed cover, such as mechanical harvesting, herbicide application or biological control; however, records of this work were unreliable.

All images from each site were compared sequentially to determine when weeds were present and when they were removed. It was possible to determine weed removal events from images and the hydrograph over the period. Figure 5 and Figure 6 show images of the two stretches of river before and after flow events indicated in Figure 7.

Figure 5. Nepean River downstream of Warragamba River confluence.

On 22 January 2010 (a), floating weeds stretched for several hundred metres of river, caught by a weed boom (behind the photographer). In February there was a small fresh flow with a peak around 12,000 ML/d. On 17 March 2010 (b), the weeds had been removed. Note the weed boom in photo b.

Figure 6. Nepean River at Devlin Road.

On 12 April 2010 there is the presence of floating weeds and algae (a) and following a flow of 1820 ML/d on 6 June 2010, the floating material has been removed (b) (image 30 June 2010).

Scale: 1cm = 50m. Weed and algal build up is visible in the left-hand picture as greenish-brown mats, indicated by the red arrow.

Eco Modeller was used to develop an ecological model to predict relative growth and removal of floating weeds under the Base Case and all the e-flow options. The two components built into the model were flow duration and water temperature. Water temperature was used to develop a simple, generic growth curve that was incorporated to capture growth and decay of floating weeds. Most floating weeds grow well between water temperatures of 15°C – 35°C, with growth rates increasing up to 35°C. This information was used to develop a simple growth rating curve (Figure 8).

Figure 7. Nepean River at Yarramundi – hydrograph for January to June 2010, showing likely weed removal events on 6 February (Penrith Weir) and 6 June (e.g. Devlin Road).

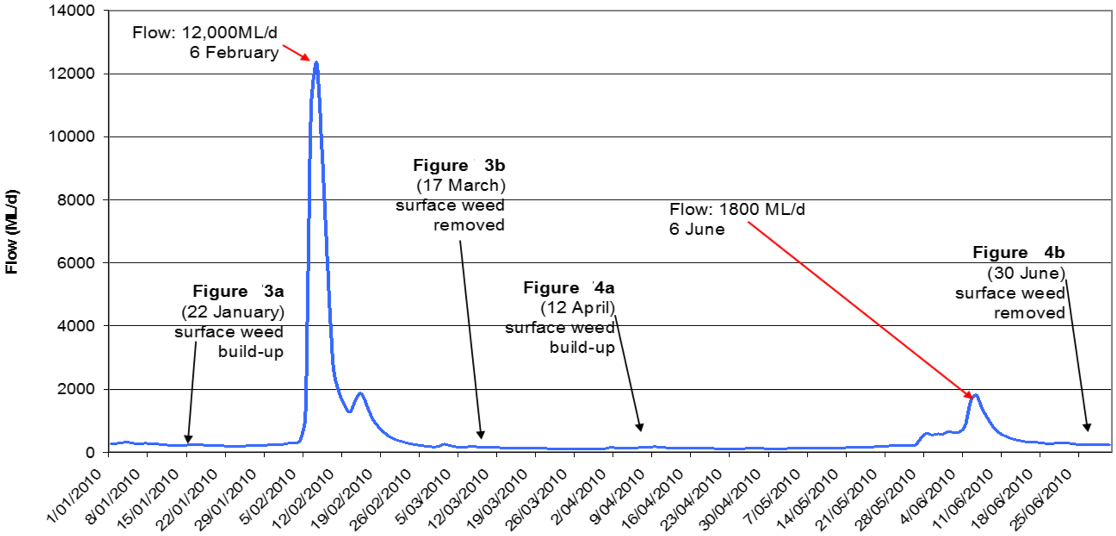
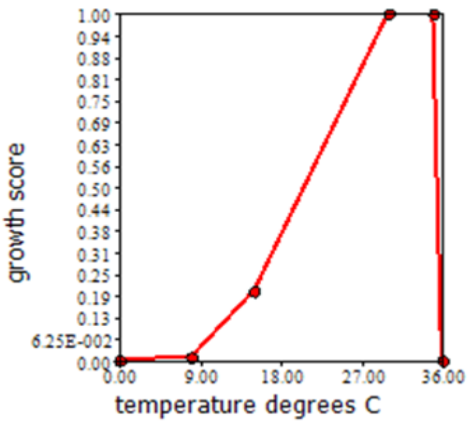


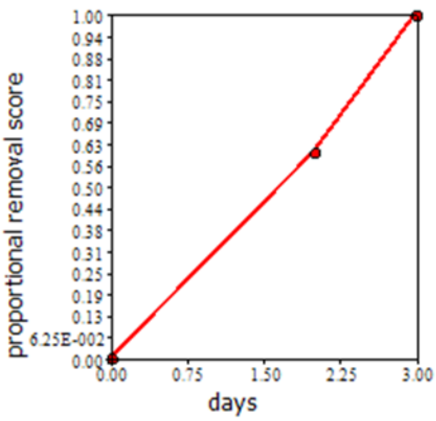
Figure 8. The floating weed growth rating curve in Eco Modeller.



X	Y
0	0
8	0.01
15	0.2
30	1
35	1
36	0

An event duration curve was included to identify periods of better / more effective weed removal. Using the flow threshold of 3,000 ML/d as the requirement to move floating aquatic weeds, and a duration of three days and over providing complete weed removal, the event duration curve was developed (Figure 9).

Figure 9. The floating weed removal event duration curve in Eco Modeller.



X	Y
0	0
2	0.6
3	1

The floating weed model takes into consideration weed growth and the number of flow events over 3,000 ML/d. It also assesses and compares the length of those events, the timing of events (events in summer are more likely to remove weeds as there is more likely to be weed growth in summer than in winter), frequency (for example, one per summer vs three per summer) and interval between events (which gives the weeds time to re-establish or not, following the previous event) for each of the e-flow options.

This output from the floating weed model was then analysed in MS Excel. The daily growth score was used as a substitute for percent cover of weeds, and the TWG determined that 30 percent floating weed cover was unacceptable in terms of visual and physical impacts on the river (e.g. reducing amenity for boating and swimming).

Initially, one model run was undertaken with real flow data from Yarramundi to compare the outputs of the model with changes in weed cover. Photographs and Nearmap images between 2007 and 2011 were examined to determine percent cover of floating weeds at Devlin Road, Coolamon Road and Yarramundi. The daily growth scores from the model run showed reasonable agreement with the photographic record, with a 73 percent match between photos classed as under 30 percent cover, and model outputs that indicated a growth score of less than 30 percent. Visual assessment of images by the TWG indicated that above 30 percent cover of aquatic weeds there were likely to be negative impacts on river ecology and river use.

A threshold of 30 percent weed cover, indicated by a daily growth score of over 30 from the model, was accepted as an indicator of an event.

Daily modelled flows from IQQM at four sites (Penrith, Yarramundi, North Richmond, and Windsor) were used to assess the Base Case and all e-flow options. This output was then analysed in MS Excel, to provide the metric "number of days over the threshold" as an indicator of differences between e-flow options and to enable comparison of each option against the Base Case.

Other metrics were developed (for example, average event length, peak cover score and reduction in the number of event days); however, the TWG considered that the number of days over the threshold was the most appropriate metric to compare scenarios.

For the economic analysis, an estimate of the worst cases of floating weed infestations on record was needed in kilometres. This was done by looking at past records and estimating cover and length of infestation (Table 6). This provided a worst-case scenario from which the predictive comparisons could be made to get a better appreciation of how environmental flows would benefit the river at these times. The percent improvement over the Base Case for each of the environmental flow scenarios was then used to determine the likely reduction in river length impacted by weed infestation under each scenario.

Table 6. Estimates of past floating weed infestations.

Reach	Length of reach	Date of worst weed infestation	Percent cover of weed infestation	km of blooms
19b	1.7		0	0
20	12.7	2012	10	1.27
21	5.4		0	0
22	18.9	2003-04	90	17.01
23	24.8	2003-04	90	22.32
24	37	2003-04	30	11.1
TOTAL	**100.5**			**51.7**

3. Results

3.1. Comparison of the different e-flow options to the Base Case

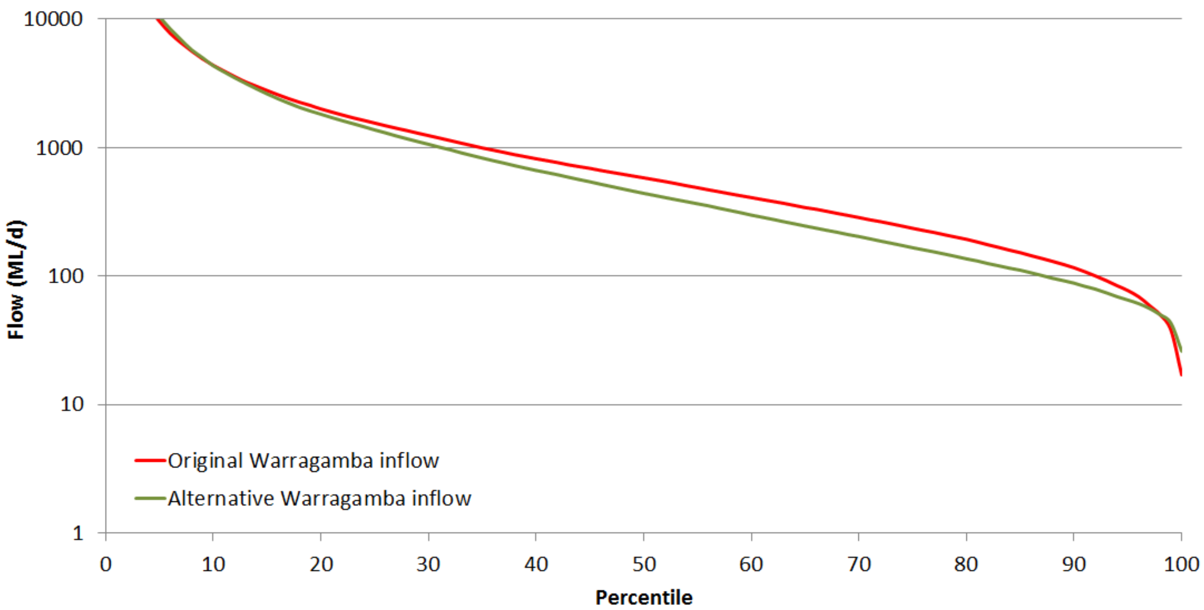
For each round of Wathnet modelling some of the assumptions, such as demand and population, changed. However, for each round, a Base Case was also modelled and so while the different e-flows scenarios cannot be compared to a single modelled Base Case, each can be compared to the Base Case run at the same time as the options.

The original e-flow options analysis showed that 80/20 and 95/20 were too 'expensive' in terms of water use and so these were rejected in favour of the 90/10 (no scaling, no halving).

Flood management options (FMOs) focused on the changes that might be seen under various operational, dam height, and e-flow options. The main result of these analyses was that if the dam were raised 14m for flood mitigation, the number and frequency of small spill events would be reduced. This resulted in a FMO +14m that was ecologically worse than the current dam height.

By the time the alternative e-flows were modelled, the Warragamba Dam inflow had been revised using a new rainfall-runoff model, and inflows below the 10th percentile were reduced (Figure 10). The Base Case was further modified for the 2018 e-flow options. Because of the revision of the Base Case over time, direct comparison of the results from the original e-flows analysis, the 2017 and 2018 analyses was not appropriate. For each round of assessments, the matched Base Case was used.

Figure 10. Comparison of the original modelled inflows to Warragamba Dam with the revised inflows used in the 2017 alternative environmental flow analyses. Only flows up to 10,000 ML/d are graphed.



