LAND & WATER
CONSERVATION

Integrated monitoring of environmental flows: design report

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Preface

The New South Wales Department of Land and Water Conservation (NSW DLWC) has established a major scientific project (IMEF: Integrated Monitoring of Environmental Flows) to provide an understanding of the response of seven major rivers and their associated wetlands to the provision of environmental water allocations. This program has been designed and progressively implemented over a period of four years (1997-2000).

IMEF represents a major departure from customary agency monitoring programs in its complexity, breadth and focus. Assessment of the effects of environmental flows has seldom if ever been attempted from such a broad perspective and over such a large spatial scale anywhere in the world.

Because of the size and novelty of this program, and its significance for integrated natural resource management in NSW, it is important to document thoroughly the steps taken in the conception, design and implementation of the project. Doing so provides a permanent record of the reasons why decisions were taken, alternatives chosen in preference to others, priorities established and particular methods adopted.

This design report has been compiled to document the logical and practical development of IMEF, and to provide the rationale for the form of the program. It is one of a series of IMEF manuals and reports. Study designs for each river valley, incorporating site descriptions and sampling frequencies, are contained in a series of operations manuals. A methods manual comprises detailed technical specifications of field and laboratory protocols. Quality assurance and quality control procedures are also defined. A data manual is being compiled to provide program staff with guidance on data management and statistical and numerical analysis. The operations, methods and data manuals are internal working documents and subject to continual improvement and updating. The first major technical report on results of the program is currently being compiled for publication.

1. Background

It is well documented in the scientific and popular literature that water resource developments, particularly for irrigated agriculture, have profoundly affected the hydrology and ecology of the regulated rivers of NSW. The construction and operation of large dams, and the extraction of water from downstream rivers, have diminished total river flows and changed their temporal pattern from the natural regime (Baker and Wright 1978; Walker 1985; Page 1988; Close 1990; Kingsford and Thomas 1995; Maheshwari *et al.* 1995; Maini and Cross 1996; Crabb 1997; Thoms and Cullen 1998; Reid and Brooks 2000; Sheldon *et al.* 2000; Thoms and Sheldon 2000). Many floodplains and wetlands are less frequently flooded than would have naturally been the case, but conversely, some wetlands and temporary streams that naturally dried periodically are now wetted permanently, or at unnatural times of the year (Bren 1988; Pressey 1990; Thornton and Briggs 1994; Frankenberg *et al.* 1996; Reid and Brooks 1998; Kingsford 2000). River regulation and water abstraction have been considered at least partly responsible for adverse ecological changes such as steep declines of native fish and waterbird populations and massive cyanobacterial blooms (Kingsford 1995; Kingsford and Thomas 1995; Bain *et al.* 1996; Bowling and Baker 1996; Harris and Gehrke 1997, Gehrke and Harris 2000). Flow changes may also be implicated in less obvious impacts such as extinctions of riverine snails and declines of water plants (e.g., Roberts and Sainty 1996; Sheldon and Walker 1997).

In response to growing environmental concerns and the need for economic restructuring of the water industry, the NSW Government has assembled a wide-ranging water reform package (Thoms and Swirepik 1998). This package clarifies the rights and obligations of consumptive water users while aiming to protect and improve the health of rivers, wetlands and estuaries. Water entitlements are being defined to increase certainty for users, as a basis for sound investment, and to facilitate greater flexibility, for example through water trading. The package includes a structured, community-based planning process to develop local flow management targets in the light of twelve broad River Flow Objectives (RFOs). These objectives (Box 1) set out key attributes of flow regimes and flow management that may be important elements in maintaining or restoring the integrity of particular aquatic ecosystems. They are strongly oriented towards the partial restoration of the natural flow regime (cf. Power *et al.* 1996; Poff *et al.* 1997).

Relevant river flow objectives may be achieved in individual valleys by a combination of the following:

- diversion limits such as the Murray-Darling basin Cap on water use at 1993-94 levels of development,

- environmental flow rules, which target specific aspects of flow regimes at various points in each river system, and

- other river and groundwater management activities such as water management plans, weir reviews and measures to mitigate the thermal impact of storage releases.

Environmental flow rules have been developed by community-based river management committees (RMCs) in each of six valleys that have major rivers regulated by large storages operated by the DLWC: the Gwydir, Hunter, Lachlan, Macquarie, Murrumbidgee and Namoi valleys. Rules have also been formed for the Barwon-Darling River which, although not formally regulated, has flows that are greatly affected by storages and water extraction on its major tributaries in both NSW and Queensland. Preliminary rules have been approved by the NSW Government. They are being implemented through the operating and licensing procedures of the DLWC. Audit reports, dealing with both compliance in implementing the rules and their environmental performance, will be produced by the DLWC for review by the RMCs and the Environment Protection Authority. Initially, the rules have been reviewed annually by the RMCs, which recommend changes to the Minister for Land and Water Conservation. Under the Water Management Act 2000, the flow rules and other aspects of water sharing plans will be reviewed less frequently. The rules for 1999-2000 are listed in Appendix 1.

Box 1. New South Wales river flow objectives

1. Protect natural water levels in river pools and wetlands during periods of no flow
2. Protect natural low flows
3. Protect or restore a portion of freshes and high flows
4. Maintain or restore the natural inundation patterns and distribution of floodwaters supporting natural wetland and floodplain ecosystems
5. Mimic the natural frequency, duration and seasonal nature of drying periods in naturally temporary streams
6. Maintain or mimic natural flow variability in all streams
7. Maintain the rates of rise and fall of river heights within natural bounds
8. Maintain groundwater within natural levels, and variability, critical to surface flows or ecosystems
9. Minimise the impact of in-stream structures
10. Minimise downstream water quality impacts of storage releases
11. Ensure that the management of river flows provides the necessary means to address contingent environmental and water quality events
12. Maintain or rehabilitate estuarine processes and habitats

2. Environmental flows monitoring

If environmental flow rules are to be reviewed in a meaningful manner, and management of rivers improved, it is essential that RMCs, natural resource management agencies and the broader community are provided with a sound scientific assessment of the effectiveness of the rules. The DLWC established IMEF to provide additional understanding of the flow responses of river and wetland ecosystems, and to evaluate the environmental performance of the flow rules, for the seven river valleys.

The **objectives** of IMEF are as follows:

- to investigate relationships between water regimes, biodiversity and ecosystem processes in the major regulated river systems and the Barwon-Darling River,
- to assess responses in hydrology, habitats, biota and ecological processes associated with specific flow events targeted by environmental flow rules, and
- to use the resulting knowledge to estimate likely long-term effects of environmental flow rules and provide information to assist in future adjustment of rules.

The intended **outcomes** of the project are as follows:

- a better understanding of the relationships between hydrology, morphology and ecology in the major regulated river systems and the Barwon-Darling river, and their trends over time,
- an evaluation of whether flow events targeted by the rules produce the expected short-term environmental responses,
- an estimation of the likely longer-term effects of environmental flows rules, and
- an informed environmental flow review process.

The intended **outputs** of the project are as follows:

- detailed technical reports, compiling regional findings and providing inter-valley comparisons,
- brochures and fact sheets presenting summarised information in a less technical format, and
- input to ‘State of the Catchment’ reports and other forms of environmental reporting.

3. Context, scope and limitations

Rivers and wetlands in NSW are currently being monitored and assessed under several State-wide and regional projects. These include the following:

- the wetland mapping and waterbird monitoring programs of the National Parks and Wildlife Service (e.g., Kingsford 1999),

- the DLWC Stressed Rivers project for unregulated streams, which classifies and reviews sub-catchments across the State according to levels of water use, environmental stress and biological conservation values (DLWC 1998),

- the DLWC Key Sites program, which monitors turbidity, salinity and phosphorus at river sites throughout NSW, and

- the hydrographic monitoring programs of the DLWC, Murray-Darling Basin Commission and other agencies.

While these and other smaller projects may provide information relevant to IMEF, they have different objectives and therefore do not fulfil IMEF's specific needs. IMEF is being established in such a way that it takes account of these other projects and does not duplicate their activities. In some cases IMEF will use data from these and other projects.

The focus of IMEF is the effects of environmental flow strategies on the ecology of regulated rivers and associated wetlands. It is not intended to assess unregulated streams other than the Barwon-Darling River, as these are dealt with under the Stressed Rivers program. However, the effects of tributary flow management on regulated main streams needs to be taken into account in IMEF. IMEF is also concerned with factors closely associated with the delivery of environmental flows, such as changes in water quality (e.g., temperature) associated with reservoir management (e.g., offtake levels).

While IMEF is a large project using up-to-date scientific methods, there are practical limitations to what any such project can achieve in a complex and dynamic natural environment. These limitations are specified below so that the expectations of the project are not unrealistic.

- The RFOs and flow rules are hydrological and not ecological. While desired ecological outcomes are understood in broad terms, they have not yet been defined as operational goals. Since the rules could affect innumerable aspects of river and wetland ecology (cf. Hart and Finelli 1999), it has been necessary to make judgements about which biota and physical and ecological processes they are most likely to influence. This has been a difficult task because while substantial research has focussed on the general effects of flow on Australian river systems, little has been done on flow rules of the type and magnitude of those now implemented in NSW.

- The implementation of environmental flows is not a controlled scientific experiment like an agricultural plot trial. Ideally, each river *with* environmental flow rules would be assessed by comparison with a 'control' group of large, regulated rivers *without* those rules but otherwise extremely similar. Such control groups could not be found because the regulated rivers of NSW vary widely in character, both naturally and in the nature of their flow regulation. Nor is there a stable ‘control’ period before the start of environmental flow rules, because flow regimes have been continually changing over recent decades as the degree of regulation and diversion have increased. Some environmental water provisions, such as the Macquarie Marshes Water Management Plan (DWR/NPWS 1986; DLWC/NPWS 1996) have also been in operation for several years. These constraints make it more difficult to determine whether observed changes are caused by environmental flows rather than other factors.

- For many variables there are also few data available prior to the establishment of environmental flows, and where data are available they are not always in the most appropriate form. This also makes it more difficult to infer which changes are due to environmental flows.

- The changes in flow regimes brought about by the flow rules are small in relation to total water use – typically less than 10% of extractive use in an average year. They are also very small in the context of natural flow variation resulting from short-term and longer-term climatic shifts (e.g., droughts and floods). Many of the effects of environmental flows are therefore subtle and difficult to distinguish from the effects of other aspects of the total flow regime. By contrast, most past research has investigated major events such as broad-scale flooding and drying (Lake 1995). While most ecosystem attributes will respond to hydrological changes of this magnitude, it is difficult to infer from such studies the extent of likely responses to much more subtle changes associated with the implementation of environmental flow rules.

- Many environmental flow rules will have effect only under specific climatic and hydrological conditions (e.g., after prolonged dry spells) and it may take many years for these rules to have a measurable impact.

- River ecosystems are affected by many other factors than flow - for example, wastewater discharges, catchment and riparian conditions, in-stream barriers and biological interactions. Many of these factors will be changing at the same time as environmental flows are provided. In some cases, river ecosystems may still be adjusting to past changes such as catchment clearing or the spread of alien pest species. These confounding factors can make it difficult to attribute particular ecological changes specifically to environmental flows.

- Ecosystem responses often are delayed, proceed at slower than expected rates, or follow trajectories towards unexpected states (i.e., other than some hoped-for condition). In some cases, recovery may not occur until a trigger such as a large flood overcomes inertia and forces a shift from one equilibrium state to another. In other cases, there may be no response to flow changes because some other factor is limiting. Flow rules could be incorrectly judged to have failed because the system has not behaved as predicted, or has not immediately shifted to the desired state. Some responses to environmental flows will take years or even decades to occur. It is hard to link particular flow changes to their specific effects over such long periods, because so many other factors may also have changed in the meantime. Even the flow rules may change from year to year.

- IMEF has limited funding, imposing restrictions on the numbers of sites that can be studied, variables that can be measured and frequency of measurement. In statistical terms, there are limits on the effect size that can be detected with a given level of confidence. Variables that are expensive to analyse or that require intensive sampling in order to obtain interpretable results are simply impractical.

4. Approach to project design and implementation

Initially, consideration was given to implementing a routine monitoring program in which a standard set of customary indicators of water quality and biological condition would be measured repeatedly at representative sites selected on a stratified random basis. Such an approach would enable the charting of changes in the selected variables over time. However, it would incur the following serious deficiencies.

- It would be difficult to decide on which indicators to include.

- Because of natural fluctuations, a very long period might be needed before clear and consistent trends emerged.

- Because of the limitations described in the previous section, it would be very hard to determine which, if any, of the observed trends could be ascribed to environmental flow changes.

- Such an approach would be unlikely to provide much understanding of the causes of observed changes, although correlations between variables could be described.

- Such an approach would provide little ability to predict the effects of future options for changing environmental flow rules.

An alternative approach was therefore developed based on the testing of specific hypotheses incorporating the likely effects of environmental flow rules. Hypothesis testing is a fundamental component of the modern scientific method, but is more commonly incorporated in controlled experiments than in monitoring programs (e.g., Havens and Aumen 2000). IMEF hypotheses were envisaged as linking four components:

1. a flow rule or rules,

2. the RFO(s) that the flow rule is designed to achieve,

3. an intended environmental outcome or outcomes of the RFO(s), and

4. the biophysical mechanism by which application of the rule is expected to lead to the outcome.

The advantages of this option were seen as follows.

- Anchoring IMEF to hypotheses would ensure that the program had clear aims, direction and focus, by stating, unequivocally and at the outset, the ecosystem responses that may be recorded if the flow rules achieve the types of environmental outcomes that the RFOs seek.

- The formulation of hypotheses incorporating rules, objectives, outcomes and mechanisms would set the direction for charting structural links between these four critical components of the environmental flows issue, and thus provide a firm basis for study design.

- Hypothesis testing would enable the expected links between flow regimes and ecology to be either confirmed or reformulated, regardless of whether or not a long-term ecological improvement is recorded.

The hypothesis-based approach was developed and progressed into the IMEF study design in the following six steps.

1. The proposed RFOs were consulted in order to identify the environmental outcomes that they are intended to achieve.

2. The changes in the regulated flow regime that are likely to result from implementation of the initial flow rules were considered.

3. Existing information was reviewed to determine which plants, animals and ecological processes are likely to be sensitive to these changes.

4. Hypotheses were developed about the responses of these components.

5. The hypotheses were prioritised according to their relevance to the intended environmental outcomes and on other appropriate criteria in each valley.

6. Appropriate study designs were devised that would enable testing of the priority hypotheses (or the construction and validation of associated models). These designs incorporated selection of study sites, variables and sampling strategies and appropriate methods of data analysis.

The following sections of this design report describe the implementation and results of each of these steps.

5. Intended environmental outcomes of RFOs

The environmental benefits that are intended to accrue from improved river flow management were listed on page 19 of the Proposed Interim Environmental Objectives for NSW Waters (EPA 1997). These benefits are listed below with some comments on their practical interpretation for IMEF.

Improved survival of ecosystems and aquatic biodiversity

Biological diversity has been defined as the variety of all life forms - the different plants, animals and microorganisms, the genes they contain, and the ecosystems of which they form a part (Commonwealth of Australia 1996). Biodiversity is normally considered at three levels in the hierarchy of biological organisation: ecosystem diversity, species diversity and genetic diversity. Each level can be considered through three attributes: composition, structure and function (Noss 1990). For example, traditional species lists for a region of interest would represent a measure of compositional diversity at the species level, whereas an understanding of the grouping of species into communities, and the spatial patterns of those communities, would address structural biodiversity.

Aquatic biodiversity has been relatively neglected in Australia (Cullen and Lake 1995), and it is obviously beyond the scope of IMEF or any feasible monitoring program to attempt a total inventory of species in the rivers affected by RFOs, let alone their genetic diversity. It has been suggested that it may be possible to use particular taxa as indicators of total biodiversity if their richness is strongly associated with the richness of much larger groups of biota (e.g., Pearson and Cassola 1992). Such indicators have been termed surrogate taxa (Oliver and Beattie 1996) or predictors (Cranston and Trueman 1997). Attempts to find suitable predictors for Australian stream fauna have not, however, been particularly successful (e.g., Chessman and Williams 1999). An alternative approach is to consider only particular groups of biota. Such biota could be chosen on a variety of criteria such as sensitivity to flow regime (see section 7), ‘charismatic’ appeal to the general public, presumed ecological importance and ease of sampling.

Monitoring the ‘survival of ecosystems’ is also a difficult proposition, since no general ecosystem classification of Australian rivers has been achieved. Classification of NSW rivers according to the distribution of macroinvertebrate families has begun at a State-wide scale (Turak *et al.* 1999), but does not enable the definition of river ecosystem types. A variety of biologically-based wetland classifications exists for the State (Pressey and Adam 1995). These are based mainly on vegetation and it is not clear whether they are equally applicable to other components of wetland ecosystems. IMEF could supplement these existing classifications by developing new ones for other groups of biota.

Improved water quality

EPA (1997) listed suspended sediment, nutrients, salinity, temperature and dissolved oxygen as aspects of water quality that can be affected by river flow. Improved flow management would aim to achieve lower levels of suspended sediment, nutrients and salinity, higher levels of dissolved oxygen and more natural water temperatures. IMEF could assess long-term trends in each of these variables. However, it should be noted that altered levels of these physical and chemical variables are not ends in themselves, but rather means by which to achieve environmental values such as visual amenity, suitability for consumptive uses and protection of aquatic ecosystems. Monitoring of such variables alone would therefore be worthwhile only in circumstances where the functional relationship between the water quality variable and the desired environmental value is well understood, so that success in attaining the environmental value does not need to be measured directly, but can be reliably predicted from the water quality variable.

For example, in clear-water lakes, there is often a close predictive relationship between the total phosphorus concentration and planktonic algal biomass (Vollenweider and Kerekes 1982). In such lakes phosphorus measurement can serve as a surrogate for algal measurement. In rivers, benthic algal growth does not have a simple relationship to a single nutrient, and is only moderately predictable from a combination of flow and nutrient data (Biggs 2000). If one were concerned about such algal growth in rivers, one would probably need to monitor growth directly. Driving variables such as flow, nitrogen and phosphorus, and perhaps light and grazing, could be measured in association, in order to assess their roles.

Healthier wetlands

The term ‘health’ is not defined by EPA (1997) and therefore practical interpretation of this intended benefit is difficult. In the ecological literature, ‘ecosystem health’ has been used to mean either similarity to natural conditions (usually termed ‘ecological integrity’) or a state desired by society (Meyer 1997). Use of the latter definition is difficult because specific societal goals for individual wetlands (and rivers) in NSW have not been prescribed.

Ecological integrity has been defined (Karr and Dudley 1981) as ‘the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity and functional organisation comparable to that of the natural habitat of the region.’ If this definition is used, two issues arise: selecting indicators by which to measure departure from natural conditions, and determining what constitutes natural levels of these indicators.

Determining natural status for indicators of wetland (or river) health is relatively straightforward in parts of the State where undisturbed or minimally disturbed wetlands and rivers still exist, and can be used as reference points for rehabilitation of degraded systems. However, it is much more difficult in many parts of NSW where virtually all water bodies have been altered from their natural condition (Pressey and Harris 1988). Historical data are severely limited, but may be useful in some cases. It may be necessary to extrapolate to desired conditions from the range of values in extant systems. A further difficulty is the dynamic nature of the biological communities in the western rivers of NSW. These communities are continually fluctuating in response to the naturally high climatic and hydrological variability of the region, and therefore are difficult to predict.

Improved habitat quality and increased availability of habitat for native fish, frogs, waterbirds and other native fauna, including invertebrates

Bio-physical habitat can be defined as those attributes of the biological and physical surroundings of an organism that are significant to its survival, growth and reproduction. Several methods of measuring aquatic habitat have been proposed, but many relate to the requirements of specific fish species, especially Northern Hemisphere salmonids – for example the Habitat Quality Index (HQI) of Binns and Eiserman (1979) and the HABSCORE of Milner *et al.* (1985). More general methods include the habitat assessment component of the Rapid Bioassessment Protocols (RBP) of the United States Environmental Protection Agency (Barbour *et al.* 1997), the Qualitative Habitat Evaluation Index (QHEI) used in Ohio (Rankin, 1995), and the habitat quality assessment (HQA) and habitat modification score (HMS) of the British River Habitat Survey (Raven *et al.* 1998). These methods involve the rating of numerous biophysical features, often by visual assessment, and their combination into composite scores.

Common approaches to habitat assessment have been criticised as lacking in accuracy, precision, repeatability and sensitivity to human disturbance (Poole *et al.* 1997), and require justification for the features included and their biological significance (Maddock 1999). Very little testing of habitat assessment methods against such criteria has been done in Australia, and the habitat requirements of most Australian aquatic species remain poorly understood.

The purpose of achieving increased habitat quantity and quality is to rehabilitate communities of aquatic and water-dependent biota. Therefore, assessment of the success of RFOs in attaining this objective could be achieved by monitoring these organisms directly. However, such an approach would not by itself elucidate the mechanisms causing population increase.

More successful breeding of native birds, fish and other native fauna, which only breed in response to specific environmental triggers, for example, rising or falling water levels in the natural seasons

Water requirements for breeding of waterbirds, native fish and frogs are relatively well understood. Less is known about water requirements for reproduction of macrophytes and invertebrates. Since breeding events occur at specific sites and times, monitoring of breeding success may need to be approached on a site-specific and event-specific basis, rather than as part of a routine, broad-scale survey. In some cases it may be possible to infer breeding success retrospectively, by considering the age structure of populations.

More natural inundation of flood plains and wetlands, leading to better health and productivity (such as grazing), protection of endangered species, biodiversity and water quality

The comments made above in relation to wetland health are also relevant to this intended benefit. Biodiversity has also been discussed in relation to benefit 1 and water quality in relation to benefit 2.

The NSW Threatened Species Conservation Act (1997) provides for the listing of endangered species and biological communities. Aquatic biota are listed under the Fisheries Management Act (1994). As yet only a few riverine species have been listed, but new species continue to be assessed by the Scientific Committee. No aquatic communities have been listed. Monitoring of threatened species is often a difficult proposition because such species are rare. Their distributions and abundance are therefore difficult to establish without extensive targeted sampling.

Discouragement of alien pest species, such as carp, which favour regulated conditions

The NSW Rivers Survey (Harris and Gehrke 1997; Gehrke and Harris 2000) has provided excellent baseline data on carp abundance in the State’s rivers, and these data have been supplemented by subsequent surveys. These surveys did not include wetlands.

Improved health of in-stream and riparian vegetation, leading to greater bank stability, improved efficiency of buffer strips in protecting water quality, and reduced erosion and turbidity

Anecdotal and some historical evidence suggest that populations of aquatic plants have generally declined in NSW rivers over the last century, but the causes of this decline and the role of altered hydrological regimes are poorly understood (Roberts and Sainty 1996). Apart from a few case studies, the effects of flow changes on riparian vegetation are also little understood.

It is unlikely that a broad-scale general monitoring program will lead to a clear understanding of the effects of RFOs on aquatic and riparian vegetation. Detailed vegetation surveys are costly, and distinguishing the effects of flow changes from confounding factors (e.g., stock grazing, invasion of alien plant species and disturbance by carp) is likely to be difficult. Manipulative experimental studies are likely to stand a greater chance of success.

If broad-scale monitoring is to be considered to document long-term trends, cost-effective techniques such as those using satellite imagery are likely to be necessary to achieve required accuracy and quantification.

Reduced frequency of algal blooms

Existing programs such as Barwon-Darling Riverwatch provide some information on the occurrence and persistence of algal and cyanobacterial blooms. Blooms occur only in particular water bodies, and monitoring could concentrate on these. A high monitoring frequency would be required to assess temporal trends accurately.

6. Likely flow changes under current flow rules

Flow volumes in regulated lowland rivers can be divided into five ranges (Table 1; Figure 1). Given the relatively small volumes of water available for environmental flows, flow rules will impact most often on the low-moderate range. However, at times the effects of the rules will extend across the full spectrum of flows.

Table 1. Flow ranges for regulated rivers in NSW (after EPA 1997)

Flow range	Approximate percentage of time flow is exceeded	Comments
Low flows/ drought	65 – 100	Abstraction for stock and farmstead use in this flow range. Regulation often maintains these flows above natural levels
Moderate flows	25 – 65	Irrigation flows are generally in this range. Water extraction can reduce frequency of these flows downstream of irrigation areas
Freshes	10 - 25	Volume and frequency substantially reduced in most regulated rivers because of capture in storages
Floods	<10	Downstream flooding can be reduced if upstream reservoirs have been heavily drawn down in antecedent dry spells

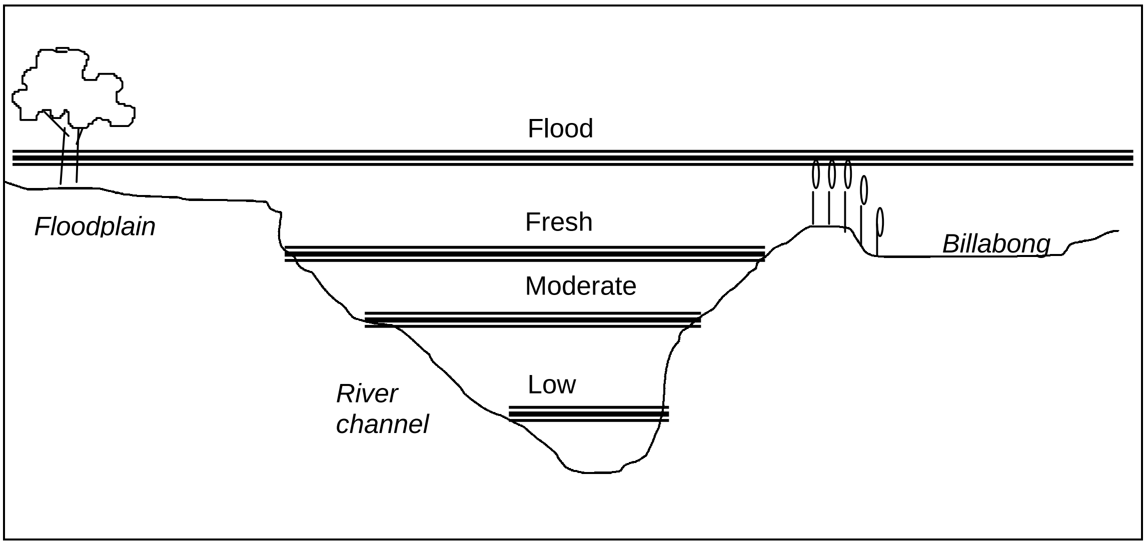

Figure 1. Different flow levels in a river-floodplain system

Different combinations of flow rules apply to each river system (see Appendix 1), but they can mostly be grouped into six categories.