3.2. Hydrology

3.2.1. Warragamba River

The Warragamba River is likely to see the biggest improvement in hydrology, given that the river below the dam currently only receives water from dam seepage, spills and local catchment run-off. Warragamba Weir is bypassed on the western abutment by a tunnel. Daily flows of 17 ML/d (winter) and 22 ML/d (summer) are released from Warragamba Pipeline No. 1 into Megarritys Creek, downstream of Warragamba Weir for drinking water supply at North Richmond. An additional 5 ML/d is also released as a dilution flow to mitigate the impacts of the Wallacia WWTP, which discharges into the Warragamba River just downstream of Megarritys Creek, into the top end of the Penrith Weir pool. This further impacts the hydrology of the river. Figure 11 to Figure 13 show the modelled flow duration curves for the e-flows scenarios. Figure 11 shows the original e-flows scenarios plus the pre-development scenario modelled. Figure 12 shows the alternative e-flows scenarios that were modelled for the 2017 Metropolitan Water Plan, and Figure 13 shows the 2018 e-flows scenarios.

Most of the improvements will be seen up to around 1,000 ML/d. The most obvious difference between the original and 2018 model outputs are the Base Case. The hydro power plant operation was included in the original model, which reduced the benefits of the e-flow options as more water was released from the dam for hydro electricity generation when the dam was full, or close to full. This means that there was little difference above the 20th percentile flow (~1000 ML/d). The hydro operation was removed for the 2017 and 2018 e-flows runs, and consequently the latter two Base Case runs have less water than the e-flow options up to around the 10th percentile. Above this, spills begin to influence the flow duration curves. Given that the three e-flow options originally modelled were rejected due to too much water use, they will not be discussed further in this report. Focus will be on the 2017 alternative e-flow options analysed for the Metropolitan Water Plan and the 2018 e-flow options.

Figure 11. Warragamba River - flow duration curves for the original Base Case, three e-flows scenarios and the pre-development scenario

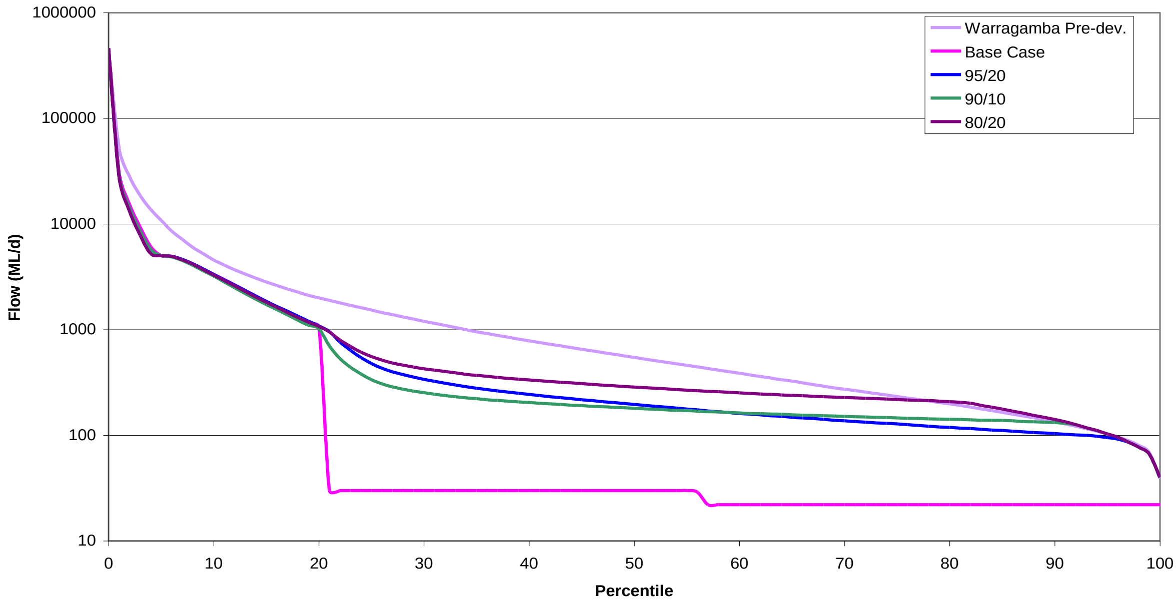


Figure 12. Warragamba River - flow duration curves for the alternative e-flow options modelled for the 2017 Metropolitan Water Plan

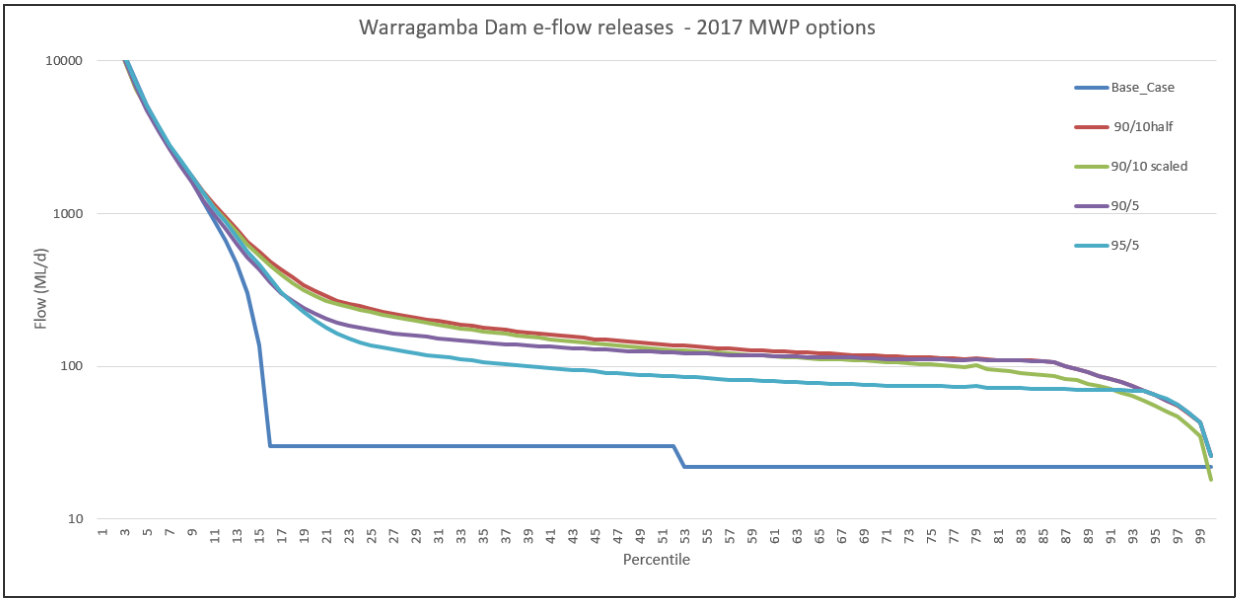
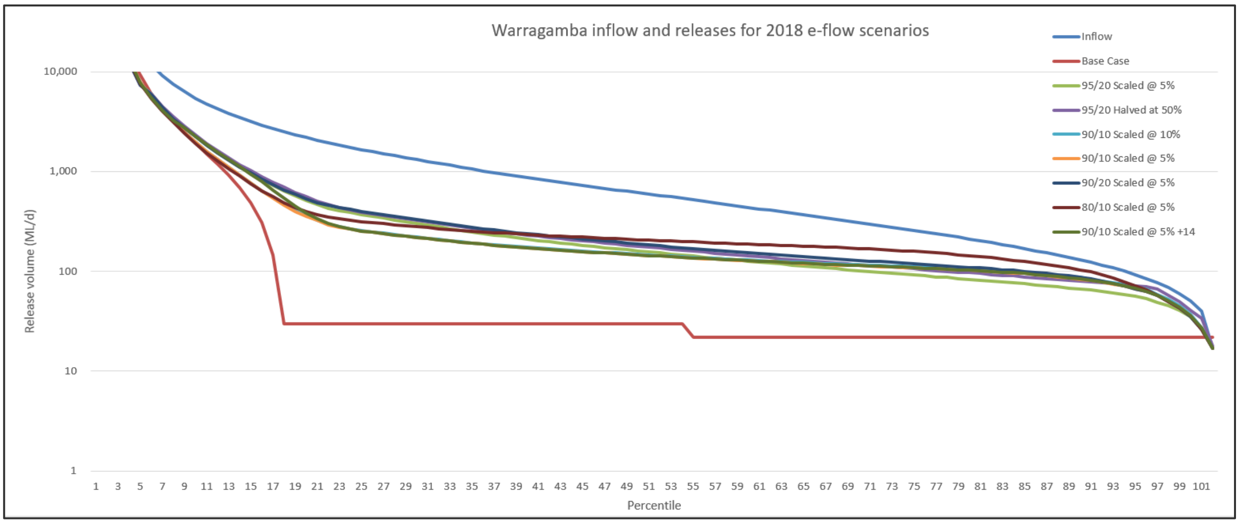


Figure 13. Warragamba River - flow duration curves for the seven 2018 e-flow options



Assessment of the percent of days in each flow class shows that under all models, the Base Case has over 80 percent of days in the very low flow class, and the e-flow options all have more days in the low and moderate flow classes (Figure 14). There is little difference between the 90/10 half and 90/10 scaled options, however the two options with the lower translucency have more days in the low flow class (around 70 percent) and fewer days in the moderate flow class than the two 90/10 options.

A very similar pattern is seen in the 2018 e-flow options (Figure 17).

Figure 14. Warragamba River - proportion of days in each flow class for the 2017 MWP e-flows rules

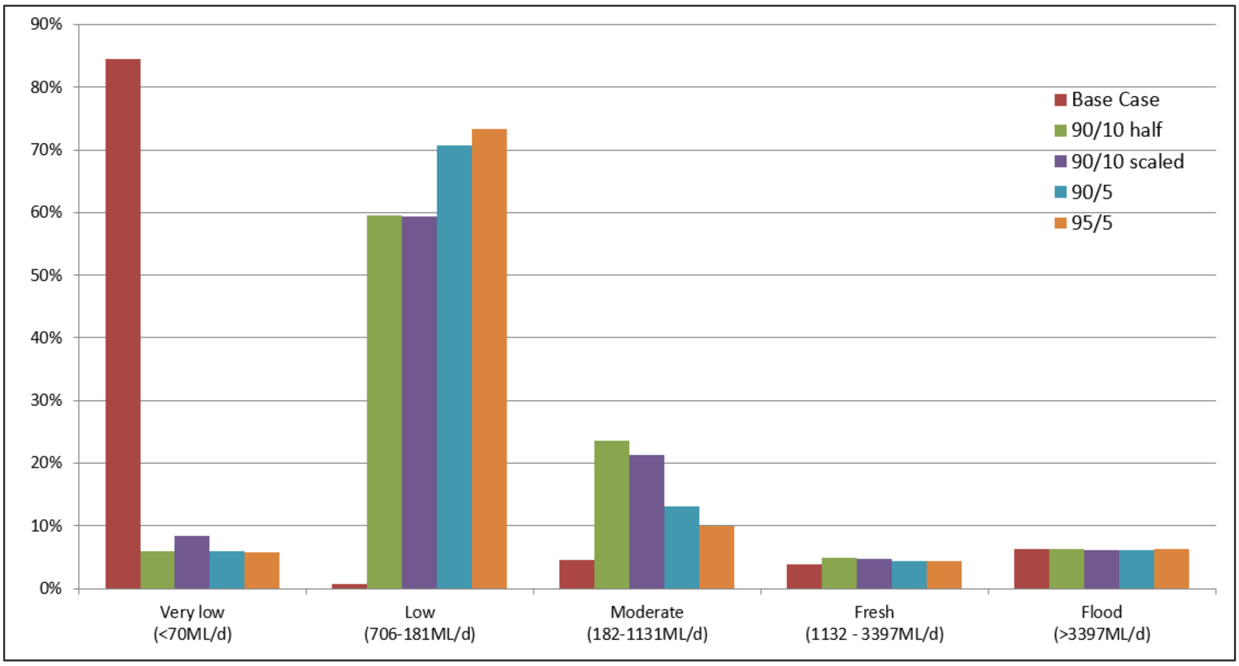
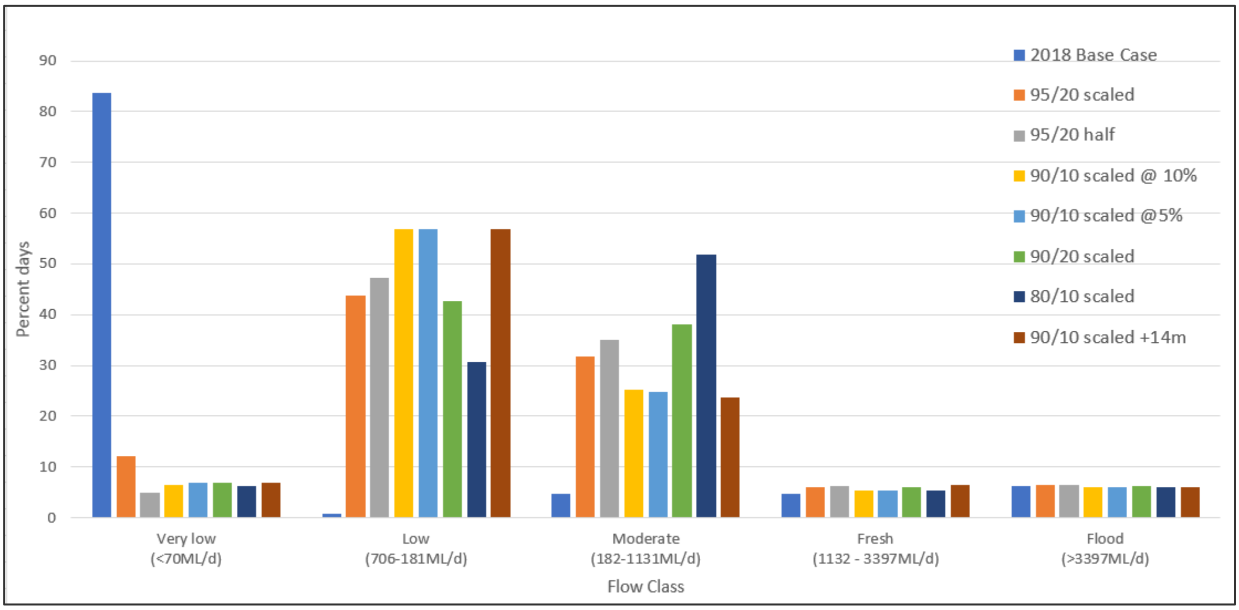


Figure 15. Warragamba River - proportion of days in each flow class for the 2018 e-flows rules



3.2.2. Nepean River at Penrith Weir

The flow at Penrith Weir and all points downstream is influenced by Nepean River flows, tributary inflows, extractions, wastewater discharges and Warragamba dam releases. The 2017 and 2018 flow duration curves for Penrith Weir are similar, with the Base Case clearly separated from all options up to around 1000 ML/d for the 2017 e-flows, and 1500 ML/d for the 2018 options (Figure 16, Figure 17). The higher 'merge' point in 2018 is due to the higher volumes being released under these options compared to the 2017 options. In the 2018 e-flow options there is little difference between the options above 1,000 ML/d, and that the 'matched' options (for example, 95/20 scaled and 90/20 halved) are indistinguishable (Figure 17).

Figure 16. Nepean River at Penrith Weir - flow duration curves for the 2017 MWP e-flow options

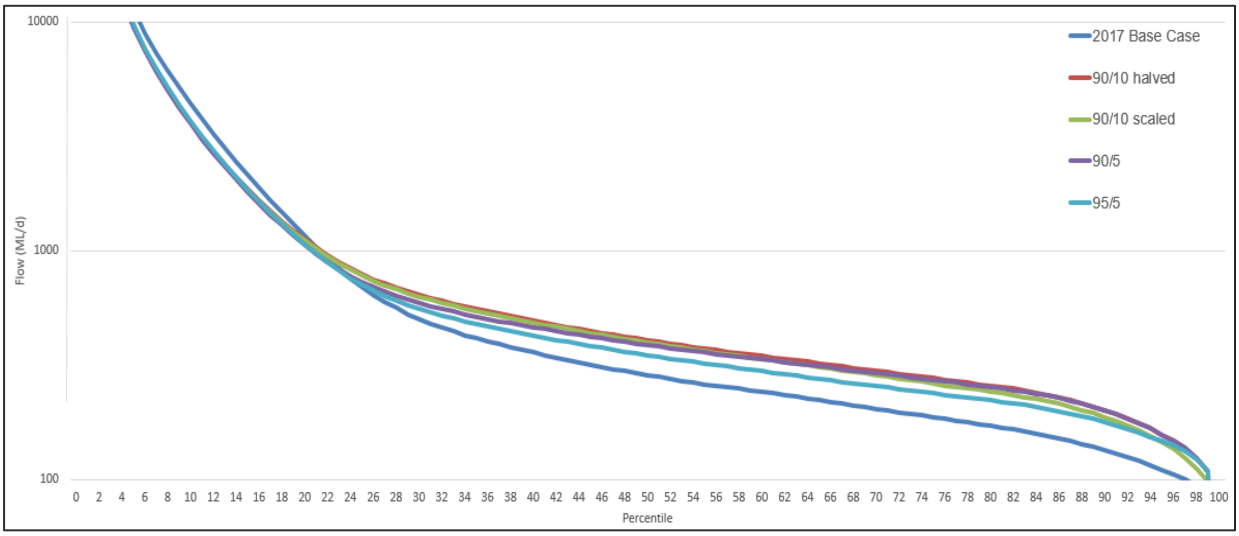


Figure 17. Nepean River at Penrith Weir - flow duration curves for the 2018 e-flow options

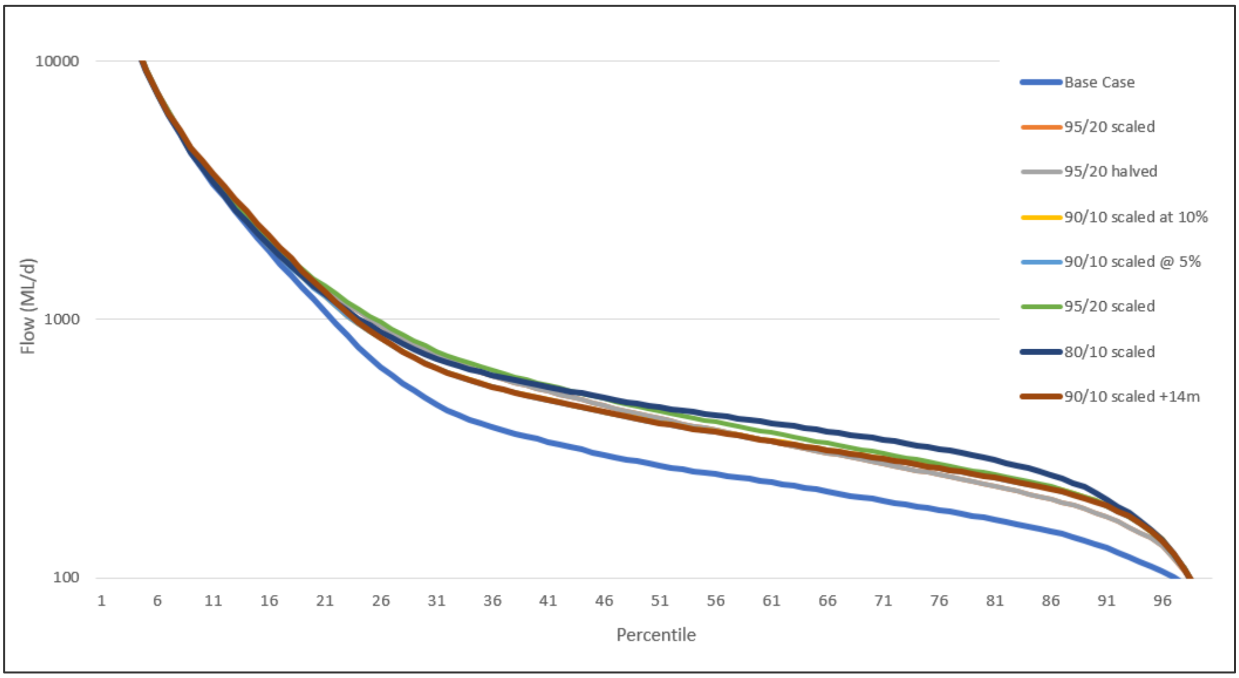


Figure 18 shows a comparison of the percent of days in each flow class for the 2017 e-flows compared to the Base Case at Penrith. There is up to 20 percent fewer days in the very low flow class for all the e-flow options. There is very little difference between halved and scaled options (around 2 percent). The 90/10 options provide more water in the Moderate flow classes than the options with the lower translucency, due to the higher transparency volume for the 90th percentile.

The 2018 options show a similar pattern as the 2017 options. The 90/10 options are similar and raising the dam wall makes no obvious difference (Figure 19). The options with the higher translucency (20 percent) have fewer days in the low flow class and more in the moderate flow class than those with the lower translucency (10 percent). All e-flow options have fewer days in the very low flow class.

Figure 18. Nepean River at Penrith Weir – percent of days in each flow class for the 2017 MWP e-flow options.

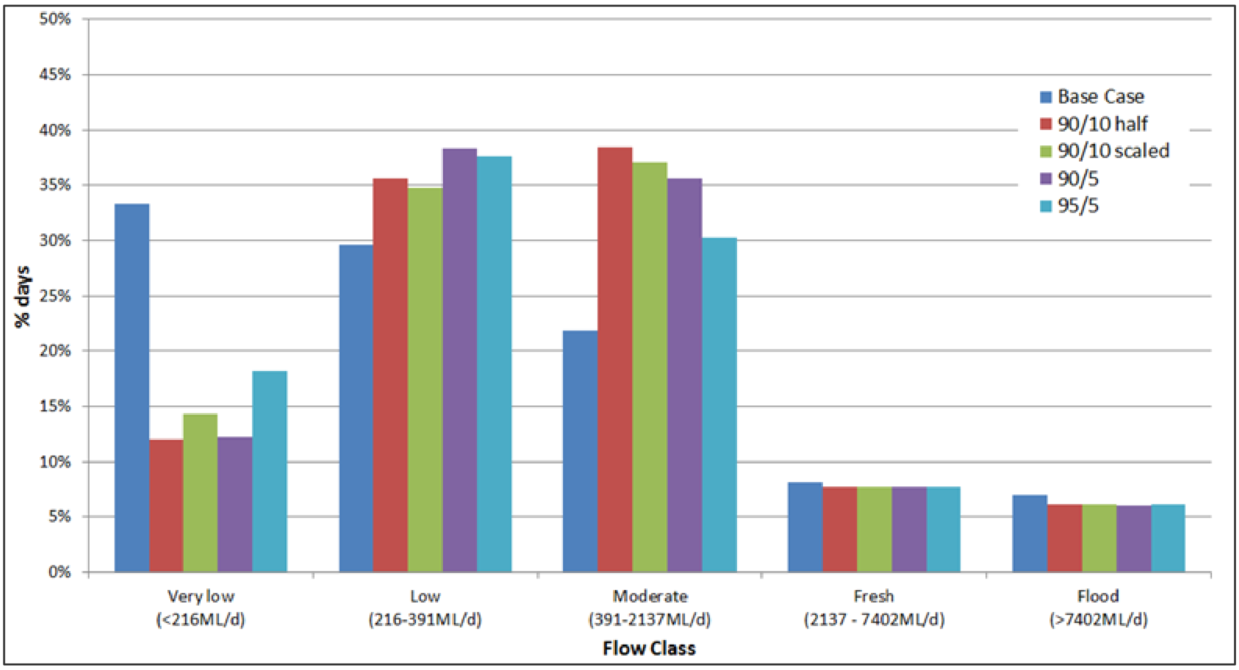
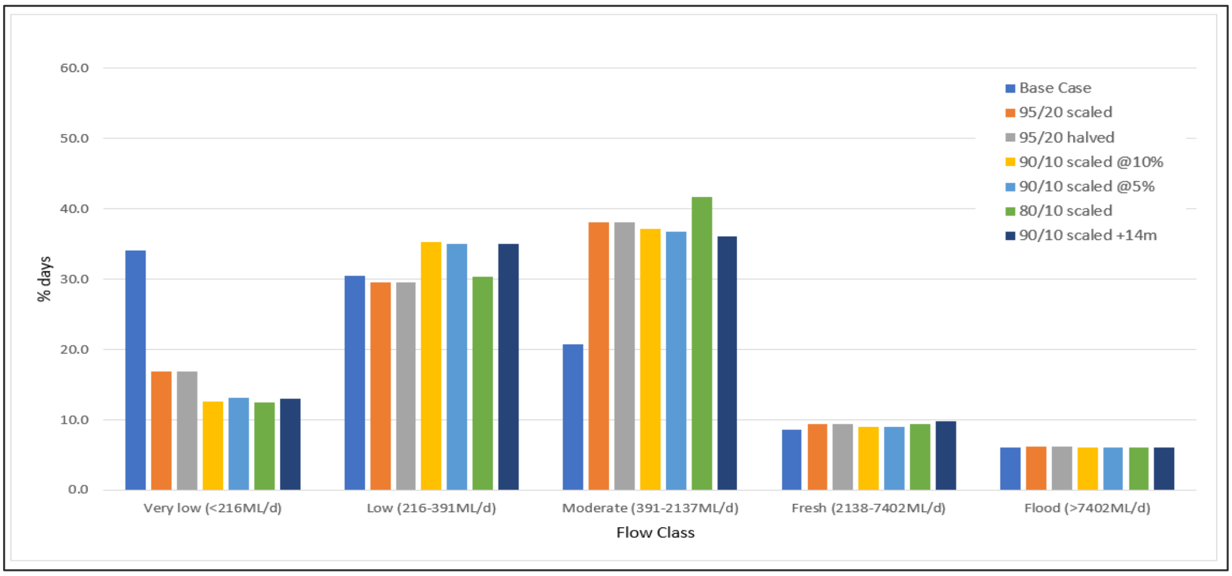