Category 1: embargos and diversion limits

The MDBC Cap limits diversions to those occurring under 1993-94 levels of development. In the Hunter Valley, rules restrict the issuing of new licences for high-yield groundwater bores and extraction from the regulated section of the Hunter River. These rules will limit further erosion of both low and higher flows.

Category 2: pumping thresholds

Thresholds prohibit water extraction if river levels are below a particular stage height. In the Barwon-Darling River, a complex series of thresholds exists for different classes of licences. Class A licences, which are generally issued to provide small amounts of water for stock and farmstead use, have lower thresholds than the large Class C irrigation licences, with Class B licences falling in between.

The main effect of imposing and raising thresholds is to protect low flows. Thresholds can also have an effect on flow variability, since there may be a tendency for pumping to stabilise flows near the threshold for extended periods.

Category 3: end-of-system flows

End-of-system rules require certain minimum flows to be retained at the downstream ends of rivers, below the areas where major extraction occurs. These rules prevent excessive draw-down under dry conditions.

Category 4: transparent and translucent dam rules

Some rules require variable releases from dams during the non-irrigation season, instead of the small and stable riparian releases that have generally been made in the past. The terms ‘transparency’ and ‘translucency’ have been used to refer to the release of the whole or a proportion of reservoir inflows respectively. Dam releases enable some approximation of natural flow variability in the low-to-medium flow range to be maintained for at least part of the year, and may be used to provide wetland flooding, particularly in conjunction with unregulated tributary flows. Upper limits on such releases may be imposed by the capacity of dam outlet works, the impact on the volume of water stored for later use, or the need to prevent downstream flood damage or economic losses.

Category 5: off-allocation access rules and high-flow rules

‘Off-allocation’ periods can be declared on inland rivers when reservoirs spill or high flows enter from unregulated tributaries. During such periods, irrigators can pump water without the quantity being debited from their annual entitlement. Off-allocation rules can set flow thresholds for off-allocation access and restrict the amount of water that can be extracted during such periods, or control its timing. They apply mainly in the northern river systems (i.e., the Gwydir, Namoi and Macquarie rivers), since water use in the south is generally within allocation. ‘High-flow’ rules in the Hunter Valley are analogous to off-allocation rules.

Such rules may vary according to event size, and between seasons and sections of the hydrograph (e.g., extractions may be allowed only on the rising stage of the hydrograph). They can help to preserve a component of natural freshes and floods.

Category 6: environmental allocations

These rules create a ‘bank’ of reservoir water that can be used specifically for environmental purposes, variously referred to as an Environmental Contingency Allowance (ECA) or Wild Life Allocation (WLA). These allocations were generally developed for specific purposes such as flushing of cyanobacterial blooms or sustaining waterfowl breeding events. This implies a more interventionist approach to environmental management than the other categories of rules, which focus on protecting a component of natural flow patterns. However, contingency allowances can also be delivered in ways that mimic natural flow.

7. Sensitive ecosystem components and attributes

Monitoring of the effects of environmental flows can be based on physical variables (flow, hydraulics and geomorphology), chemical variables (water quality), biological variables (groups of plants and animals), ecological variables (ecosystem process measurements) or some combination of these. Because it is not practical to measure all available variables, the most sensitive ones need to be identified and selected. In this section, a range of candidate variables and their potential importance and sensitivity are briefly reviewed.

Hydrology

Changes in river flows, water levels in wetlands and groundwater recharge will be the immediate effects of the implementation of environmental flow rules. In most cases flow rules will generate higher flows and water levels, but in some instances flow rules may result in reduced watering at particular times. Hydrological monitoring is necessary, firstly to determine whether intended environmental flows have actually been delivered, and secondly, to provide hydrological measures that can be correlated with ecological changes.

The existing hydrographic network is geared primarily to providing information on water level and flow rate at river stations, but IMEF may require other hydrological information such as wetted area and depth in both river channels and wetlands. Recent extensions to the DLWC’s IQQM (Integrated Quality and Quantity Model) software can be used to relate flow to wetted area and to compare actual inundation with that which would have occurred had environmental flow rules not been implemented. Satellite imagery may be useful to monitor inundation (Green *et al.* 1998).

Hydrology can be viewed on three temporal scales: flood pulse (days – weeks), flow history (weeks – years) and flow regime (decades or longer) (Thoms and Sheldon 2000). At each scale, continuous water-level data can be summarised by a range of statistics indicating both central tendency and variability (Poff 1996; Richter *et al.* 1996; Puckridge *et al.* 1998; Sheldon *et al.* 2000). For the Hawkesbury-Nepean River, Growns and Growns (1997) have related spatial patterns in such statistics to variations in the composition of diatom and invertebrate communities; Clausen and Biggs (1997, 1998) have done similar analyses for New Zealand streams. NSW Fisheries has a current research project that is examining the relationships between hydrological indices and fish communities throughout the State. While hydrological statistics and indices are readily calculated from continuous or monthly flow data, the major difficulty lies in deciding which of the hundreds of possible indices are ecologically most relevant.

Hydraulics

Hydrological changes affect the aquatic biota primarily by modifying the hydraulic environment (Statzner and Higler 1986). For example, greater flow increases water depth and velocity, which in turn affect turbulence, shear stress and the boundary layers above submerged objects. These factors may be closely associated with the composition of plant, macroinvertebrate and fish assemblages (Growns and Davis 1994; Quinn and Hickey 1994; Biggs 1996; Lamouroux *et al.* 1999). Hydraulic variables cannot be predicted simply from flow volume, because they depend on other factors such as stream gradient, channel geometry and substratum roughness.

Physical adjustments: channel morphology and sedimentology

Channel morphology can show a complex response in space and time to upstream impoundment (Petts 1980; Ligon *et al.* 1995). Obvious morphological changes below some NSW reservoirs are scouring of the immediate downstream zone where the sediment supply has been interrupted by impoundment, and conversely, channel narrowing and encroachment by vegetation where mean annual flow or flood frequency and magnitude have been reduced (Rutherfurd 2000). Changes in sediment composition are associated with these morphological differences. Artificially elevated rates of rise and fall are often hypothesised to induce slumping and other forms of erosion, but little supporting evidence is available (Rutherfurd 2000).

Flows at particular levels may serve to maintain certain geomorphological features in river channels because they entrain the movement of substratum particles of particular sizes (critical flows). If these flows are removed, the features may be gradually lost. Thoms and Sheldon (1996, 1997) have reported that flatter portions of the channel cross-section in the Darling River between Walgett and Wilcannia coincide with water levels that occur frequently. However, it is not clear which is the cause and which is the effect in this relationship. It may be that frequent flows mould the flatter features at the levels at which they occur, but conversely, the ‘banding’ of water levels may be simply because a greater increase in flow is needed to produce a given rise in water level on a gently sloping bank than on a steep bank.

It seems unlikely that environmental flow rules will induce measurable shifts in channel morphology during the life of IMEF, since the hydrological changes effected by environmental flow rules are so small in comparison with overall flow variation. Ongoing morphological adjustments to altered runoff following clearing (Walker *et al.* 1993), and natural long-term hydrological cycles, particularly between drier and wetter climatic periods lasting for several decades (Warner 1995), are likely to obscure any small responses to flow rules. The time lags for observing channel changes in response to environmental flow rules are also likely to be in the order of decades or more, since even the major changes occasioned by flow regulation can take centuries to reach equilibrium (Church 1995).

Water quality

Many water quality characteristics are well known to vary with river discharge, mainly because of the role of streamflow in dilution of point-source discharges, and temporal variations in the relative contributions to streamflow from groundwater influx (generally high in dissolved constituents) and surface runoff after rainstorms (generally high in suspended constituents mobilised by erosion). Relationships with flow are often complex, depending on the sources of the constituents (point-source discharges or diffuse runoff from catchments) and runoff patterns. For diffuse inputs, the patterns of constituent concentrations over the duration of high flows will be determined by where the rain falls in relation to land use, supply of the constituent, and rainfall duration and intensity. The contribution of diffuse source inputs can also vary with the time of year that rain occurs; for example, pesticides and herbicides are applied only at certain stages of crop development and the concentrations in storm runoff will be highest when rainfall coincides with pesticide application. Finally, variation in climatic conditions will also influence the relationship between constituent concentration and flow. Overland flow will be greater following prolonged dry periods when there is little ground cover to inhibit runoff. Water quality in NSW wetlands is also influenced by the water regime. Flooding of dry soils releases nutrients that may be subsequently taken up as a result of biological activity (Briggs *et al.* 1985).

Storage management directly influences downstream water quality according to patterns of reservoir stratification and depths from which water is released. Most large dams in NSW release water from near the bottom, which can result in a downstream suppression of the annual temperature range (warmer in winter; colder in summer) and a lag in the seasonal cycle (Walker 1979). These effects can persist in an attenuating form for hundreds of kilometres (Walker *et al.* 1979). Bottom-release water may also be depleted of oxygen and enriched with iron, manganese and sulphide (Walker 1979), which can be toxic to sensitive forms of aquatic life. Regardless of the provision of environmental flows, there is little scope to improve the quality of releases from such storages unless multi-level outlets are installed.

It is important to appreciate that changes in water quality associated with environmental flows are likely to be less than changes associated with flow shifts that are of similar magnitude, but result from natural runoff. For example, an artificial spate produced by a controlled reservoir release would be expected to produce much lower suspended sediment concentrations than a natural spate after heavy rainfall. However, environmental releases from reservoirs could provide significant local dilution of wastewater inputs such as discharges from sewage treatment plants and drainage from irrigation districts. There may also be some opportunities to improve the quality of reservoir releases by using more appropriate offtake levels.

The key water quality variables that are likely to be affected by environmental flows are temperature (relevant to fish breeding and shifts in aquatic ecosystems in general), electrical conductivity (relevant to suitability for irrigation and aquatic ecosystems; see for example Goonan *et al.* 1992), turbidity (relevant to aesthetics, cyanobacterial and algal blooms and macrophyte growth), dissolved oxygen (particularly in relation to stratification in weir pools and deep natural pools), soluble reactive phosphorus, oxidised and ammoniacal nitrogen (relevant to cyanobacterial blooms and aquatic plant productivity) and dissolved organic matter (relevant to microbial productivity). Other variables such as pH and pesticides may be ecologically relevant locally, but their response to environmental flows is likely to be much less than their response to other factors such as disturbance of acid sulphate soils and patterns of agrichemical use and surface runoff. Vertical thermal stratification is an especially important phenomenon because of its influence on algal and cyanobacterial blooms (Bormans *et al.* 1997; Sherman *et al.* 1998), and is highly dependent on flow (Bormans and Condie 1998).

Many water quality variables have high temporal and spatial variability, so that a high sampling frequency is required for adequate assessment; this impacts on monitoring costs.

Periphyton (biofilms) and sediment microbes.

Periphyton assemblages comprise algae, fungi, bacteria and detritus, often embedded in a polysaccharide matrix, attached to underwater stones and other firm surfaces (Geesey *et al.* 1978, Lock *et al.* 1984). Algal and cyanobacterial-dominated periphyton may be an important energy source for food webs in Australian billabongs (Bunn and Boon 1993) and dryland rivers (Walker *et al.* 1995; Bunn and Davies 1999). However, there is little information on the sensitivity of periphyton to flow alteration in Australian rivers. Chessman (1985a) found that periphyton biomass in the LaTrobe River, Victoria, was related to annual cycles in both flow and nutrient concentrations. Burns *et al.* (1994) compared periphytic algal assemblages upstream and downstream of Lock 1 on the lower Murray River. Biomass peaked at shallow depths above the lock where water levels were relatively stable and in deeper water below, where levels fluctuated. Community composition varied more with depth at the downstream site. Burns and Walker (2000) suggested that river levels could be managed to maintain diverse successional stages of biofilms as resources for grazing macroinvertebrates.

River periphyton is prone to scouring during high flows (Biggs *et al.* 1999a). Scouring resistance and post-spate biomass are governed by interactions between water velocity, light, nutrient availability, recolonisation mechanisms and macroinvertebrate grazing (Horner and Welch 1981; Lindström and Traaen 1984; Keithan and Lowe 1985; Stevenson 1990; DeNicola *et al.* 1992; Peterson *et al.* 1994; Biggs 1995; Poff and Ward 1995; Peterson 1996; Biggs *et al.* 1998a, 1999b; Bourassa and Cattaneo 1998). Different algal groups are best adapted to particular frequencies of resource supply and physical disturbance (Biggs *et al.* 1998b), and an intermediate level of flood disturbance can maintain a high diversity of periphytic algal species (Ács and Kiss 1993; Fayolle *et al.* 1998).

Biofilms are also an important element in wetlands, where they may play a major role in carbon fixation (Bunn and Boon 1993). Wetland sediments also harbour a diverse microbial flora, whose composition appears to be related to the water regime (Boon *et al.* 1996).

Filamentous benthic algae

Removal of nuisance growths of benthic algae is sometimes an objective of environmental flow allocations (e.g., Elber *et al.* 1996). However, such nuisance growths do not seem to be a major issue for the regulated rivers of NSW. In some circumstances, filamentous algae can play an important role in food webs (Bunn and Davies 1999).