Figure 19. Nepean River at Penrith Weir - percent of days in each flow class for the 2018 e-flow options



The 2017 MWP e-flow options were analysed in e-Water's River Analysis Package (RAP) and the major differences between the 2017 MWP e-flow options are presented in Table 7.

Table 7. Nepean River at Penrith Weir - RAP analysis results the 2017 MWP e-flows scenarios.

Penrith	Base Case	90/10 half	90/10 scaled	90/5	95/50
Mean	2,882	2,931	2,921	2,915	2,947
Median	286	408	398	387	350
95th percentile	111	158	145	158	148
80th percentile	172	258	244	256	222
30th percentile	502	643	631	590	557

The same analysis was undertaken for the 2018 e-flow options, and the results are presented in Table 8.

Table 8. Nepean River at Penrith Weir - RAP analysis results for the 2018 e-flows scenarios.

Penrith	Base Case	95/20 scaled	95/20 half	90/10 scaled @ 10%	90/10 scaled @ 5%	90/20 scaled	80/10 scaled	90/10 scaled +14m
Mean	2,751	2,803	2,804	2,789	2,789	2,812	2,803	2,810
Median	277	422	422	406	404	450	465	404
95th percentile	111	143	143	153	151	151	154	152
80th percentile	171	232	232	251	248	256	292	249
30th percentile	497	763	763	680	678	791	735	679

3.2.3. Nepean River at Yarramundi

The flow duration curves for the 2017 MWP options show little difference in the e-flows above 1,000 ML/d (Figure 20). The flow duration curves for the 2018 e-flow options (Figure 21) shows there is little difference between the options above 1,700 ML/d.

There is little difference between halved and scaled options. However, at Penrith the 95/20 options provide more water in the Moderate and Fresh flow classes than the 90/10 options, and at Yarramundi there is little difference between them. Raising the dam wall makes little difference to the days in each flow class for the 90/10 options. The 80/10 scaled option has up to 10 percent more days than the other e-flow options in the Moderate flow class.

Figure 20. Nepean River at Yarramundi - flow duration curves for the 2017 MWP e-flow options

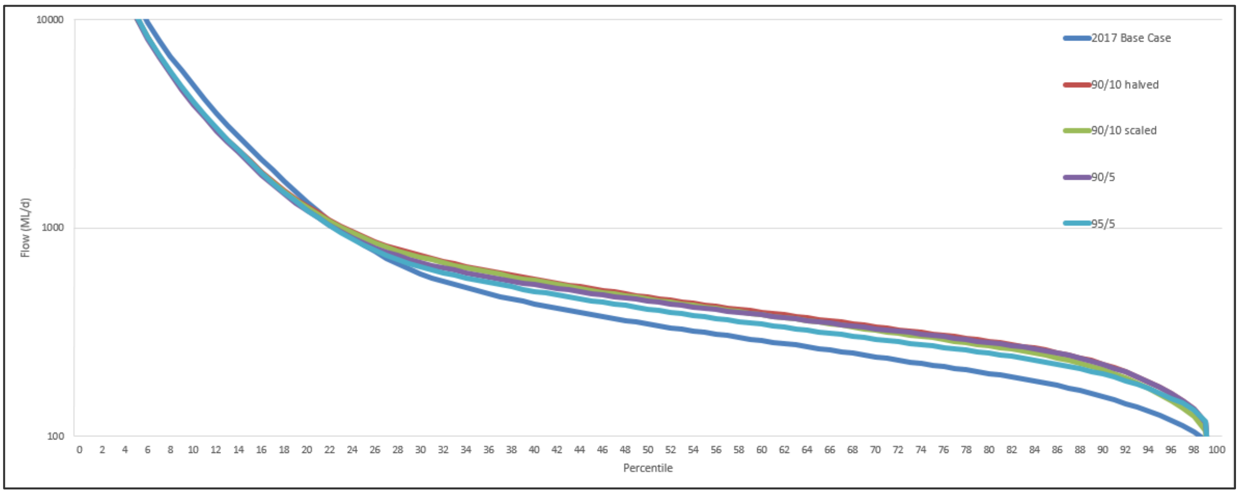


Figure 21. Nepean River at Yarramundi - flow duration curves for the 2018 e-flow options

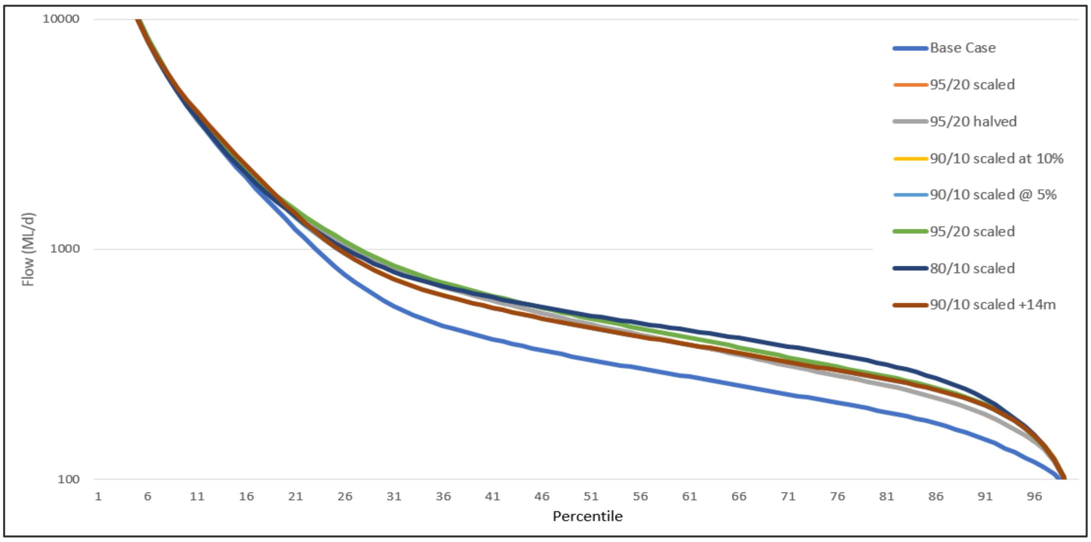


Figure 22. Nepean River at Yarramundi - percent of days in each flow class for the 2017 MWP e-flow options

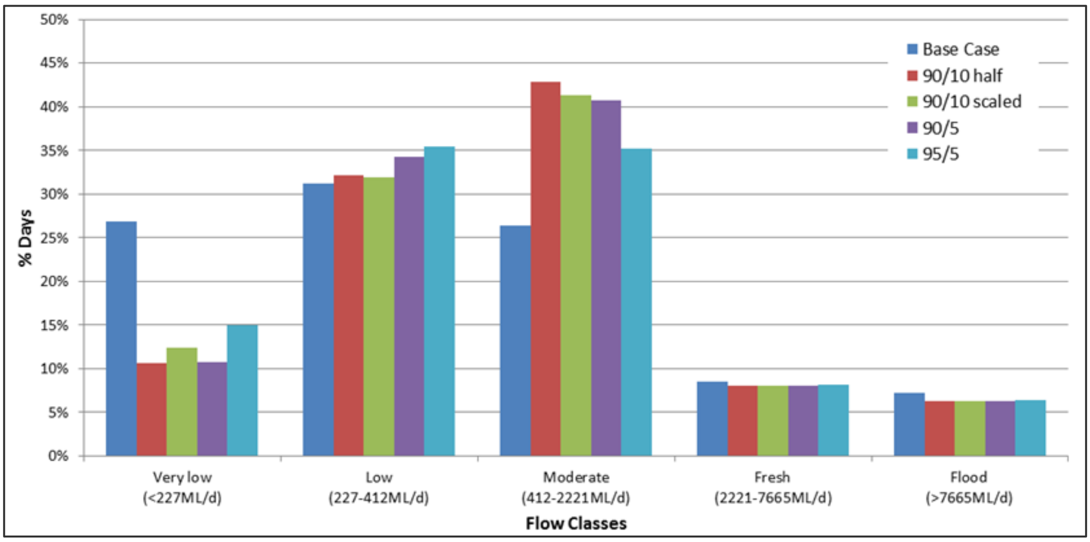


Figure 23. Nepean River at Yarramundi - percent of days in each flow class for the 2018 e-flow options

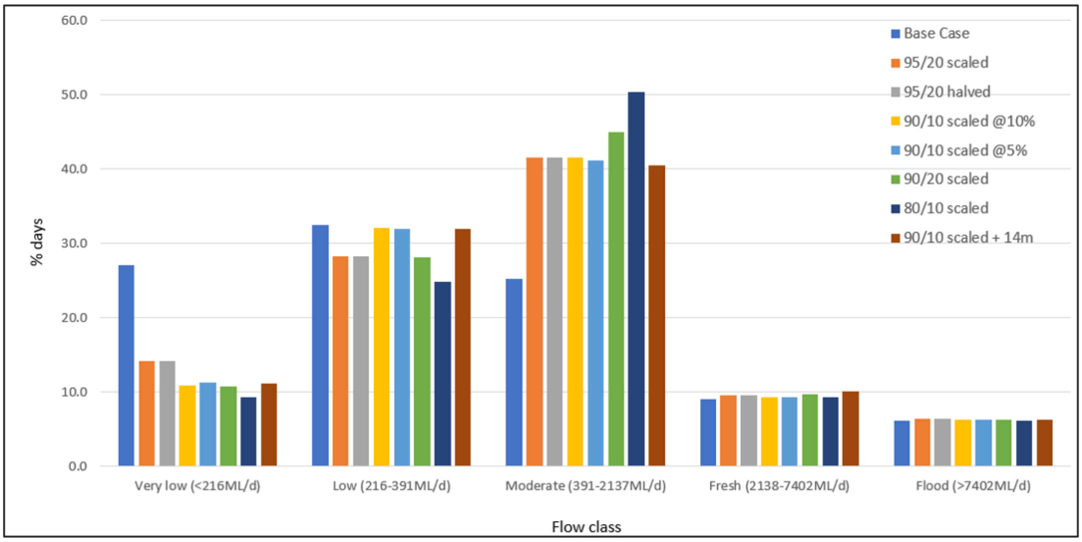


Table 9. Nepean River at Yarramundi - RAP analysis results for the 2017 MWP e-flows scenarios.

Yarramundi	Base Case	90/10 half	90/10 scaled	90/5	95/5
Mean	3,084	3,133	3,122	3,116	3,148
Median	346	466	456	446	408
95th percentile	126	172	159	182	161
80th percentile	201	285	271	282	250
30th percentile	602	735	725	685	652

Table 10. Nepean River at Yarramundi - RAP analysis results for the 2018 e-flows scenarios.

Yarramundi	Base Case	95/20 scaled	95/20 half	90/10 scaled @ 10%	90/10 scaled @5%	90/20 scaled	80/10 scaled	90/10 scaled +14m
Mean	2,996	3,050	3,050	3,035	3,035	3,059	3,049	3,056
Median	337	483	483	466	463	510	524	464
95th percentile	126	157	157	171	169	169	172	169
80th percentile	202	264	264	283	280	288	325	281
30th percentile	598	861	861	779	775	890	834	776

The Base Case in both 2017 and 2018 e-flow options has between 25 and 30 percent of days in the very low flow class, and proportionally fewer days in the moderate flow class. All the e-flow options provide a higher proportion of days in the low and moderate classes. There is little difference in the percent of days in each class for the various 90/10 options – changing when releases are modified due to storage levels (5 or 10 percent) has little impact on time in different flow classes. Similarly, raising the dam wall without changing the operation has no observable impact on the e-flows releases.

3.2.4. Hawkesbury River at Windsor

At Yarramundi, the Grose and Nepean rivers join to form the Hawkesbury River, which is tidal up to Yarramundi. Tributary inflows at this section of the river further muted low flow impacts under the Base Case as well as the increased flows from Warragamba Dam under the various e-flows scenarios.

For both the 2017 and 2018 e-flow options, the Base Case and the e-flows converge around 1,800 ML/d (Figure 24, Figure 25). All e-flow options have higher flows than the Base Case up to around the 15th percentile.

Figure 24. Hawkesbury River at Windsor – flow duration curves for the 2017 MWP e-flow options

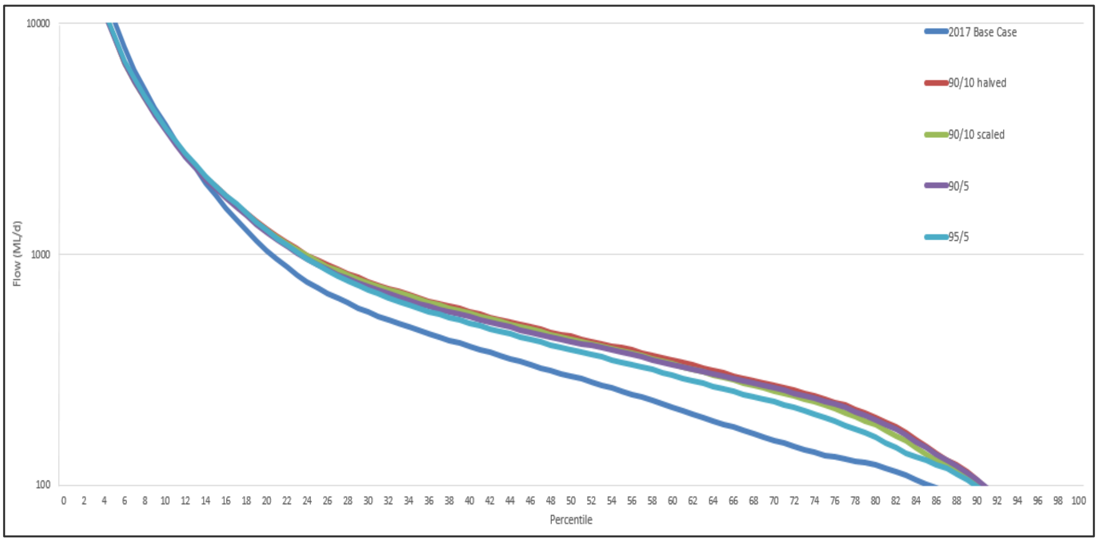
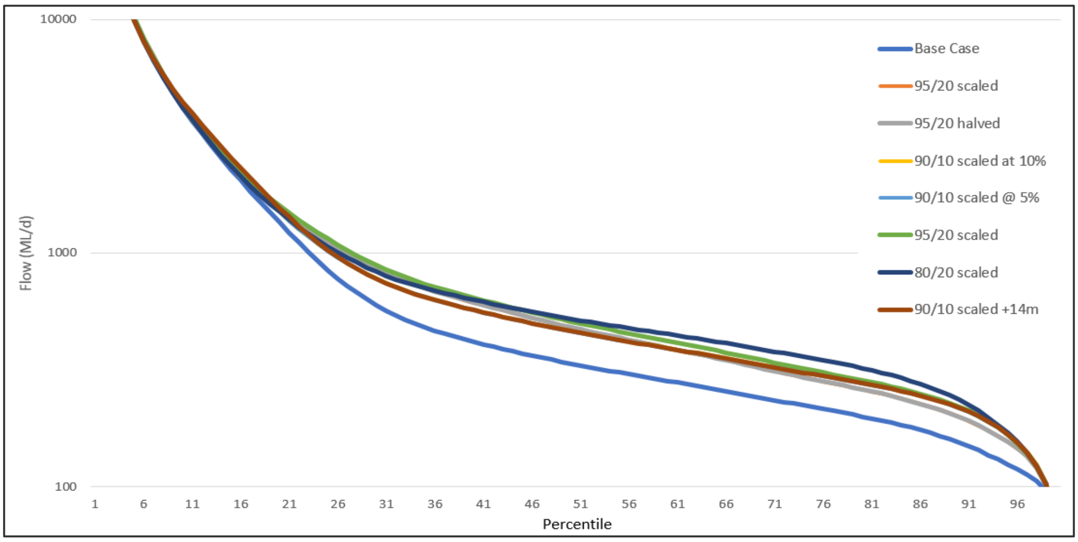


Figure 25. Hawkesbury River at Windsor - flow duration curves for the 2018 e-flow options



The flow classes for the 2017 MWP e-flows at North Richmond show a similar pattern to the other sites (Figure 26). There is still a clear distinction between the Base Case and the e-flow options in both the 2017 and 2018 e-flow options in the very low flow class (Figure 26, Figure 27). The 80/10 e-flows option provides the highest proportion of days in both the low and moderate flow classes (Figure 27).

Figure 26. Hawkesbury River at Windsor - percent of days in each flow class for the 2017 MWP e-flow options

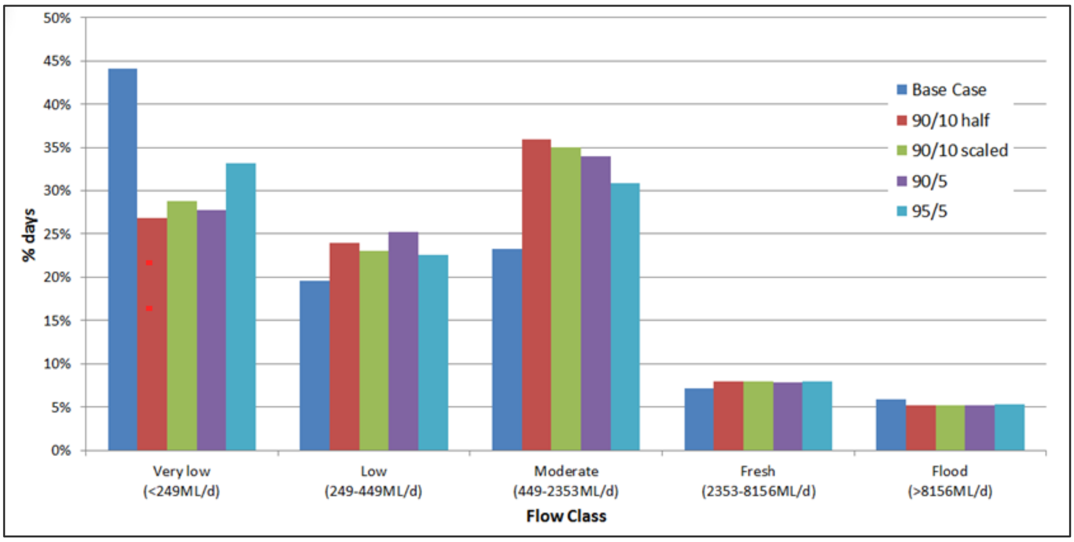


Figure 27. Hawkesbury River at Windsor - percent of days in each flow class for the 2018 e-flow options

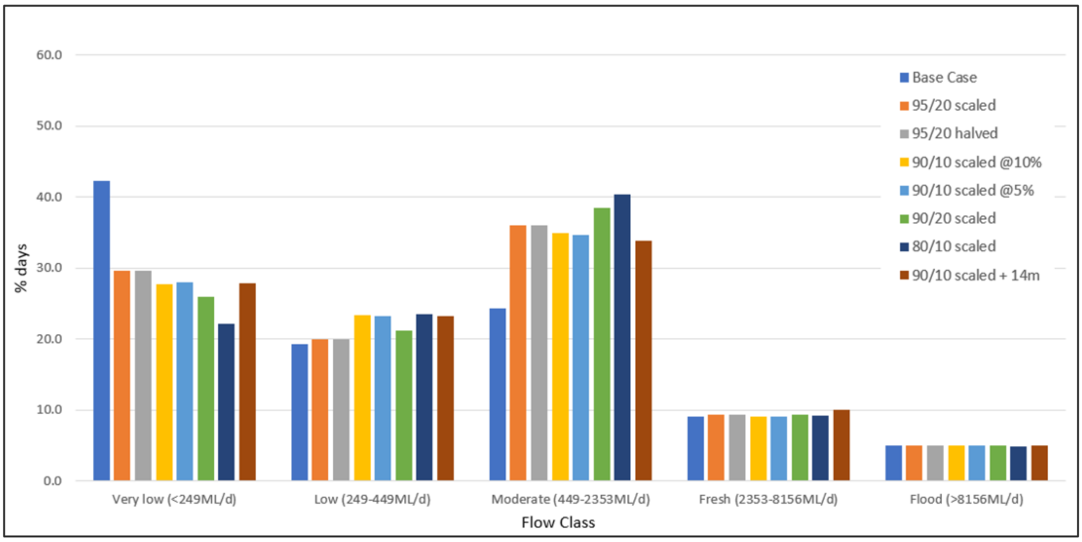


Table 11. Hawkesbury River at Windsor - RAP analysis results for the 2017 MWP e-flows scenarios.

Windsor	Base Case	90/10 half	90/10 scaled	90/5	95/5
Mean	2,388	2,090	2,079	2,067	2,086
Median	297	441	430	420	386
95th percentile	74	77	77	77	77
80th percentile	122	197	182	192	161
30th percentile	562	764	753	723	701

Table 12. Hawkesbury River at Windsor - RAP analysis results for the 2018 e-flows scenarios.