Phytoplankton and bacterioplankton

Phytoplankton populations in rivers are highly dynamic because the constituent algal and cyanobacterial species have short life cycles and, within underlying seasonal patterns, are governed by complex and often rapidly-changing interactions between turbulence, light regimes, nutrients, competition and grazing (Sullivan *et al.* 1988; Sullivan 1990). The role of flow as a regulating factor for Australian riverine phytoplankton has been established by correlative studies (Burch *et al.* 1994; Hötzel and Croome 1994; Sherman *et al.* 1994; Bowling and Baker 1996; Oliver *et al.* 1998; Webster *et al.* 2000; Mitrovic *et al.* 2001), and confirmed by successful flow-related modelling of population responses (Bormans and Webster 1994; Bormans and Condie 1998). Wetland phytoplankton communities are also highly individualistic, and different patterns of seasonal succession occur in each water body (Suter *et al.* 1993).

Standard sampling protocols for phytoplankton in Australian rivers are well developed (Hötzel and Croome 1998) and substantial progress has been made in the use of fluorimetry and other rapid techniques (Oliver *et al.* 1995). Nevertheless, detailed monitoring of changes in phytoplankton species composition is expensive because of the sampling frequency required to cope with high spatial and temporal variability (cf. Hötzel and Croome 1994; Bowling and Baker 1996).

Much of the focus on phytoplankton in Australian lowland rivers relates to the development of blooms, particularly of cyanobacteria, that are detrimental to human consumptive and recreational uses of water (Wasson *et al.* 1996). However, phytoplankton and bacterioplankton play major roles in carbon dynamics of lowland rivers (Robertson *et al.* 1999). Planktonic bacteria occur in wetlands, and to a lesser extent rivers, in large numbers (Boon 1991) where they play a major role in the processing of dissolved organic carbon (Findlay and Sinsabaugh 1999). The response of planktonic bacteria to flow regimes in Australian rivers is not well understood (Robertson *et al.* 1999).

Zooplankton

As for phytoplankton, the major issue involved in the monitoring of zooplankton is high temporal and spatial variability. The Darling and Murray rivers are dominated by two very different plankton communities (Shiel 1978, 1990). The Darling supports a warm-water, riverine assemblage dominated by rotifers and protozoans whereas the Murray upstream of the Darling confluence carries a lacustrine fauna dominated by Cladocera, Copepoda and Rotifera. The zooplankton of the Murray below the confluence comprises a diverse assemblage largely determined by the relative inputs from the two river systems (Shiel *et al*. 1982; Shiel and Walker 1984). The creation of extensive impoundments on the River Murray has largely displaced the ‘billabong’ species with lacustrine species adapted to colder, deeper waters. Downstream of these reservoirs, the zooplankton is composed of an element from the impoundments and a billabong element from the floodplain, the relative proportions depending on connectivity with the floodplain and river heights.

Billabongs contain a highly diverse range of zooplankton in abundances that are likely to be an order of magnitude higher than in reservoirs (Shiel 1990). The distribution of zooplankton among different billabongs is extremely patchy, each billabong having a different assemblage reflecting the heterogeneity of environmental conditions (Boon *et al*. 1990; Suter *et al*. 1993).

Zooplankton densities and species composition are highly patchy in space and over short time scales (Shiel *et al.* 1982). Community composition is influenced by physical and chemical conditions and by biotic interactions (e.g., predation, competition and phytoplanktonic food supply). The assemblage at a particular location may change rapidly as different water sources from tributaries transport new assemblages down a river. Zooplankton communities are highly responsive to changes in flow, particularly broad-scale flooding and the wetting and drying cycles in temporary wetlands (Crome and Carpenter 1988; Boulton and Lloyd 1992; Suter *et al*. 1993; Nielsen *et al.* 2000). It has been hypothesised that these cycles are important in maintaining overall species richness, since there appear to be fugitive species that colonise temporarily after wetting (Crome and Carpenter 1988).

There is evidence that zooplankton body mass is negatively correlated with river flow, although other factors such as turbidity, temperature and food conditions may also be correlated with biomass (Pace *et al*. 1992; Basu and Pick 1996; Kobayashi 1997). These other factors are often related to flow.

Macroinvertebrates

Macrobenthic communities in rivers and wetlands are typically dominated by aquatic insects, although they have a strong representation of annelid worms, molluscs, crustaceans, mites and other macroinvertebrate groups. A wealth of international literature demonstrates that macroinvertebrate assemblages are generally sensitive to anthropogenic alteration of water regimes. However, little information is available on macroinvertebrate responses to flow regulation in NSW rivers and wetlands. Long-term monitoring of 14 sites on the Murray River and its tributaries showed a gradual longitudinal change along the river but also marked reductions in abundance and taxonomic richness immediately downstream of the Hume Dam and Yarrawonga Weir, and in South Australia (Bennison *et al.* 1989). Comparative studies of the Darling, Diamantina and Cooper and Murray rivers by Sheldon and Walker (1998) have suggested that an interaction between flow regimes and habitat heterogeneity may be important in structuring macroinvertebrate communities. Similar findings have been reported elsewhere (e.g., Humphries 1996; Humphries *et al.* 1996), and suggest that monitoring of macroinvertebrates needs to be tied to habitat assessment.

Macroinvertebrate communities of wetlands in the Murray-Darling basin generally show a strong response to flooding (Maher 1984; Maher and Carpenter 1984; Suter *et al.* 1993; Quinn *et al.* 2000). Flooding after dry periods results in a rapid succession of macroinvertebrate populations in association with emergence from desiccation-resistant eggs and other methods of recolonisation. Boulton and Lloyd (1992) and Jenkins and Boulton (1998) found that more frequently flooded soils yielded the greatest biomass and numbers of emerging invertebrates, although many species hatched from soils that had not been flooded for many years. Following falls in floodwaters, the invertebrate communities of the main river channels are enriched (B. Chessman, pers. obs.). The various habitats in freshwater wetlands support very different macroinvertebrate communities, and there is some evidence that intermittently flooded wetlands may support more diverse communities than permanently flooded water bodies (Boulton and Lloyd 1991). In a mesocosm study near Albury, Nielsen *et al.* (1999) found that seasonal temperature cycles, the abundance of macrophytes and the presence of fish had a greater impact on macroinvertebrate communities than water regime *per se.* However, the variations in macrophytes that they observed were influenced by water regimes (Nielsen and Chick 1997), and the regimes they tested did not involve drying phases.

Freshwater mussels

Six species of freshwater mussel are found in the rivers, south of the Richmond River, draining to the east coast: *Velesunio ambiguus, Hyridella australis, H. depressa*, *H. drapeta*, *Alathyria profuga* (two forms) and *Cucumerunio novaehollandiae*. The effects of flow regulation on these eastern species are poorly understood, although large populations of *H. depressa* live in major storages on the Hawkesbury-Nepean and Shoalhaven river systems. All species of *Hyridella* and *V. ambiguus* breed only in the warmer months but spawning of *C. novaehollandiae* is highly synchronised and occurs in late summer or autumn. It may be triggered by flooding when mussels are in the advanced stages of gametogenic development (Jones *et al*. 1986).

Only three species of freshwater mussel occur in the Murray-Darling basin: *Velesunio ambiguus*, *Alathyria jacksoni* and *A. condola*. *A. condola* is restricted to parts of the Lachlan and Murrumbidgee rivers and possibly the middle sections of the Murray River. The ecology of *V. ambiguus* and *A. jacksoni* in the lower River Murray is well understood (Walker 1981, 1990) and the distributions of these species appear to have altered in response to river regulation. *V. ambiguus* is a ‘floodplain’ or ‘billabong’ species with physiological adaptations that enable it to withstand drought and periods of anoxia. *A. jacksoni*, on the other hand, is far narrower in its physiological tolerances and is confined to the deeper parts of river channels that are well oxygenated. The construction of weirs on the river has favoured *V. ambiguus* over *A. jacksoni* (Walker 1990), probably because the changed flow conditions have allowed the development of stratification and consequent anoxic conditions within weir pools.

The distribution and relative abundances of *V. ambiguus* and *A. jacksoni* in other parts of the Murray-Darling basin are poorly understood and little is known of their status prior to flow regulation. Museum records and the presence of freshwater mussels in aboriginal middens could be useful for establishing historical and prehistorical distributions.

The decline in native fish populations together with the large numbers of weirs that impede fish movement along rivers of the Murray-Darling basin have probably also impacted on freshwater mussel populations, since fish are obligate hosts for mussel larvae.

Aquatic snails

Historically the inland river systems of south-eastern Australia supported rich assemblages of aquatic snails. In the River Murray in South Australia, a marked decline in populations of most species, and local extinctions of some, have paralleled increasing flow regulation over the past half century (Sheldon and Walker 1993). The viviparids *Notopala sublineata sublineata* and *N. s. hanleyi* and the thiarid *Thiara balonnensis* have been particularly affected. Sheldon and Walker (1997) have speculated that the loss of detritivorous snails is related to a shift from bacterially to algal-dominated littoral biofilms occasioned by stabilisation of river levels following the construction of dams and weirs. Extensive surveys of the western rivers of NSW have failed to locate any extant populations of *Notopala*, and have found *Thiara* at only a few localities (DLWC unpublished data). The rarity of these snails may make their use in IMEF problematic, whereas those snail species that are still abundant are likely to be insensitive to changes in managed flow regimes.

Decapod crustaceans

Two freshwater crayfish species, the yabby *Cherax destructor* and the Murray crayfish *Euastacus armatus*, are widely distributed in the Murray-Darling basin. The latter is restricted to flowing waters and is less tolerant of reduced oxygen concentrations that the former, which is abundant in wetlands (see McKinnon 1995). *E armatus* may be extinct in South Australia (Walker 1986) and is believed to have declined in abundance throughout much of its range, possibly through overfishing (Geddes 1990). While this species may have been disadvantaged by flow regulation, there is a lack of direct evidence.

The shrimp *Paratya australiensis* and the prawn *Macrobrachium australiense* are widespread in the Murray-Darling basin. Both species are extremely abundant and therefore do not appear to have been disadvantaged by flow regulation.

Fish

Native species

Commercial catch statistics and anecdotal information indicate that populations of at least the larger native freshwater fish species have declined appallingly over much of NSW over the last 180 years (Faragher and Harris 1994). Strong circumstantial evidence suggests that these declines are due in large measure to interference with migration through the construction of dams, weirs and levees, and interference with environmental cues for spawning (temperature depression from hypolimnetic releases and reduced flooding frequencies) (Cadwallader 1978; Cadwallader and Lawrence 1990). For example, two warm-water species, the golden perch (*Macquaria ambigua*) and the freshwater catfish (*Tandanus tandanus*), apparently disappeared from the Murray River downstream of the Hume Dam shortly after its construction (Cadwallader 1977). Likewise, Dartmouth Dam resulted in the loss of native warm-water fishes from the lower Mitta Mitta River, Victoria (Koehn *et al.* 1995 cited in Thoms *et al.* 2000). In coastal rivers, about half of the total stream length potentially available to migratory species such as Australian bass (*Macquaria novemaculeata*) has been alienated by the construction of artificial barriers (Harris 1984). Recruitment of this species in the Hawkesbury-Nepean River system appears to be positively correlated with the magnitude of river discharge (Harris 1988). Gehrke *et al.* (1995, 1999) compared the native fish fauna at sites on the Darling, Murray, Murrumbidgee and Paroo rivers, and observed a strong correlation between the diversity of native fish (measured by the Shannon-Wiener index) and the deviation of monthly flows from the natural regime.

Since fish, especially the larger species of interest to anglers and commercial fishers, are long-lived and migrate over large distances (Llewellyn 1968; Reynolds 1976), changes in populations in response to environmental flow rules are likely to be slow and evident at large spatial scales. The low numbers of some native fish species may inhibit population recovery. Recovery may also depend on climatic patterns such as a series of floods and favourable conditions following spawning. The modification or removal of in-stream structures in conjunction with refinement of environmental flow management may also be needed.

The recent development of techniques for sampling of fish larvae (Humphries and Lake 2000) raises the possibility of assessing fish breeding success rapidly and at smaller spatial scales. This could be done after specific events, such as artificially maintained or enhanced freshes and consequent flooding of breeding habitat. However, it is important to recognise that the presence of large numbers of native fish larvae does not guarantee that these larvae will survive and be recruited into the adult population. Fish recruitment may be difficult to relate to environmental flows because of the large spatial scale at which responses occur. For example, riverine fish could be recruited as a result of reproduction in floodplain wetlands, and the survival of juvenile fish to adulthood may also be largely dependent on the availability of these wetlands as nursery areas (but see Humphries *et al.* 1999).

Alien species

Recent studies (Gehrke *et al.* 1995; Harris 1997; Harris and Gehrke 1997; Gehrke and Harris 2000) have found that alien species such as carp and gambusia dominate fish catches in many rivers. Native species richness tends to be lower, and the proportion of alien species higher, in highly regulated rivers than in unregulated or semi-regulated systems.

Waterbirds

In south-eastern Australia the breeding of many waterbirds is enhanced during periods of high rainfall when wetlands are inundated (Crome 1988; Kingsford *et al.* 1999). Altricial waterbirds (those that feed their young) will breed successfully in wetlands that are flooded for at least four months and have suitable nesting habitat (Briggs *et al.* 1997). Some species, such as darters, great cormorants and Pacific herons, will nest in the dead river red gums that characterise many wetlands that have been converted from temporary to permanently flooded by hydrological control. Others such as little black cormorants, little pied cormorants, white-faced herons and yellow-billed spoonbills prefer live trees at the edge of open water in wetlands that are flooded for shorter periods. Precocial waterbirds such as ducks, whose young feed independently and so depend on the nesting wetland for food, favour neither those wetlands with erratic fluctuations in water levels nor those with stable permanent water. This may be a consequence of the greater availability of aquatic invertebrates and plants in wetlands with intermediate water regimes (Broome and Jarman 1983; Maher and Carpenter 1984; Briggs and Maher 1985; Roberts and Ludwig 1991; Briggs *et al.* 1997). River regulation has reduced breeding success of many waterbirds by decreasing the frequency and extent of inundation. Permanent flooding of formerly temporary wetlands as a result of hydrological controls may have partly compensated, but mainly for altricial species (Briggs *et al.* 1997).