Windsor	Base Case	95/20 scaled	95/20 half	90/10 scaled @ 10%	90/10 scaled @5%	90/20 scaled	80/10 scaled	90/10 scaled +14m
Mean	1,926	2,009	2,009	1,987	1,985	2,021	2,007	2,078
Median	312	454	454	438	436	482	493	467
95th percentile	74	74	75	75	77	77	77	77
80th percentile	126	172	172	192	189	199	229	189
30th percentile	650	869	869	798	896	895	846	801

3.2.5. Hawkesbury River at Wilberforce

South Creek flows into the Hawkesbury River just downstream of Windsor. At Wilberforce, downstream of South Creek, there are only small differences between Wilberforce and Windsor. The e-flow options are still distinguishable from the Base Case in both the 2017 and 2018 e-flows modelling.

The flow duration curves for the 2017 MWP e-flow options shows that the 95/5 option provides the least amount of water over the bottom of the flow duration curve, with the other three options generally indistinguishable over most of the curve. The curves merge with the Base Case at around the 16th percentile (Figure 28). This is similar to the 2018 options, which converge around the 20th percentile (Figure 29).

All e-flow options provide more days in the low and moderate flow classes (Figure 30, Figure 31). The 95/5 has more days in the very low flow class than any other e-flows option, and the 95/20 options provide less water in the moderate flow classes than the 90/10 options. As at the other sites, there is little difference between halved and scaled options. Raising the dam wall makes little difference to the days in each flow class for the 90/10 options.

Figure 28. Hawkesbury River at Wilberforce – flow duration curves for the 2017 MWP e-flow options

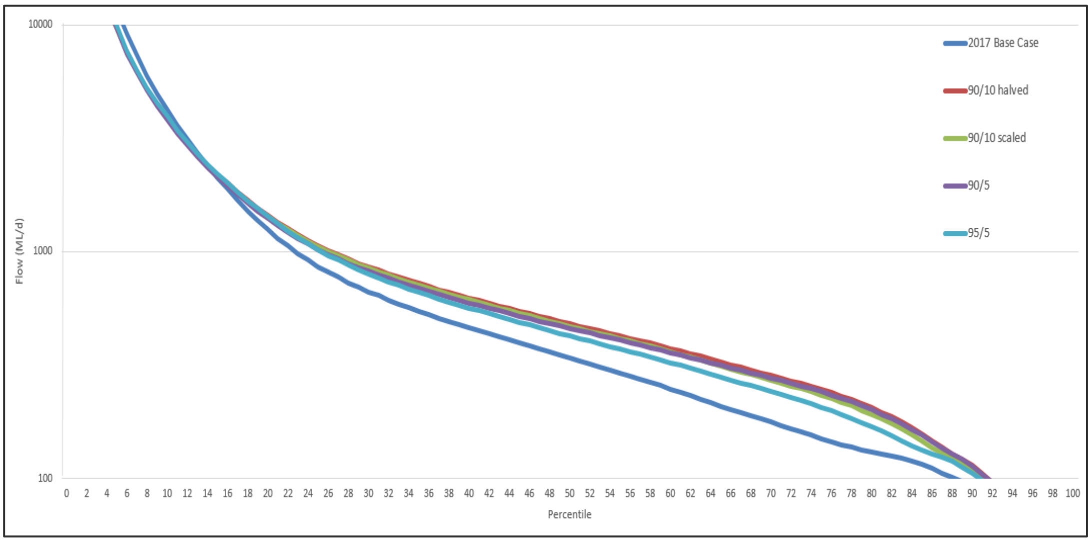


Figure 29. Hawkesbury River at Wilberforce – flow duration curves for the 2078 e-flow options

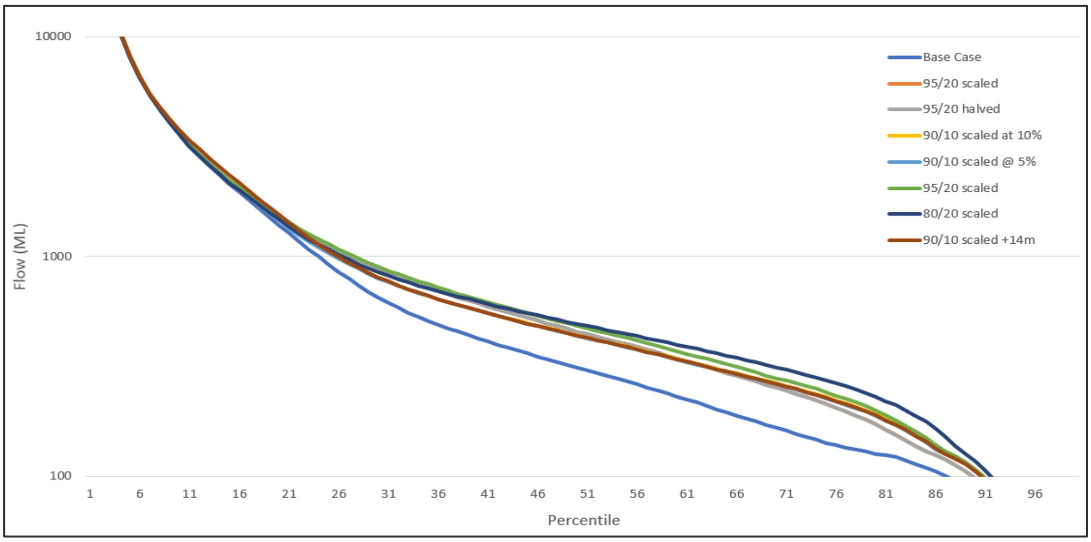


Figure 30. Hawkesbury River at Wilberforce - percent of days in each flow class for the 2017 MWP e-flow options

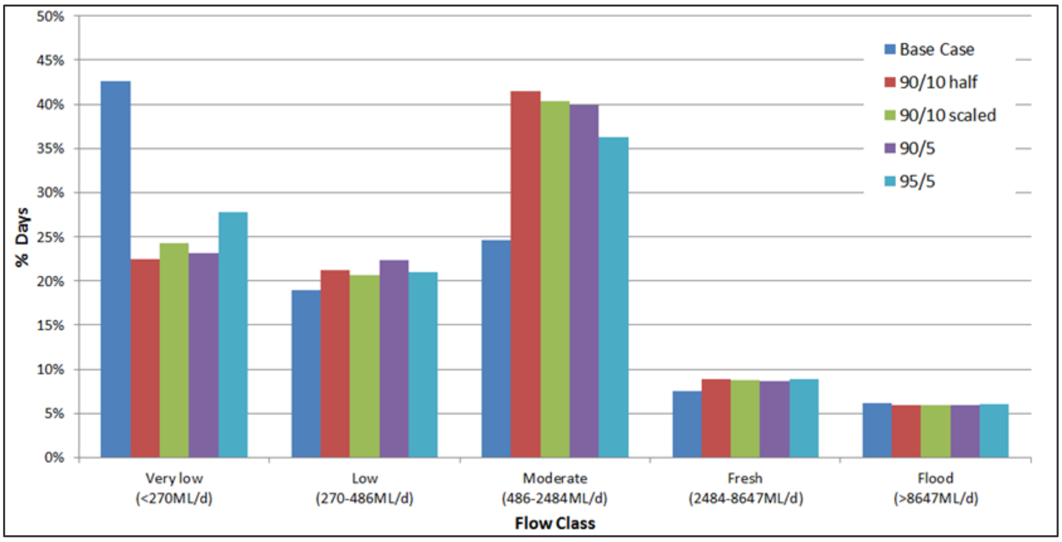


Figure 31. Hawkesbury River at Wilberforce - percent of days in each flow class for the 2018 e-flow options

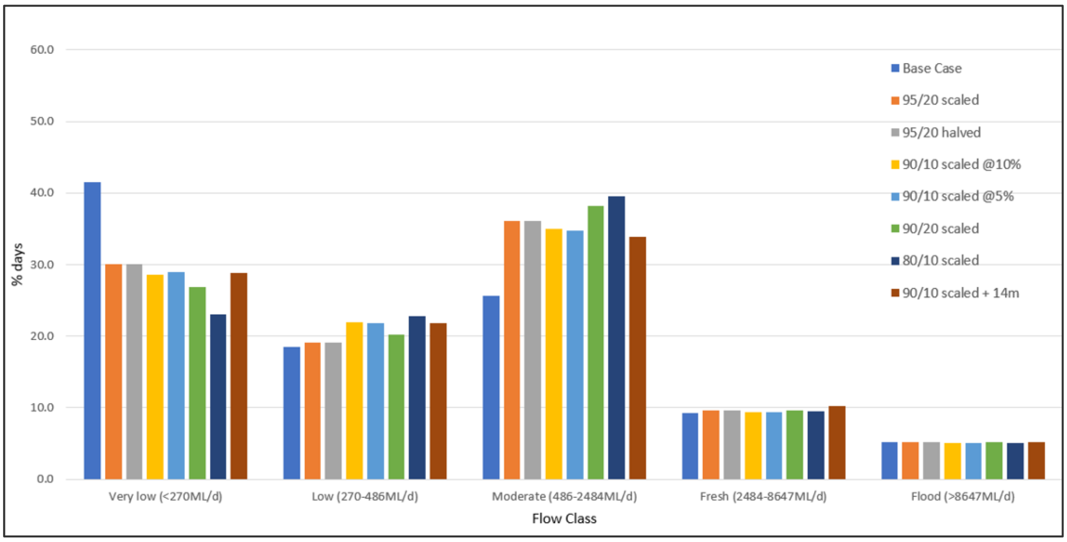


Table 13. Hawkesbury River at Wilberforce - RAP analysis results for the 2017 MWP e-flows scenarios.

Wilberforce	Base Case	90/10 half	90/10 scaled	90/5	95/50
Mean	2,640	2,342	2,331	2,319	2,339
Median	339	480	169	459	425
95th percentile	76	80	79	80	79
80th percentile	131	206	192	201	169
30th percentile	665	856	846	817	798

Table 14. Hawkesbury River at Wilberforce - RAP analysis results for the 2018 e-flows scenarios.

Wilberforce	Base Case	95/20 scaled	95/20 half	90/10 scaled @ 5%	90/10 scaled @10%	90/20 scaled	80/10 scaled	90/10 scaled +14m
Mean	1926	2009	2009	1986	1985	2020	2007	2078
Median	312	454	454	438	436	481	493	437
95th percentile	111	143	143	153	151	151	154	152
80th percentile	171	232	232	251	248	256	292	249
30th percentile	497	763	763	680	678	791	735	679

3.3. Water Quality

3.3.1. Penrith and Yarramundi

The water quality dilution model described in the methods section was used to assess both the 2017 MWP e-flow options and the 2018 e-flow options. For the 2017 options, there was up to a 5.0km improvement in length of river suitable for swimming (Table 15). For the 2018 e-flow options, improvements between 4.4km and 6.2km are expected (Table 16).

Table 15. Improvement in river length swimmable over the Base Case for the 2017 MWP e-flow options.