Suter *et al*. (1993) regarded waterbird numbers as often too variable in space and time to be of much use as an ecological indicators. They point out that the scarcity of waterbirds in an area does not necessarily mean that conditions are unfavourable; because of their high mobility, birds could be taking advantage of even more suitable conditions elsewhere. Nevertheless, waterbird abundances have been successfully related to hydrological regimes at a local scale (e.g., Briggs *et al.* 1998).

Amphibians, aquatic reptiles and aquatic mammals

In general, frogs are likely to be most affected by environmental flow rules through enhanced breeding opportunities. Breeding is likely to be localised in time and space, according to the distribution of adult populations and the seasonal timing of breeding of each species. Frogs are most active on warmer, humid nights and following rainfall (Cogger 1992; Robinson 1993; Barker *et al.* 1995). Frog populations at breeding times can be assessed through recording of male mating calls.

Aquatic and water-dependent reptiles in NSW include tortoises, certain snakes, water dragons and water skinks. Different tortoise species show particular preferences for permanent or temporary water bodies, and changes in flow regimes are likely to have been to the detriment of the snake-necked tortoise, *Chelodina longicollis*, which is adapted to exploit flooding of temporary water bodies (Chessman 1989). Specimens collected from river channels after long periods without flooding sometimes show symptoms of partial starvation (B. Chessman, pers. obs.). Riparian snakes such as the red-bellied black snake (*Pseudechis porphyriacus*) may also be dependent on flooding to produce a food supply of frogs and other fauna. The effects of changes in flow regimes on the platypus are poorly understood, though the general environmental requirements of the species are known (Grant and Bishop 1998).

Aquatic and semi-aquatic vascular plants

The responsiveness of south-eastern Australian aquatic and floodplain plants to water regimes has been demonstrated by both observational and experimental studies (Briggs and Maher 1985; Bren and Gibbs 1986; Brock 1986; Craig *et al*. 1991; Bren 1992; Walker *et al.* 1992; Bacon *et al.* 1993; Rea and Ganf 1994; Brock and Casanova 1997; Nielsen and Chick 1997; Ackeroyd *et al.* 1998; Blanch and Walker 1998; Blanch *et al.* 1999; Casanova and Brock 2000; Nicol and Ganf 2000). Some species such as cumbungi (*Typha* spp.) and ribbon plant (*Vallisneria americana*) are strongly favoured by hydrological stability and are typically associated with permanently wetted sites. Floodplain species range from those associated with frequent flooding, such as giant rush (*Juncus ingens*), through those favoured by moderate flooding frequencies (e.g., moira grass, *Pseudoraphis spinescens*), to those like lignum (*Muehlenbeckia florentula*) that thrive under infrequent flooding. Many species, for example common reed (*Phragmites australis*) and water couch (*Paspalum distichum*), tolerate a wide range of flooding and drying regimes (Blanch *et al.* 1999). These interspecific differences allow the various plant species to be classified into functional groups according to their water regime responses (Brock and Casanova 1997). As a result of their effects on plant life cycles, temporal patterns of drying and flooding influence macrophyte succession and production (Maher 1984; Briggs and Maher 1985).

Flow regulation has had a dramatic effect on the extent and condition of aquatic and semi-aquatic vegetation in floodplain wetlands, for example in the Gwydir wetlands and Macquarie Marshes (Kingsford and Thomas 1995; Kingsford 2000). It has been hypothesised that more permanent wetting or drying will result in lower species richness than fluctuating water regimes (Brock and Casanova 1997), and experimental data lend some support to this notion (Nielsen and Chick 1997). The situation in rivers is less clear; anecdotal evidence suggests widespread historical declines of water plants (e.g., Roberts and Sainty 1996) but the causes are poorly understood. Changes in littoral plant communities along the lower River Murray have been described by Walker *et al.* (1994) and Blanch *et al.* (2000). In many cases, the effect of water regimes on both riverine and wetland vegetation may be confounded by the effects of grazing and trampling by stock, and other farming impacts (Robertson 1997; Ogden 2000; Robertson and Rowling 2000).

One feature of plants that does not apply to most other indicators is that the extent and condition of emergent and riparian vegetation can be mapped at broad spatial scales by satellite imagery (e.g., Shaikh *et al.* 1998) or airborne radar techniques.

Ecosystem processes

Numerous ecosystem processes can be considered in restoration ecology (Ehrenfeld 2000). Two areas of functional ecology that have received particular attention in relation to Australian river regulation are energetics and responses to physical disturbance.

Energetics and production

Changes in flow regimes are likely to have many effects on energy sources and transformation in the lowland rivers of NSW. The effects of flow on phytoplankton, biofilm and macrophyte composition and abundance (discussed above) will be reflected in fluctuations in planktonic and benthic primary productivity (e.g., Briggs and Maher 1985; Chessman 1985b). Allochthonous sources of energy will also be affected by river flow and wetland inundation. Trees such as *Eucalyptus camaldulensis* contribute large quantities of litter to lowland rivers and floodplains in south-eastern Australia (Briggs and Maher 1983). Some of this litter falls directly into water bodies at times of low flow, but much of it remains on dry floodplains (Robertson *et al.* 1999) and in-channel surfaces (Thoms and Sheldon 1996, 1997) until inundated by rises in river levels. While shredding macroinvertebrates may play only a minor role in leaf processing in these rivers (Francis and Sheldon in prep.), dissolved organic matter (DOM) is readily leached from wetted leaves (Baldwin 1999; Glazebrook and Robertson 1999; Francis and Sheldon 2000), and subsequently used as a food source by bacteria (Baldwin 1999) and probably fungi (cf. Findlay and Sinsabaugh 1999). Microbes feeding on DOM are probably in turn one of the primary food sources for zooplankton (Boon and Shiel 1990). The full implications of the erratic pulsing of litter availability to NSW floodplain rivers are not understood. However, studies in other countries show that floodplain inundation stimulates organic matter exchange and the production of riverine fish and other biota (Junk *et al.* 1989; Bayley 1991; Ward and Stanford 1995; Tockner *et al.* 1999).

Stable isotope ratios have been used with some success to elucidate patterns of nutrient and energy flow through Australian aquatic ecosystems (e.g., Bunn and Boon 1993). They could be a potential technique for investigating food web shifts occasioned by flow manipulation, although some aspects of this approach are still somewhat controversial (e.g., Doucett *et al.* 1996; France 1996). Direct assessments of whole-river metabolism can be made by diel oxygen measurement (e.g., Chessman 1985b), and measurements can be made at a smaller scale of substratum patches using chambers (Treadwell *et al.* 1997; Bunn *et al*. 1999).

Disturbance regimes

An area of river research developing rapidly in recent years is the study of disturbance regimes and their relationships to biological communities, particularly biofilms and macroinvertebrates (Lake 1990). Most such studies have involved artificially disturbing small patches of stream beds and measuring consequent patterns of species loss and recolonisation, observations that have dubious relevance to broad-scale disturbance resulting from major hydrological events (Bond and Downes 2000). However, recently techniques have been developed for assessing bed movement in upland rivers as one measure of the disturbance regime (Downes *et al.* 1997, 1998; Townsend *et al.* 1997a). Measurements of disturbance can be coupled to biological community studies (e.g., Townsend *et al.* 1997b), in the context of ecological theory such as the intermediate disturbance hypothesis (Grime 1973). These types of studies can help to elucidate the disturbance regimes that are associated with maintaining a high level of species diversity.

In lowland rivers and wetlands disturbance might be measured as frequencies of littoral drying and wetting rather than bed scouring or movement.

Conclusions

IMEF hypotheses would ideally incorporate ecologically important variables that will respond to the implementation of flow rules. A wide range of biota and ecosystem attributes has been reviewed, and most if not all of them are sensitive to flow variation in broad terms. However, it is not an easy matter to anticipate likely responses to flow rules. The main problems are in assessing the following:

- the strength of likely responses,
- relationships of each variable to different types of flow rules,
- the likely spatial scales and spatial variability of responses,
- the likely form of the response over time (e.g., time lags, pulse and press responses, other temporally variable responses), and
- the likelihood of interactions among the response variables (and with confounding variables) and potential difficulties in unravelling these.

Anthropogenic impacts can be classed as first, second and third-order according to their time-lags (Petts 1987). First-order impacts are immediate effects on environmental processes such as water movement and sediment transport. Second-order impacts are changes in form resulting from alterations to processes (e.g., changes in channel morphology), which may gradually reach a new equilibrium over periods of up to a century or even longer. Finally, third-order impacts constitute ecological adjustments to changes in form, such as long-term shifts in fish and invertebrate populations in response to altered habitat conditions. These third-order responses may also take long periods to develop.

First-order responses are easiest to measure and interpret because they occur rapidly and often have an unequivocal link to altered management. However, community concern over the impacts of flow regulation on ecosystems often relates to second or third-order impacts such as changes in channel morphology, declines in fish populations and increases in the incidence of toxic cyanobacterial blooms. These responses are more problematic to assess because they are related to management intervention through a series of steps, in interaction with other factors, making causal links difficult to establish.

In these circumstances the safest strategy for IMEF is to include hypotheses that embody a combination of variables — physical, chemical, biological and ecological, and first-order, second-order and third-order. Such an approach should provide the necessary mix of process understanding and long-term tracking of the condition of critical ecological resources. For each type of variable specific measurements can be selected that are expected to be sensitive to flow rules, at least as far as can be determined from available information.

8. Development of hypotheses

The format selected for the hypotheses combines RFOs, flow rules, environmental benefits and biophysical mechanisms. Hypotheses were not developed for some RFOs, as they either do not apply to the seven valleys included in the project, or are not addressed by the current rules. RFO1 refers to river water levels during periods of no flow and is not relevant to regulated rivers, where some flow is always maintained for stock and farmstead supply. RFO8 is not pertinent to IMEF as it relates to groundwater. RFO9 relates to artificial in-stream structures that prevent the migration of fish and other animals. It is marginally relevant to IMEF in that in some cases environmental flows may drown weirs and so permit fish passage for short periods. However, the issue of fish passage is best addressed by the provision of permanent fishways. Hypotheses were not framed around the effects of environmental contingency allocations (RFO 11), because the purposes to which such allocations will be put had not been fully defined. However, it is likely that contingency releases will fulfil other RFOs.

Initially, a set of over 40 hypotheses was constructed by associating relevant RFOs with the principal types of flow rules, linking them to flow-sensitive response variables and postulating a linkage mechanism. This large set was culled after considering the views of scientific experts and the following criteria:

- relevance to intended environmental benefits of RFOs,
- strength of *a priori* support for the hypothesis from previous scientific studies and expert opinion,
- practicality of testing the hypothesis (including cost),
- temporal and spatial applicability of the hypothesis (giving preference to hypotheses that apply widely rather than at particular times and places),
- strength of the expected response to flow rule implementation,
- sensitivity to confounding factors,
- community perception of the importance of the hypothesis, and
- availability of relevant historical data.

This process produced a short-list of generic (State-wide) hypotheses. The applicability of this generic set to each valley was assessed through a series of regional workshops with local agency staff and RMC representatives, and by reviewing existing information. Some of the generic hypotheses were not relevant to a particular valley because of its bio-physical features or the nature of the local flow rules and their likely outcomes. In some cases minor modification of a hypothesis was needed to suit local circumstances. A few additional hypotheses relevant to individual valleys were added as a consequence of the regional workshops. The hypotheses are listed in Box 2.