2017 MWP e-flow options	Kilometres improvement	Total swimmable kilometres
Base Case		36.9
90/10 half	5.0	41.9
90/10 scaled	4.2	41.2
90/5	4.6	41.5
95/5	3.9	40.8

Table 16. Results of water quality analyses – percent compliance and kilometre change for all scenarios, compared to the Base Case for the 2018 e-flow options

<table>
<tr><th>Scenario</th><th>Site</th><th>% time compliant</th><th>Km compliant</th><th colspan="2">Additional km compliant</th><th>Total km (Penrith to Wisemans Ferry)</th></tr>
<tr><td rowspan="2">Base Case</td><td>Penrith</td><td>40%</td><td>11.7</td><td></td><td rowspan="2"></td><td rowspan="2">36.9</td></tr>
<tr><td>Yarramundi</td><td>29%</td><td>5.0</td><td></td></tr>
<tr><td rowspan="2">S1
95/20 scaled</td><td>Penrith</td><td>49%</td><td>14.4</td><td>3.4</td><td rowspan="2">5.8</td><td rowspan="2">41.9</td></tr>
<tr><td>Yarramundi</td><td>42%</td><td>7.2</td><td>2.4</td></tr>
<tr><td rowspan="2">S2
95/20 halved</td><td>Penrith</td><td>52%</td><td>15.1</td><td>3.4</td><td rowspan="2">5.8</td><td rowspan="2">42.8</td></tr>
<tr><td>Yarramundi</td><td>43%</td><td>7.3</td><td>2.4</td></tr>
<tr><td rowspan="2">S3
90/10 scaled @10%</td><td>Penrith</td><td>48%</td><td>14.1</td><td>2.4</td><td rowspan="2">4.4</td><td rowspan="2">41.4</td></tr>
<tr><td>Yarramundi</td><td>41%</td><td>7.0</td><td>2.0</td></tr>
<tr><td rowspan="2">S4
90/10 scaled @5%</td><td>Penrith</td><td>48%</td><td>14.1</td><td>2.4</td><td rowspan="2">4.4</td><td rowspan="2">41.4</td></tr>
<tr><td>Yarramundi</td><td>41%</td><td>7.0</td><td>2.0</td></tr>
<tr><td rowspan="2">S5
90/20 scaled</td><td>Penrith</td><td>52%</td><td>15.1</td><td>3.4</td><td rowspan="2">6.0</td><td rowspan="2">42.9</td></tr>
<tr><td>Yarramundi</td><td>45%</td><td>7.5</td><td>2.6</td></tr>
<tr><td rowspan="2">S6
80/10 scaled</td><td>Penrith</td><td>53%</td><td>15.5</td><td>3.8</td><td rowspan="2">6.0</td><td rowspan="2">43.5</td></tr>
<tr><td>Yarramundi</td><td>46%</td><td>7.7</td><td>2.8</td></tr>
<tr><td rowspan="2">S7
90/10 scaled + 14m dam</td><td>Penrith</td><td>48%</td><td>14.1</td><td>2.4</td><td rowspan="2">4.4</td><td rowspan="2">41.4</td></tr>
<tr><td>Yarramundi</td><td>29%</td><td>7.0</td><td>2.0</td></tr>
</table>

Note: scenarios scaled at 5 percent total storage unless stated otherwise

3.4. Fish migration opportunities

Eco Modeller (using he IQQM daily flow data) was used to calculate the mean migration scores for each of the e-flow scenarios, fish species and direction. For each e-flow scenario, the mean migration scores were compared to the Base Case to assess the benefit that would be achieved under each proposed e-flow option. This indicated the potential improvement in fish populations over the Base Case, based on the increased migration opportunities for Australian bass and freshwater mullet. Of all the 2017 MWP e-flow fish models, the 90/10 half option was the most effective at providing fish passage opportunities, while the 90/10 scaled option provided similar improvements (Table 17).

These numbers were then converted to minutes to catch an Australian bass for input to the economic model. The 2017 e-flow options calculations for time to catch a bass are provided in

Table 18.

Table 17. 2017 MWP e-flow results – mean daily potential fish migration scores over the Base Case.

		Species and direction				All species and directions
		Bass downstream	Bass upstream	Mullet downstream	Mullet upstream	Mean of the mean migration scores
Base Case	score	0.135	0.072	0.073	0.110	0.098
90/10 half	score	0.179	0.099	0.099	0.135	0.128
	% change	**32**	**38**	**35**	**22**	**32**
90/10 scaled	score	0.175	0.097	0.096	0.132	0.125
	% change	**30**	**35**	**32**	**20**	**29**
90/5	score	0.168	0.084	0.092	0.129	0.118
	% change	**25**	**17**	**26**	**17**	**21**
95/5	score	0.152	0.092	0.085	1.121	0.113
	% change	**12**	**28**	**16**	**10**	**17**

Table 18. 2017 MWP e-flow options – estimated change in time to catch an Australian bass.

	Bass upstream Daily score	Percent change	Time to catch a bass (minutes)
Base Case	0.072	-	**90**
90/10 half	0.099	37%	**65**
90/10 scaled	0.097	35%	**67**
90/5	0.084	17%	**77**
95/5	0.092	28%	**70**

The same Eco Modeller models were run using the 2018 e-flow options for all model options (Table 19), and the results for the Base Case and 90/10 scaled options are similar between the two separate model runs.

The 80/10 scaled provides the highest migration scores for any of the fish models, with the 90/20 scaled slightly lower. Both options provide a much greater benefit over the Base Case, particularly when looking at the mean of the mean migration scores.

Table 19. 2018 e-flow results – mean daily potential fish migration scores over the Base Case.

	Species and direction				All species and directions
	Bass downstream	Bass upstream	Mullet downstream	Mullet upstream	Mean of the mean migration scores
Base Case	0.136	0.073	0.068	0.105	0.096
S1 95/20 scaled	0.189	0.111	0.104	0.133	0.134
S2 95/20 halved	0.183	0.111	0.104	0.132	0.132
S3 90/10 scaled @ 10%	0.182	0.103	0.099	0.131	0.129
S4 90/10 scaled @ 5%	0.182	0.103	0.098	0.130	0.129
S5 90/20 scaled	0.198	0.118	0.110	0.138	0.141
S6 80/10 scaled	0.203	0.120	0.113	0.144	0.145
S7 90/10 scaled + 14m dam	0.182	0.103	0.098	0.130	0.129

Converting the daily migration scores to time to catch a bass, the 80/10 option provides the greatest reduction in minutes to catch a bass (55 minutes), with 90/20 at 56 minutes and the 95/20 options at 59 minutes (Table 20). The 90/10 scaled options result in a fishing time of 64 minutes, which is the highest of the 2018 e-flow options; however, this is slightly less than the 67 minutes for the 2017 90/10 scaled options (Table 18).

Table 20 – 2018 e-flow options - estimated change in time to catch an Australian bass.

Scenario	Daily score	Bass upstream % change	Minutes to catch a bass
Base Case	0.073		**90**
S1 95/20 scaled	0.111	51.9%	**59**
S2 95/20 halved	0.111	51.9%	**59**
S3 90/10 scaled @ 10%	0.103	41.0%	**64**
S4 90/10 scaled @ 5%	0.103	40.6%	**64**
S5 90/20 scaled	0.118	61.4%	**56**
S6 80/10 scaled	0.120	64.7%	**55**
S7 90/10 scaled + 14m dam	0.103	40.8%	**64**

Note: scenarios scaled at 5 percent total storage unless stated otherwise

3.5. Floating macrophyte cover

The floating macrophyte model was run using the 2017 and 2018 e-flow options outputs from the IQQM model for Penrith, Yarramundi, Windsor, and Wilberforce. Comparison of the Base Cases with the e-flow options show that there is an improvement (that is, a reduction) in the risk of floating weed cover exceeding 30 percent for all e-flow options.

Eco Modeller daily growth scores were converted to the "sum of scores" for each e-flow option. This was then compared to the Base Cases to determine the change in sum of scores, which indicates the macrophyte cover risk. The higher the sum of scores, the worse the result.

At Penrith, for the 2017 e-flow options showed that there was a greater proportion of improvement at Penrith and Yarramundi than downstream at Windsor and Wilberforce (Table 21). The 90/10 options had a better proportional improvement than the 90/5 and 95/5.

Table 21 – 2017 MWP e-flow options – summary of the sum of scores and percent increase over the Base Case in river length free of floating aquatic macrophyte outbreaks.

Scenario	Site	Penrith	Yarramundi	Windsor	Wilberforce	Average % change
Base Case	Sum of scores	66,862	44,828	44,663	36,007	48,090
90/10 half	Sum of Scores	39,329	30917	34524	28,347	33,279
	% change	**41**	**31**	**23**	**21**	**29**
90/10 scaled	Sum of Scores	48,326	31,950	35,776	28,882	36,233
	% change	**28**	**29**	**20**	**20**	**24**
90/5	Sum of Scores	55,050	34,376	37,825	28,853	39,026
	% change	**18**	**23**	**15**	**12**	**17**
95/5	Sum of Scores	56,861	35,907	39,194	30,571	40,633
	% change	**15**	**21**	**12**	**15**	**16**

The 2018 e-flow options show a similar range of improvement over the Base Case, with the average improvement across all sites and an options of 25 to 31 percent. Again, more substantial improvements are seen upstream where the e-flows have more of an influence on river flows.

These numbers were used to determine the estimates of additional river length free of floating macrophytes (Table 23, Table 24)

Table 22. 2018 e-flow options - summary of the sum of scores and percent increase over the Base Case in river length free of floating aquatic macrophyte outbreaks.

Scenario	Site	Penrith	Yarramundi	Windsor	Wilberforce	Average % change
Base Case	Sum of scores	56,439	40,809	44,536	35,164	44,237
S1 95/20 scaled	Sum of Scores	31,234	27,204	35,052	27,540	30,258
	% change	**45**	**33**	**21**	**22**	**30**
S2 95/20 halved	Sum of Scores	31,230	27,201	35,050	27,538	30,255
	% change	**45**	**33**	**21**	**22**	**30**
S3 90/10 scaled @ 10%	Sum of Scores	37,926	30,418	35,358	27,722	32,856
	% change	**33**	**25**	**21**	**21**	**25**
S4 90/10 scaled @ 5%	Sum of Scores	38,368	30,595	36,0351	27,814	114,282
	% change	**32**	**25**	**19**	**21**	**24**
S5 90/20 scaled	Sum of Scores	38,368	26,266	33,640	26,995	31,317
	% change	**32**	**36**	**24**	**23**	**29**
S6 80/10 scaled	Sum of Scores	30,356	28,800	33,853	26,541	29,888
	% change	**46**	**29**	**24**	**25**	**31**
S7 90/10 scaled + 14m dam	Sum of Scores	35,921	30,451	35,924	27,715	32,503
	% change	**36**	**25**	**19**	**21**	**25**

Note: scenarios scaled at 5 percent total storage unless stated otherwise

Table 23. 2017 MWP e-flow options - estimates of the additional length of river free of floating aquatic macrophyte outbreaks compared to the Base Case, and total river length free.

2017	Base Case	90/10 half	90/10 scaled	90/5	95/5
Additional km bloom free	0	7.2	6.6	6.3	5.1
Total river length bloom free (km)	68.8	76.0	75.2	75.0	73.9

Table 24. 2018 e-flow options - estimates of the additional length of river free of floating aquatic macrophyte outbreaks compared to the Base Case, and total river length free.

	Base Case	S1 95/20 scaled	S2 95/20 halved	S3 90/10 scaled @ 10%	S4 90/10 scaled @ 5%	S5 90/20 scaled	S6 80/10 scaled	S7 90/10 scaled + 14m
Additional km bloom free		10.2	11.0	9.4	10.2	11.8	11.0	10.2
Total river length bloom free (km)	68.8	79.0	79.8	78.2	79.0	80.6	79.8	79.0

4. Discussion

Under the 2017 MWP, the Government committed to e-flows from Warragamba Dam, and agreed that additional e-flow options should be analysed to determine the most appropriate e-flows from Warragamba Dam. There is a trade-off between the volume released and the environmental benefits, as any e-flow release may bring forward the time of the next water supply augmentation. Further analysis of the 2018 options using economic modelling (Metronet in particular) will allow an overall assessment of the costs and benefits. While this assessment examines the benefits of the most recent e-flow options, water "lost" to the supply system is also of interest.

Since the economic analysis will rely on both water use and the 'abilities', the e-flow options have been ranked based on the abilities – swimability (Table 16), fishability (Table 20) and boatability (Table 24).

Ranking the 2018 e-flow options based on the improvements seen in each of the abilities shows, predictably, that the scenarios with more water released (S5 and S6) ranked better than the others with less water released (Table 25).