Box 2. Generic and valley-specific response hypotheses

Hypothesis 1 (generic). Suppressing blooms

Protecting natural low flows (RFO 2), for example by raising pumping thresholds, will reduce the frequency and severity of algal and cyanobacterial blooms by making conditions less favourable for bloom development (more turbulence; less stratification)

Hypothesis 2 (generic). Improving low-flow habitat

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

Hypothesis 3 (generic). Flushing blooms

Protecting or restoring a portion of freshes and high flows, and otherwise maintaining natural flow variability (RFOs 3 and 6), through off-allocation use restrictions and dam releases, will flush algal and cyanobacterial blooms from the water column, making blooms less prevalent

Hypothesis 4 (generic). Conditioning stony beds

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

Hypothesis 5 (generic). Wetting terrestrial organic matter

Protecting or restoring a portion of freshes and high flows, and otherwise maintaining natural flow variability (RFOs 3 and 6), through off-allocation use restrictions and dam releases, will increase the wetting of coarse terrestrial organic matter on river banks, benches and floodplains, and consequently increase microbial activity and the populations of animals that feed on detritus or on the microbes that use dissolved organic matter

Hypothesis 6 (generic). Resetting lowland biofilms

Protecting or restoring a portion of freshes and high flows, and otherwise maintaining natural flow variability (RFOs 3 and 6), through off-allocation use restrictions and dam releases, will cause scouring and level changes that will shift the species composition of river biofilms on snags and in the littoral zone towards a greater representation of pioneering taxa such as diatoms, heterotrophic bacteria and fungi relative to filamentous algae and cyanobacteria, and consequently increase macroinvertebrate diversity

Hypothesis 7 (generic). Replenishing wetlands

Protecting or restoring a portion of freshes and high flows, and otherwise maintaining natural flow variability (RFOs 3, 4 and 6), through off-allocation use restrictions and dam releases, will replenish in-channel and floodplain wetlands, restoring their biodiversity

Hypothesis 8 (generic). Rehabilitating fish communities

Protecting or restoring a portion of freshes and high flows, and otherwise maintaining natural flow variability (RFOs 3 and 6), through off-allocation use restrictions and dam releases, will increase the abundance and dominance of native fish to rehabilitate fish communities, by creating conditions more favourable for native fish recruitment and less favourable for carp

Box 2 (continued). Generic and valley-specific response hypotheses

Hypothesis 9 (generic). Restoring natural drying

Mimicking the natural frequency, duration and seasonal nature of drying periods in naturally temporary anabranches and distributary channels (RFO5), by restricting diversions, will cause shifts towards more diverse biota by creating an intermediate level of disturbance

Hypothesis 10 (generic). Reducing bank erosion

Maintaining the rates of rise and fall of river heights within natural bounds (RFO7) will reduce bank slumping and scouring, and consequently reduce losses of riparian vegetation

Hypothesis 11 (specific to the Hunter Valley). Maintaining estuarine productivity

Protecting or restoring a portion of freshes and high flows, and otherwise maintaining natural flow variability (RFOs 3 and 6), through off-allocation use restrictions and dam releases, will maintain the supply of nutrients and organic carbon to the estuary, thereby sustaining production of organisms such as prawns and fish (RFO12)

Hypothesis 12 (specific to the Hunter Valley). Restructuring habitat

Protecting or restoring a portion of freshes and high flows, and thereby mimicking natural flow variability (RFOs 3 and 6), through off-allocation use restrictions and dam releases, will cause scouring and level changes that will improve habitat structure and diversity in morphologically unstable sections of the river

Hypothesis 13 (specific to the Lachlan Valley). Regenerating riparian vegetation

Protecting or restoring a portion of freshes and high flows, and thereby mimicking natural flow variability (RFOs 3 and 6), through dam releases and off-allocation restrictions, will result in increased wetting of riparian zones, and thereby promote the regeneration of native riparian vegetation

Hypothesis 14 (specific to the Hunter Valley). Phasing in temperature changes

Minimising the downstream water quality impacts of storage releases (RFO 10), by gradually increasing and reducing release volumes, will reduce the risk of thermal shock in summer when reservoir water temperatures are lower than tributary water temperatures, thereby fostering more natural fish and macroinvertebrate communities

Hypothesis 15 (specific to the Lachlan Valley). Increasing light for water plants

Improving water quality (RFO10), by winter and spring releases of clear reservoir water, will increase light penetration to the river bed, thereby fostering the recovery of water plants

Hypothesis 16 (specific to the Murrumbidgee Valley). Reducing temperature depression

Minimising the downstream water quality impacts of storage releases (RFO 10), by the use of the stony sluice at Burrinjuck Dam, will reduce downstream temperature depression, thereby fostering more natural fish and macroinvertebrate communities

9. Prioritisation of hypotheses

A series of river inspections by DLWC staff served to further refine and prioritise the hypotheses relevant to each river valley. Priorities were set according to the following criteria:

- likelihood that a measurable response of the type described by hypothesis will occur, given the magnitude of environmental flows in relation to other flow variation,
- practicality of testing the hypothesis using techniques that can be implemented in a routine monitoring program at a large spatial scale,
- feasibility of developing an effective sampling and statistical design to test the hypothesis, bearing in mind likely confounding factors,
- length of river to which the hypothesis might apply (giving lower priority to hypotheses with only localised applicability), and
- lack of existing studies already producing information relevant to the hypothesis.

Valley-specific priorities are explained in Appendix 2 and summarised in Table 2.

Table 2. Priority of testing hypotheses in each valley. NA, not applicable

Hypothesis	Barwon-Darling	Gwydir	Hunter	Lachlan	Macquarie	Murrumbidgee	Namoi
1. Suppressing blooms	=1	NA	NA	NA	NA	=4	NA
2. Improving low-flow habitat	3	3	NA	NA	5	8	NA
3. Flushing blooms	=1	NA	5	3	NA	=4	4
4. Conditioning stony beds	NA	4	3	7	3	3	NA
5. Wetting terrestrial organic matter	4	5	6	5	6	6	3
6. Resetting lowland biofilms	6	6	NA	6	4	7	5
7. Replenishing wetlands	5	1	NA	1	1	1	1
8. Rehabilitating fish communities	2	2	2	2	2	2	2
9. Restoring natural drying	NA	NA	NA	8	NA	NA	NA
10. Reducing bank erosion	NA	NA	NA	9	NA	NA	NA
11. Maintaining estuarine productivity	NA	NA	1	NA	NA	NA	NA
12. Restructuring habitat	NA	NA	7	NA	NA	NA	NA
13. Regenerating riparian vegetation	NA	NA	NA	10	NA	NA	NA
14. Phasing in temperature changes	NA	NA	4	NA	NA	NA	NA
15. Increasing light for water plants	NA	NA	NA	4	NA	NA	NA
16. Reducing temperature depression	NA	NA	NA	NA	NA	5	NA

10. Study design and statistical analysis

Designs were formulated for hypotheses 1-5, 7, 8 and 11, which were of sufficient priority to be developed into studies in at least one valley. Designs incorporate the elements of statistical (or numerical) framework, site and variable selection and sampling protocols.

Frameworks

BACI designs

The best known, and arguably the most sensitive, family of designs for detecting impacts of human disturbance on ecosystems includes the various derivatives of Before versus After and Control versus Impact (BACI) (Green 1979). In the simplest BACI design, a location affected by the disturbance and an unaffected but otherwise similar location are sampled before and after the disturbance starts. An impact is inferred if the change over time is significantly greater at the disturbed location. This simple design can be extended by sampling the two locations simultaneously on several occasions before and after the disturbance. The means of the differences between the two locations before and after the disturbance are compared by a t-test (Bernstein and Zalinski 1983; Stewart-Oaten *et al*. 1986). This is often called a paired BACI design (BACIP: e.g., Osenberg *et al*. 1994).

However, the statistical inference is weak when there is only one disturbed and one undisturbed location, and hence no true replication. It is possible that the two locations may follow different trajectories over time for reasons unrelated to the putative impact (Eberhardt 1976; Hurlbert 1984). This potential flaw may be overcome by selecting multiple control locations for comparison with a single disturbed location (MBACI design). Such designs are more robust because there is less likelihood that all of the control locations will, simply by chance, behave differently from the disturbed location.

MBACI designs can be modified to include both spatial and temporal hierarchical arrangements of samples. Some of these complex ‘beyond BACI’ designs (Underwood 1991, 1992, 1993, 1994; Ellis and Schneider 1997) are capable not only of detecting shifts in mean values of variables following a disturbance but also of detecting changes in the variance. Hierarchical designs of this level of sophistication have however been criticised on the grounds that they are very difficult to optimise and can be extremely complex (Keough and Mapstone 1995).

If BACI or ‘beyond BACI’ designs were to be implemented in IMEF, the human disturbance of interest would be the application of flow rules, the ‘before’ situation would be that prior to the implementation of the rules, ‘impact’ sites would be those on rivers with flow rules, and ‘control’ sites would be on physically matched and similarly regulated rivers without flow rules. However, most of the study rivers had flow rules in operation at the start of the project, so that there was little opportunity to obtain ‘before’ data. Those ‘before’ data that exist from previous projects are seldom suited to testing the IMEF hypotheses at the appropriate spatial and temporal scales. It is also very difficult to find appropriate ‘control’ rivers. While some of the larger impounded rivers currently do not have flow rules, these rivers are physically different, and have different regulated flow regimes, from the rivers with flow rules.

For example, the Cudgegong River in the central west of the State is regulated by Windamere Dam. This river is a tributary of Lake Burrendong, a large impoundment on the Macquarie River. The Cudgegong River is a potential control river for the middle reaches of the Macquarie, since no environmental flow rules currently apply to the Cudgegong (though they may in the future). However, the Cudgegong River is smaller than the Macquarie, has a stony bed for much of its length, and has no extensive floodplain wetlands. Conversely, the regulated part of the Macquarie River is mostly a meandering plains river with a sand, silt and clay bed and extensive floodplain wetlands. Furthermore, releases down the Cudgegong River from Lake Windemere occur very infrequently, in contrast to the frequent and extended irrigation releases down the Macquarie.

Trend analysis

Where suitable control locations are lacking but management changes are expected to produce responses during the period of observation, hypotheses can be tested by time series analysis. Several approaches have been developed for analysing temporal trends in univariate data, including multiple linear regression, generalised linear models, generalised additive models and the seasonal Kendall test (van Belle and Hughes 1984; Gilbert 1987; Hirsch *et al.* 1982, 1991; Loftis *et al.* 1991; Zetterqvist 1991; Esterby 1993; Jolly *et al.* 2001). If the data are multivariate, they can be reduced by principal components analysis or correspondence analysis, and trend analysis applied to the derived variables (e.g., Cobelas *et al.* 1995). Alternatively, trends in various biological indices can be measured.

Of the parametric techniques, generalised linear models may be used in place of ordinary least squares regression when the error term is not normally distributed. However, parametric techniques for trend analysis are most suited to fairly steady, long-term rising or falling trends. Many responses to flow rules may not be of this type and non-parametric regression techniques such as generalised additive models (Hastie and Tibshirani 1990) may be more appropriate. The non-parametric Kendall test has mostly been applied to water quality data but is equally suited to ecological data.

A major limitation of trend analysis (without control sites) is that the logical connection of any observed response to the management change is weak. Confounding by other changes occurring at the same time is quite likely. Predictable external factors such as seasonal cycles can be incorporated in the design, for example by using periodic regression (Batschelet 1981) or the seasonal Kendall test (Hirsch *et al.* 1982). However, the effect of less predictable or well understood factors is more difficult to incorporate. Supporting evidence such as bio-physical process information can strengthen confidence in statistical inference in some cases.

Intervention analysis

This is a statistical technique that is applied to evenly-spaced, time-series data to model the effect of a sudden change, or intervention, at a single site. Intervention analysis has an advantage over other statistical methods in that it includes events (e.g., rainfall, freshes or floods) that have occurred in the recent past (Box and Tiao 1975). Other methods (e.g., multiple regression) generally lack memory, that is, they deal with coincident data. Different forms of response to one or more interventions can be modelled by fitting dynamic transfer function models in terms of current and past values of the response variable or covariables.

Examples of responses that can be modelled in this way include immediate and delayed step changes in response to a press impact and gradual adjustments to the intervention (see Hipel *et al.* 1975 for details). Intervention analysis has been successively applied in water quality and biological monitoring studies to detect complex responses to interventions (Welsh and Stewart 1989; Badcock 1993).

Intervention analysis may be a useful technique for analysing responses to discrete events during the course of IMEF, such as freshes and small floods produced by contingency releases. However, its success depends heavily on obtaining an extensive time series of data before the intervention. In many instances this may not be possible, because insufficient warning can be given prior to application of a rule to enable adequate 'before' data to be collected. The problems of confounding factors that apply to trend analysis also apply to intervention analysis, particularly when responses to an intervention are delayed.

Predictive modelling

Most flow rules affect the long-term flow regime and thus have subtle and lagged effects entangled in a web of natural change, fluctuations in extractive use and confounding effects of extraneous variables. In these cases it may be impossible to measure responses to rules directly. However, the hypotheses can be used as a starting point for the formulation of mathematical models connecting hydrological drivers with ecological responses and incorporating confounding factors as well as intermediary variables associated with mechanisms of action. Such models could be used to infer the effects of environmental flow rules. Hydrological modelling using the integrated quality and quantity model (IQQM) developed by the DLWC would enable actual flow regimes under flow rules to be compared with modelled regimes without these rules and with simulated natural flows. The ecological response models produced through IMEF would then be used to deduce the likely ecological consequences of different hydrological regimes. Such an approach would also create a predictive capability, because the hydrological and ecological models could be run with different possible future flow management scenarios.

Variable selection

Table 3 shows the variables that need to be measured to test the priority hypotheses, and to provide information relevant to the construction of predictive models. Variable selection was generally dictated by the hypothesis, but some ancillary variables, not included in the wording of the hypotheses, have been added to take account of potentially confounding factors. For example, although it is expected that environmental flows will impact on cyanobacterial blooms primarily by affecting turbulence and mixing of the water column, measurements of nutrients (nitrogen and phosphorus) have been included because of their importance as potential alternative factors in the control of blooms.

Table 3. Indicative list of variables necessary to test priority hypotheses (numbers 1, 2, 3, 4, 5, 7, 8 and 11), and the likely methods of measurement

Variable	Relevant hypotheses	Likely methods of measurement
Flow volume	All	Continuous stage recording; stage calibration by gauging
Wetted area	2, 5, 7, 8	Surveying; aerial or satellite imagery of inundation
Current velocity	2, 4	Hydrographic current meters; substratum profiling
Channel morphology	2, 5, 8	Cross-sectional surveys
Temperature	1, 3	Field probes through depth profile
Turbidity or illumination	1, 3	Turbidimeters; quantum sensors
Dissolved oxygen	2	Field probes through depth profile
Salinity	1, 2, 3	Field probes through depth profile
Nitrogen, phosphorus	1, 3, 11	Depth-integrated samples
Sediment laminae	4	Scrubbing of rock surfaces
Non-living organic matter	5, 11	Dissolved and particulate organic carbon analysis
Cyanobacteria	1, 3	Chlorophyll measurement; cell counts
Biofilms	4	Floristic analysis; pigment analysis; measurement of organic: inorganic ratios
Water plants	2, 7	Transect / quadrat surveys
Invertebrates	2, 4, 7	Sweep and kick net samples
Fish	2, 7, 8	Electrofishing
Frogs	7	Call identification; timed searches
Water birds	7	Transect or point surveys
Production and respiration	4	Chamber measurements for specific substrata (rocks)
Food sources	5	Stable isotope analysis of invertebrates and foods

Site selection and sample stratification

The various river basins are climatically, topographically and biologically distinct and have different regulating structures and management regimes. Accordingly, for those hypotheses that are a high priority for more than one valley, separate studies have been planned in each valley.