Table 25. Ranking the 2018 e-flow options for each of the abilities, based on all three abilities.

<table>
<tr><th>RANK</th><th colspan="3">Scenario</th><th>Water released (average ML/a)*</th><th>Swimability</th><th>Fishability</th><th>Boatability</th></tr>
<tr><td>1</td><td>S2</td><td>95/20</td><td>halved</td><td>94,759</td><td>S6</td><td>S6</td><td>S5</td></tr>
<tr><td>2</td><td>S5</td><td>90/20</td><td>scaled</td><td>92,722</td><td>S5</td><td>S5</td><td rowspan="2">S6
S2</td></tr>
<tr><td>3</td><td>S1</td><td>95/20</td><td>scaled</td><td>83,859</td><td>S2</td><td rowspan="2">S1
S2</td></tr>
<tr><td>4</td><td>S6</td><td>80/10</td><td>scaled</td><td>74,347</td><td>S1</td><td rowspan="3">S1,
S4
S7</td></tr>
<tr><td>5</td><td>S3</td><td>90/10</td><td>scaled 10%</td><td>58,835</td><td rowspan="3">S3
S4
S7</td><td rowspan="3">S3
S4
S7</td></tr>
<tr><td>6</td><td>S7</td><td>90/10</td><td>scaled + 14m</td><td>59,287</td></tr>
<tr><td>7</td><td>S4</td><td>90/10</td><td>scaled 5%</td><td>57,382</td><td>S3</td></tr>
</table>

*Appendix 1 lists the total volume released annually for each of the 2018 e-flow options

While Scenarios 6 and 5 have the greatest ecological benefit, Scenario 5 also ranks second in water use, which means that it is likely to be one of the most expensive options and is likely to bring forward the time for the next water supply augmentation. Scenario 6 uses considerably less water on average (20 gigalitres less per annum) than Scenario 5. Scenario 2 requires the second highest average annual volume of water released, but provides lower benefits than Scenario 6 for Swimability and Fishability. Scenario 1 uses slightly more water than Scenario 6, but only provides reduced weed cover risk.

Scenarios selected for additional economic analysis, based on the balance of water use and environmental benefit, are:

- Scenario 1 – 95/20 scaled – good benefits, 3rd highest water use
- Scenario 4 – 90/10 scaled at five percent - uses the least amount of water, provides lower ecological benefits
- Scenario 6 – 80/10 scaled – 4th highest water use, but greatest benefit for fish, swimming. Boating benefit good.

Scenarios now excluded from Metronet and other economic modelling are:

- Scenario 5 – 90/20 scaled – excellent ecological benefits for all abilities, but the second highest water use
- Scenario 2 – 95/20 half - uses the most water of all the options
- Scenario 3 – 90/10 scaled at 10 percent – similar ecological benefits to Scenarios 4 and 5, similar water use
- Scenario 5 – 90/10 scaled at 5 percent plus dam raised 14m – very similar to Scenarios 3 and 4 for both ecological benefits and water use

Attachment A

Table 26 – 2018 e-flow options - total modelled volume (megalitres) released each year

Colour coding indicates which scenario had the highest, middle, lowest etc release each year.

Year	S1 95/20 sc	S6 80/10 sc	S3 90/10 sc 10%	S4 90/10 sc 5%	S7 90/10 sc+14	S2 95/20 half	S5 90/20 sc
1909	37,823	40,161	32,159	31,307	31,307	49,647	43,633
1910	57,723	59,214	46,671	44,456	44,466	76,633	65,793
1911	188,596	140,388	121,733	117,355	119,614	206,528	198,127
1912	75,965	80,694	59,001	57,526	64,010	91,683	83,886
1913	68,278	68,292	54,296	53,077	53,187	71,239	76,285
1914	101,881	95,473	75,520	75,265	74,807	102,834	111,799
1915	112,251	96,565	68,651	68,509	68,546	112,605	122,879
1916	81,466	67,431	56,815	54,438	60,909	91,748	89,827
1917	95,909	92,249	71,533	68,929	68,987	99,645	106,503
1918	93,285	82,586	63,062	60,143	61,315	96,280	102,402
1919	73,510	69,507	59,710	57,422	57,815	84,018	80,146
1920	112,996	99,892	87,358	85,037	85,474	131,963	119,347
1921	98,265	73,876	57,877	57,521	57,405	111,234	116,130
1922	2,313	1,273	1,275	1,275	1,275	2,436	2,343
1923	109,842	87,372	73,263	71,905	71,589	118,751	120,673
1924	33,614	52,371	36,291	35,420	35,527	38,951	43,468
1925	117,057	99,505	85,807	83,981	90,713	126,438	125,447
1926	97,989	79,379	65,612	63,325	64,394	100,377	105,405
1927	60,815	72,308	53,499	52,325	59,145	63,023	70,940
1928	112,585	95,497	73,271	72,559	71,470	116,378	126,336
1929	115,190	92,593	70,994	70,675	77,281	115,831	125,154
1930	97,181	84,490	64,614	63,030	64,796	99,680	108,483
1931	80,291	71,616	56,397	54,636	60,428	82,420	87,816
1932	66,987	73,663	54,425	53,242	53,786	74,417	77,128
1933	101,866	90,265	70,819	70,660	70,742	115,604	109,618
1934	91,043	72,782	56,368	56,368	62,656	94,512	99,729
1935	52,906	61,604	43,941	43,358	43,099	54,895	65,347
1936	91,730	81,577	66,817	64,597	65,170	108,422	100,051
1937	65,188	67,872	50,160	49,736	50,027	84,040	73,715
1938	94,851	87,838	71,437	69,350	69,544	113,119	102,136
1939	56,820	60,535	46,227	44,530	44,710	70,664	64,396
1940	13,939	16,142	13,632	12,335	12,403	26,495	16,450
1941	22,804	25,826	21,073	19,487	19,867	39,615	27,100
1942	98,635	74,692	68,501	66,026	66,282	125,586	103,150
1943	81,983	76,036	60,295	60,177	66,438	94,877	90,194
1944	37,228	51,129	37,517	36,303	36,424	40,069	45,991
1945	104,274	95,788	77,235	76,403	76,273	114,031	119,209
1946	62,789	63,512	51,675	50,181	50,564	69,104	71,333
1947	127,360	100,912	87,641	85,048	85,226	150,646	135,218
1948	134,899	100,936	81,259	76,523	78,585	150,647	150,764
1949	117,221	92,496	75,863	73,949	73,366	125,397	131,001

Year	S1 95/20sc	S6 80/10sc	S3 90/10sc10%	S4 90/10sc5%	S7 90/10sc+14	S2 95/20half	S5 90/20sc
1950	20,821	19,343	15,279	15,279	15,024	20,821	23,696
1951	48,324	49,267	33,809	33,809	40,095	48,324	55,456
1952	80,362	64,177	52,926	51,804	51,596	81,518	87,266
1953	67,447	74,274	57,695	52,489	57,050	68,473	81,425
1954	61,636	64,105	49,231	48,583	48,960	72,800	70,647
1955	157,053	115,836	98,444	96,867	103,921	170,387	166,005
1956	46,467	41,092	31,287	31,124	38,388	47,134	52,499
1957	36,084	46,342	34,839	33,974	34,175	40,609	43,481
1958	137,957	113,699	97,478	94,444	94,852	148,784	147,778
1959	145,822	101,680	80,765	75,697	80,129	150,634	154,604
1960	123,352	105,078	84,563	83,128	83,430	126,610	133,947
1961	85,947	78,376	56,347	56,106	62,640	86,624	98,127
1962	78,120	70,862	52,391	52,391	51,402	78,120	87,525
1963	59,010	44,069	31,555	31,555	30,559	59,010	68,098
1964	66,975	73,311	52,836	52,707	58,657	67,110	76,472
1965	84,859	71,611	61,558	59,691	60,082	95,938	92,352
1966	93,014	83,538	66,728	65,612	65,986	109,915	102,852
1967	101,755	89,156	71,361	68,977	75,391	108,803	111,504
1968	60,850	67,483	51,224	49,538	49,824	65,379	70,363
1969	134,423	98,567	82,370	81,210	87,649	153,276	151,949
1970	83,671	83,453	64,128	62,960	63,924	87,591	94,133
1971	108,863	89,262	72,682	71,463	71,755	114,838	118,559
1972	70,615	73,595	56,660	55,448	55,163	72,850	79,279
1973	136,022	111,924	86,510	85,165	87,344	141,757	149,754
1974	90,220	69,457	51,181	51,038	50,527	90,432	100,224
1975	71,556	70,613	53,987	52,683	58,913	73,095	82,243
1976	78,451	73,839	52,667	52,667	58,660	78,451	87,977
1977	79,852	71,192	51,228	50,647	55,034	80,848	89,301
1978	113,397	83,103	68,230	67,558	73,807	115,967	122,557
1979	22,401	38,399	28,272	27,496	27,681	25,290	30,282
1980	31,252	37,655	28,326	27,578	27,774	46,655	37,538
1981	102,574	78,258	66,315	64,388	64,644	159,601	108,250
1982	23,664	31,843	23,848	23,089	23,231	40,419	28,892
1983	121,581	87,589	77,892	75,422	75,572	166,778	126,741
1984	164,165	127,136	99,602	97,439	105,261	205,586	182,267
1985	113,895	87,319	67,804	66,426	66,739	119,090	126,415
1986	52,443	58,919	43,965	43,500	49,687	53,349	61,740
1987	120,646	108,144	74,131	72,385	79,159	121,551	131,422
1988	100,119	78,574	60,888	60,092	64,042	101,021	108,915
1989	70,818	59,971	44,182	43,958	44,003	71,053	77,711
1990	78,154	60,079	44,082	43,374	46,462	78,904	84,055
1991	71,775	70,005	56,473	55,619	62,718	73,579	80,153
1992	82,649	82,763	61,303	60,622	60,784	85,026	93,137
1993	35,805	51,070	36,332	35,326	35,648	42,888	44,592

Year	S1 95/20sc	S6 80/10sc	S3 90/10sc10%	S4 90/10sc5%	S7 90/10sc+14	S2 95/20half	S5 90/20sc
1994	25,599	29,435	24,287	22,915	23,040	38,356	29,664
1995	76,590	65,549	53,152	51,879	52,287	124,641	82,823
1996	73,736	67,362	54,163	52,375	53,043	105,180	79,931
1997	57,922	56,487	46,408	44,478	44,591	85,422	64,497
1998	108,426	85,783	68,590	60,457	67,468	145,469	114,621
1999	109,023	97,779	78,614	76,187	76,617	116,427	119,345
2000	134,629	108,159	80,879	79,426	85,471	144,451	151,620
2001	69,256	70,824	51,531	50,647	50,760	70,640	79,945
2002	57,972	55,719	44,323	43,651	43,750	66,846	64,901
2003	52,417	55,042	42,373	40,955	41,371	73,251	59,217
2004	19,044	26,983	20,550	19,362	19,542	37,010	23,845
2005	59,941	53,294	43,314	41,295	41,431	92,762	65,197
2006	29,145	34,857	26,820	25,981	26,117	53,050	34,728
2007	170,327	123,504	113,532	110,884	111,041	209,242	176,690
2008	83,461	84,349	65,920	63,985	63,955	94,698	92,400
2009	95,399	86,880	73,128	70,181	70,181	112,010	103,715
2010	168,494	129,044	109,930	108,614	108,626	206,592	182,115
average	83,859	74,347	58,835	57,382	59,287	94,759	92,772

	S1 95/20 sc	S6 80/10 sc	S3 90/10 sc10%	S4 90/10 sc5%	S7 90/10 sc+14	S2 95/20 half	S5 90/20 sc
No years highest							58
No years second						44	
No years third	69						
No years fourth		33					
No years fifth			75				
No years sixth					56		
No years seventh				85			