Within each valley, and for each study, sites are generally selected on a stratified random design. Randomisation ensures that sites are representative and unbiased, while stratification ensures that all areas of interest are covered. Strata may be reaches along a river, regions within a valley, or different types of water bodies. More than one stratum generally needs to be sampled for one or more of the following reasons.

- Ecosystem responses to flow vary spatially for many reasons. Flow rules vary spatially, and their effects may lessen with distance from the point of application of the rule. Natural flow patterns, and confounding factors that modify responses to flow, also vary across space. Stratification of areas where different levels or types of responses are expected ensures the full range of responses is recorded.

- The construction of predictive models relating ecosystem responses to flow regimes requires that a range of regimes is studied, in order that the models have a broad predictive capability. It would be hazardous to use a model constructed for only a narrow range of flow regimes to extrapolate outside of that range, yet extrapolation might be needed in order to make predictions for other times and places, and for future flow options.

When considering the number and disposition of strata it is useful to recognise that the spatial relationships within a river system can be summarised by a hierarchical model of nested components (Frissell *et al*. 1986). Major geomorphic zones within a valley correspond to the major areas of sediment erosion (headwaters), transport (slopes), and deposition (floodplains) (Schumm 1988). These components can be defined according to factors such as landscape relief and channel and valley morphology (pool-riffle development, sinuosity range, sedimentology, connectivity with the floodplain, and riparian and floodplain vegetation) (Figure 2). A river zone may be broken into segments related to land or water use, within which there are macrohabitats (e.g., anabranches, ox-bow lakes, fluvial channels and weir pools) formed mostly by medium-scale fluvial processes like channel migration (Salo 1990). These can be divided further into mesohabitats that can be affected by intra-annual variations in the flow regime (Walker *et al.* 1995). Definitions of mesohabitats will vary with the organism or other variable considered: snags and macrophyte beds may be important mesohabitats for macroinvertebrates, and different strata of the water column are relevant to planktonic algae, while local in-channel geomorphic features like submerged bars are important factors determining mesohabitats for fish. Mesohabitats can be further divided into microhabitats (e.g., individual boulders, different faces on the same boulder and pits on a boulder face), but this level of resolution is too fine for IMEF.

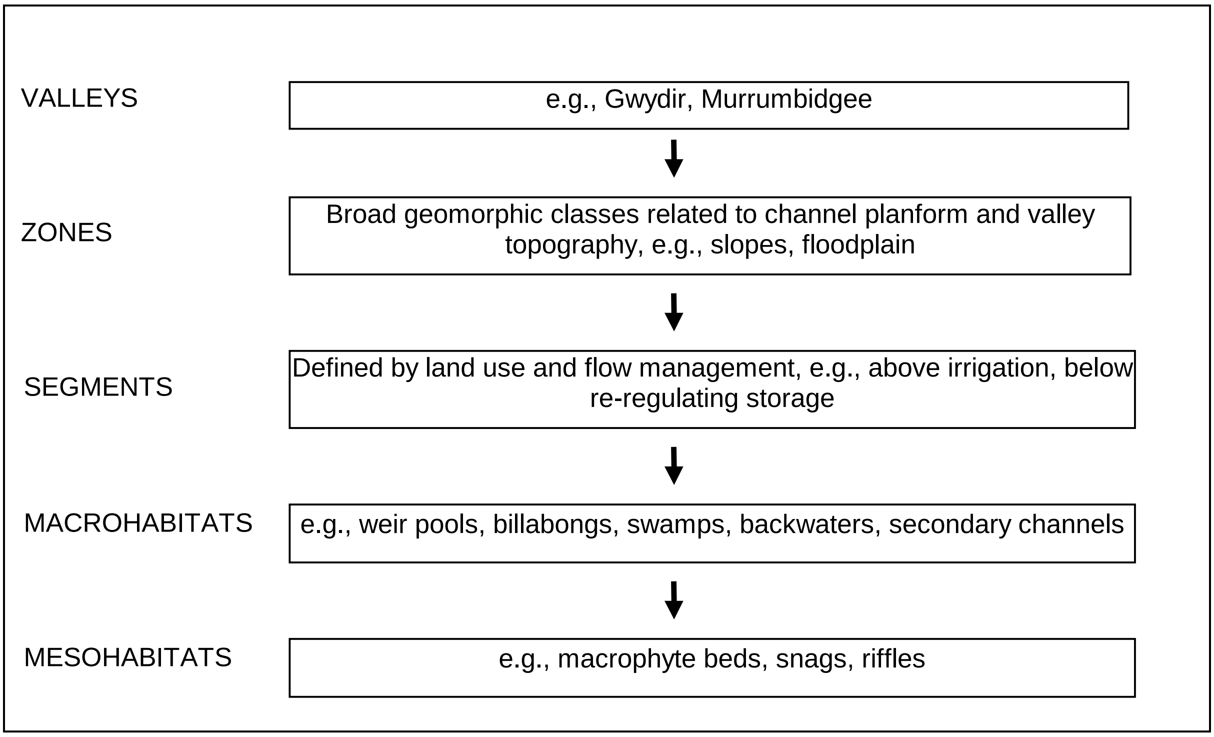

Figure 2. Diagrammatic summary of the hierarchy of spatial scales

Analysis

Appropriate sampling designs are required to enable the priority hypotheses to be tested with the maximum power that can be achieved within the available resources (Fairweather 1991; Maher *et al.* 1994; Dixon and Chiswell 1996). The priority hypotheses and associated indicators are diverse, incorporating responses to flow rules with time scales ranging from minutes (scouring by freshes) to years (recovery of adult fish populations), and with spatial scales from centimetres (scouring of individual stones) to kilometres (inundation of floodplain wetlands). Some responses will last for short periods and others will be sustained; some will involve changes in central tendency whereas others will involve increased or reduced temporal variability. Sampling strategies need to be framed within statistical designs and methods of data analysis and modelling that can cope with these different facets of response (Thomas *et al.* 1981; Underwood 1989, 1992; Eberhardt and Thomas 1991; Glasby and Underwood 1996; Michener 1997).

It is difficult to be prescriptive about the fine detail of IMEF data analysis in advance, because the appropriate methods will depend to some degree on data properties such as normality, homoscedasticity and spatial and serial autocorrelation. In addition, methods need to be customised to deal with each local situation. A separate technical manual on statistical techniques for descriptive and exploratory data analysis, and for hypothesis testing, is being prepared.

11. Review

Periodic review of the monitoring program, by the study personnel and independent scientists, is essential. Monitoring of environmental flows on this scale has not previously been attempted in NSW, and it is unrealistic to expect that an ideal design and methodology can be developed from scratch. Early experience in the program is likely to modify scientific understanding of NSW rivers considerably, and to point to new hypotheses and directions for monitoring. A flexible approach must be maintained, in which the program can be revised as circumstances warrant. A close relationship between the monitoring program and river management planning is also needed, so that the program can inform the management process and can change as the management strategies change (i.e., the aim is adaptive management and monitoring).

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Appendix 1: Flow rules for 1999-2000

Barwon-Darling Valley

The Barwon-Darling environmental flow rules were not implemented until August 2000 because of delays in establishing five new stream-flow gauging stations. These stations are critical to the operation of the rules. New ‘commence-to-pump’ thresholds have been applied to water users as detailed in Table 4.

The Unregulated Flow Management Plan for the North-West continues to operate. This plan covers the major regulated rivers in the north-west of NSW as well as the Barwon-Darling River. It seeks to ensure minimum flows for the protection of basic river health as well as protecting high flows for algal suppression and fish migration.

Gwydir Valley

The 1999-2000 flow rules for the Gwydir protect low flows, share high-flow events between water users and the environment and provide water for environmental contingencies. The individual rules are reproduced below.

Rule 1: *When tributary inflow downstream of Copeton Dam is less than 500 ML/d, pass flows through to the wetlands.*

Rule 2 *Off-allocation extractions are limited to 50% of each flow event and off-allocation will not be declared unless flows exceed immediate water use requirements by at least 1000 ML/d. The volume available to irrigation is calculated from the flow volume above this threshold.*

Rule 3: *Each year a volume equal to 25 000 ML multiplied by the percentage allocation available to general security users is to be set aside for use in supporting bird breeding events.*

Table 4. Barwon-Darling environmental flow rules for 2000/01 - commence-to-pump thresholds (ML/day)

Reach	Licence class	Mungindi	Presbury	Mogil Mogil	Collarenebri	Woorawadian	Walgett	u/s Macquarie	d/s Macquarie	Brewarrina	u/s Culgoa	d/s Culgoa	Bourke	Louth	Tilpa	Wilcannia
Mungindi to Boomi R. confluence	A	230	220													
	B		270													
	C		1500													
Boomi R. confluence to u/s Mogil Mogil weir pool	A		220	190												
	B		270	230												
	C															
Mogil Mogil weir pool	A															
	B			570												
	C															
Mogil Mogil to Collarenebri	A			190	165											
	B			570	500											
	C				1100											
Collarenebri to u/s Walgett weir pool	A				165	100										
	B				500	430										
	C															
Walgett weir pool	A															
	B						900									
	C															
Walgett to Macquarie R. confluence	A						600	530								
	B						900	870								
	C															
Macquarie R. confluence to Brewarrina	A								530	460						
	B								870	840						
	C															
Brewarrina to Culgoa R. confluence	A									460	400					
	B									840	760					
	C															
Culgoa R. confluence to Bourke	A											400	350			
	B											1330	1250			
	C															
Bourke to Louth	A												350	260		
	B												1250	1130		
	C															
Louth to Tilpa	A													260	215	
	B													1130	1010	
	C															
Tilpa to Wilcannia	A														215	123
	B														1010	850
	C															
Wilcannia to u/s Lake Wetherill	A															123
	B															850
	C															

Hunter Valley

The 1999-2000 flow rules for the Hunter provide an environmental contingency allocation, limit access to off-allocation flows, separate surface water and groundwater access, provide end-of-system flows, manage water use in the estuarine section, protect water quality and embargo new water entitlements. The rules are reproduced below (with explanatory notes in parentheses).

Rule 1: *Allowance of 20 000 ML on the Hunter, shared between Glennies and Glenbawn dams and 2000 ML on the Paterson in Lostock Dam.*

Rule 2: *Access to high flows will be as follows:*

- *First 12 hours of the flow event be allowed to pass. Water previously ordered can still be diverted.*
- *Maintain a minimum river flow in the Hunter River at Singleton of 120 ML/d from 1 May to 30 September and 300 ML/d from 1 October to 30 April. Maintain a minimum river flow at Jerry's Plains of 100 ML/d from 1 May to 30 September and 150 ML/d from 1 October to 30 April.*

Maximum 50% extraction of high flow.

End of system flow at twice target flow.

(The term 'target flow' refers to the minimum river flow at Singleton.)

Rule 3: *Continue the integration of regulated and unregulated river system flow issues and their associated alluvial groundwater areas by developing rules to achieve access security and equity for water users and the environment.*

Rule 4: *Conjunctive use of surface water and ground water should continue in 1999-2000, with in principle support for separation in subsequent years.*

Allocations and access rules will be established for subsequent years, following better definition of the boundary between surface water and ground water, and assessment of economic impacts and the extent of anomalies.

Bores within 200 m of the river (i.e., surface water bores) to continue to be assessed as use of surface water and not ground water.

(Some water users are licensed to take both surface and ground water. 'Conjuctive use' occurs where access to ground water depends on the availability of surface water, i.e., access to ground water increases as available surface water declines.)

Rule 5a: *Rules which introduce variability in delivery of end of system flows will be developed following further information on ecological and biological processes and the effectiveness of variability.*

Rule 5b: *Licence water use in the tidal zone.*

Rule 6: *Water use below Oakhampton Bridge and Gostwyck will be managed in future years, once legislative change is made and a plan is developed which ensures consistent management of the regulated section of the Hunter River.*

Develop access strategies for users in tidal sections to improve estuarine habitat.

Rule 7: *Continue development of current Salinity Trading Scheme.*

(The goal of the Salinity Trading Scheme is to control the discharge of saline water from the numerous mines along the Hunter River, in order to maintain conductivity below 900 µS/cm at Singleton. Salinity discharge credits were created, limiting the volume of saline groundwater that could be discharged to the river. The Scheme encourages mines to invest in retention works and then trade their discharge credits to other enterprises. It also sets flow thresholds for the discharge of saline water.)

Rule 8: *The embargo on the issue of new water licences on the regulated section of the Hunter River continue.*

Lachlan Valley

The 1999-2000 flow rules for the Lachlan set conditions for translucent releases from Wyangala Dam, provide an Environmental Contingency Allocation, limit off-allocation diversions and set a minimum end-of-system daily flow. The rules are reproduced below (with explanatory notes in parentheses).

Rule 1: *Translucent releases are to be made from Wyangala Dam during the period 1 June to 31 October to attain, in combination with tributary inflows, flows at Lake Brewster of 3500 ML/d to a variable upper window.*

This is to apply to an upper limit of 350 000 ML per annum, measured at Lake Brewster, including the translucent releases and tributary inflows.

(Translucent dam operation requires the release of a portion of reservoir inflow. Releases are triggered when total system inflows are sufficient to provide flows below Lake Brewster of 3500 ML/d to 8000 ML/d. The upper limit to translucent flows (‘variable upper window’) depends on the storage level of Wyangala Reservoir. For example, when Wyangala is empty the target flow range downstream of Lake Brewster is 3500 - 4000 ML/d. When it is 60% full it is 3500 – 5500 ML/d. When it is 100% full the target flow range is 3500 – 8000 ML/d. The translucent release rules for the Lachlan have been designed to deliver flows to the wetlands in the lower system.)

Rule 2: *A 20 000 ML high security Environmental Contingency Allowance (ECA) is established for management of critical (contingent) environmental events, e.g., algal blooms, salinity, bird breeding and fish breeding. The ECA will be eliminated during years when the 1st July allocation announcement is below 50% and is not re-instated until allocation announcements exceed 75%.*

Rule 3: *A limit of 30 000 ML per annum on off-allocation diversions.*

Rule 4: *Minimum flow of 100 ML/d at Booligal to maintain a visible flow at 'Geramy'.*

Macquarie Valley

The 1999-2000 flow rules for the Macquarie provide a contingency allocation, set conditions for declaring access to off-allocation, limit off-allocation diversions and set maximum annual replenishment flows in anabranches and distributaries in the lower system. The rules are reproduced below (with explanatory notes in parentheses).

> *A Wild Life Allocation (WLA) of up to 125 000 ML is made available each season. It has two components. The first is a 50 000 ML 'high security' allocation which is provided every season. The second is a 75 000 ML general security allocation. The general security volume actually provided each year is equal to 75 000 ML multiplied by the percentage allocation announced for general security irrigation licences.*

(In this rule 'season' means 'water year'. At the start of the water year, the volume of water held in storage is assessed and a 'percentage allocation' is announced. This is the proportion of the entitlement volume that appears on each irrigation licence that the licensee is permitted to use in that year. The percentage allocation is reviewed during the year and can be increased if substantial reservoir inflows occur.)

> *Carry over of up to 100% of the WLA and general security irrigator allocations is also permitted with no twelve month limitation.*

(Any unused WLA or general security irrigator allocation can be carried forward indefinitely from year to year, provided the amount of water in the 'carryover account' does not exceed 100% of the general security allocation (e.g., for the WLA, the maximum amount of water that can be held in the 'carryover account' at any point in time is 75 000 ML).)

> *Whenever Burrendong Dam fills and spills, both the WLA carryover account and any irrigator carryover accounts are reduced in proportion to the volume of spill.*

(For example, if the volume spilt is 50% of the volume carried forward, the carry-over account is reduced by 50%.)

> *All allocations to be reset at 100% when all carry over water has been spilt.*
>
> *Off-allocation may be declared when flow in the river, in excess of water user orders, is greater than 5000 ML/d at Warren. Off-allocation declarations must not prevent minimum annual stock and domestic flows being met during the year. An annual limit of 50 000 ML also applies to total off-allocation diversions.*
>
> *All tributary flows and unused storage releases will be directed to the Marshes for a period of up to 45 days when water is necessary for the satisfactory completion of a waterbird breeding event.*

Each year, the following creeks will be provided with maximum flow of:

-	*Marra Creek*	*15 000 ML*
-	*Lower Bogan River*	*15 000 ML*
-	*Crooked Creek below 'Mumblebone'*	*4000 ML*
-	*Gum Cowal/Terrigal Creek*	*1000 ML*
-	*Bogan River between Nyngan and Gunningbar Creek confluence*	*10 000 ML*
-	*Beleringar Creek downstream of Albert Priest Canal*	*1000 ML*
-	*Reddenville Break*	*1500 ML*
-	*Beleringar Creek*	*5000 ML*

Murrumbidgee Valley

The 1999-2000 flow rules for the Murrumbidgee set conditions for transparent releases from Burrinjuck and Blowering dams and translucent releases from Burrinjuck Dam, set an end-of-system flow target and provide water for environmental contingencies. The rules are reproduced below (with explanatory notes in parentheses).

Rule 1: *Release a minimum of 615 ML/d from Burrinjuck and 560 ML/d from Blowering unless inflows are lower, in which case releases are to be at least equivalent to inflows.*

(Transparent dam operation requires the amount of water released from the dam to be the same as the inflow to the reservoir, up to a set limit. Transparency rules are designed to provide or protect low flows in the reach immediately downstream of the dam and are generally applied all year.

For example, the current transparency rule for Burrinjuck Dam requires all reservoir inflows up to 615 ML/d to be passed. If the total inflow to the reservoir on a given day is 400 ML/d then 400 ML/d is released. If the total inflow is 700 ML/d then 615 ML/d is released under this rule. If there is no inflow to the reservoir there is no transparent dam release.)

Rule 2: *Flow in the Murrumbidgee at Balranald to be at least 300 ML/d when irrigation water allocations exceed 80% or 200 ML/d when allocations are below 80%.*

Rule 3: *Between April and October release a portion of Burrinjuck inflows, which varies with climate and the rate of natural inflow to the storages.*

- *Wet curve releases – a ceiling level of 50% translucent releases until Burrinjuck reaches an equivalent of 30% storage capacity minus borrow.*

> - *Normal curve releases – a ceiling level of 50% translucent release until Burrinjuck reaches an equivalent of 50% storage capacity plus carryover minus borrow.*
>
> *When allocation reaches 80% the clipped translucency volume below the two thresholds identified above is set aside. The allocation cannot increase until the clipped volume is fully paid back and additional storage available to provide an increase.*
>
> *If the clipped translucency volume is set aside before 31 October, 100% of that volume is available for use as additional Environmental Contingency Allowance up to 31 October.*
>
> *If not used by 31 October 50% of that clipped translucency payback is available for use as additional Environmental Contingency Allowance until 31 December (the other half reverts to provisional storage).*
>
> *If the clipped translucency volume is set aside after 31 October but before 31 December, only 50% of that volume is available as additional ECA up until 31 December.*
>
> *If the amount of clipped translucency volume (converted to additional ECA) is not used by 31 December or set aside after this date, it remains in the dam as provisional storage in that year and is available for allocation to irrigators in the following water year.*
>
> *If the allocation in the second year reaches 80%, the clipped volume carrying over from year 1 as provisional storage is again set aside in the provisional storage for allocation to irrigators in the third year.*

(The goals of translucent dam rules in the Murrumbidgee are to allow some of the natural flow to pass Burrinjuck Dam from late autumn to spring (the non-irrigation season) but also to start the irrigation season with a large volume of water in storage.

The timing of translucent releases is set by the Goodradigbee River, which is the most naturally flowing of the three rivers entering Burrinjuck Reservoir. Each day the Goodradigbee flow is used to determine whether flow conditions are ‘dry’, ‘normal’ or ‘wet’. For each of these conditions there is a separate translucency curve, which shows the level of translucency prescribed for each date. This is the percentage of the total inflow to Burrinjuck required to be passed through as translucent flow.

There are some constraints on the volume of water that can be released under this rule. When Burrinjuck Reservoir is less than 30% full, a maximum of 50% of inflows will be released as translucent water when conditions are determined as ‘wet’ or ‘normal’.

This means, for example, that if the dam is 20% full, conditions are ‘wet’ and the curve indicates a translucency of 68%, releases are constrained to 50% of inflows. But if conditions are assessed as ‘dry’, 68% is released.

When Burrinjuck is between 30% and 50% full, translucency is capped at 50% of inflows when conditions are determined as ‘normal’. This constraint does not apply when conditions are ‘dry’ or ‘wet’. When Burrinjuck Dam reaches a threshold of 50%, full translucent releases occur.

‘Percentage allocation’ is the proportion of the entitlement volume that appears on each irrigation licence that the licensee is permitted to use. The general security allocation increases as the volume in storage rises, and when it reaches 80%, the volume not released under the above constraints, the ‘clipped translucency volume’, (e.g., the difference between 68% and 50% in the example) is set aside. The allocation cannot increase beyond 80% until this volume is returned to the environmental account.

‘Provisional storage’ is the amount of clipped translucency volume that has been converted to ECA but not used by 31 December. This volume of water is held in the dam for use by irrigators in the following water year.)

Rule 4: *Reservation of 25 000 ML annually to provide water to meet water quality needs and algal bloom suppression, fish breeding and forest and wetland watering.*

Water will also be reserved to buffer the impact of environmental releases on irrigators during sequences of dry years and to ensure environmental allocations will be available. This additional volume will be 25 000 ML when allocations are below 80% and will increase from 25 000 to 200 000 ML for allocations between 80% and 100%.

The 25 000 ML ECA plus the 25 000 provisional storage (totalling 50 000 ML) is loaned to irrigation for increase in early season announcements.

For this year only the 50 000 ML is boosted by 25 000 ML ECA carry-over from last year (1998-99) as well as 13 500 ML clipped Gundagai translucency. This amount provides a total potential early season loan to irrigation, for this year only, of 88 500 ML.

The ECA/provisional storage borrowed in the early part of the season is to be repaid to the ECA account and provisional storage account when the allocation reaches 60%.

Namoi Valley

The 1999-2000 flow rules for the Namoi set a limit on the annual volume of off-allocation diversions, retain the Interim North-West Unregulated Flow Plan and share high flow events between water users and the environment. The individual rules are reproduced below (with explanatory notes in parentheses).

Rule 1: *A maximum annual off-allocation diversion of water in the Namoi regulated system of 110 GL.*

Rule 2: *Retention of the Interim North West Unregulated Flow Plan. This ensures minimum flow for protection of basic river health and protection of high flow for algal suppression and fish migration.*

(The Interim North-West Unregulated Flow Plan sets flow targets that determine off-allocation access for irrigators during high flow events.)

Rule 3: *50:50 sharing of unregulated flows, with off-allocation being declared according to the following thresholds.*

a) If the available water for irrigation exceeds the valley equivalent of 35% announced allocation, then off-allocation access to be as follows:

1 Aug to 31 Dec - starts at 5000 ML/d and stops at 3000 ML/d at Narrabri

1 Jan to 31 Jan - starts at 4000 ML/d and stops at 2000 ML/d at Narrabri

1 Feb to 31 Jul - starts at 2000 ML/d and stops at 1000 ML/d at Narrabri.

(‘Percentage allocation’ is the proportion of the entitlement volume that appears on each irrigation licence that the licensee is permitted to use. The allocation increases as the volume in storage rises. In the Namoi, irrigators are permitted to carry forward any unused allocation to the next year. The above off-allocation thresholds apply when the total available water (i.e., announced allocation plus the carry-over from the previous year) exceeds a volume equivalent to an announced allocation of 35%.)

b) If the available water for irrigation is less than or equal to the valley equivalent of 35% announced allocation, then off-allocation access to be when Narrabri flow exceeds 500 ML/d.

c) In the Peel Valley if the flow at Carroll Gap is in excess of, or likely to be in excess of 50 ML/d, the Peel operator may announce access to unregulated flow as off-allocation. Access to such flows will be related to the current water ordering sections:

1. *Chaffey Dam to Paradise*

2. *Paradise to Attunga Ck*

3. *Attunga Ck to Namoi junction.*

As unregulated flow recedes from an upstream section the off-allocation access will be rescinded. If there is no unregulated flow in a section, then off-allocation will not be declared in that section. Off-allocation access is not available to high security licences.

Appendix 2: Priority of hypotheses in each valley

Table 5. Priority of generic hypotheses for the Barwon-Darling Valley. There are no valley-specific hypotheses for this valley

Priority	No.	Short description	Rationale
=1	1	Suppressing blooms	Cyanobacterial blooms are common in the Barwon-Darling River and are a major issue for the local community
=1	3	Flushing blooms	Cyanobacterial blooms are common in the Barwon-Darling River and are a major issue for the local community
2	8	Rehabilitating fish communities	The rehabilitation of native fish populations is a major environmental concern in the Barwon-Darling valley. Increased wetting within the channel and low-flow habitat enhancement may create improved conditions for breeding and recruitment of native fish
3	2	Improving low-flow habitat	Deoxygenation might be expected in the Barwon-Darling River during low-flow periods; loss of wetted area when river levels are low is also an important issue
4	5	Wetting terrestrial organic matter	The environmental flow rules will have little effect on over-bank flooding, but will affect wetting of banks and in-channel benches, which often contain abundant leaf litter. Other studies (CRC for Freshwater Ecology) are addressing this hypothesis
5	7	Replenishing wetlands	Although numerous wetlands occur along the river, they are perched above the level of the river channel, and so few if any will be filled in the flow range addressed by the current rules
6	6	Resetting lowland biofilms	High turbidity in the Darling probably limits autotrophic biofilm development
Not applicable	4	Conditioning stony beds	There is little opportunity to influence high flows in the Barwon-Darling River as the system is not regulated
Not applicable	9	Restoring natural drying	Current flow management does not reduce the frequency or duration of natural drying in the Barwon-Darling
Not applicable	10	Reducing bank erosion	Rates of rise and fall are not addressed by the current rules

Table 6. Priority of generic hypotheses for the Gwydir Valley. There are no valley-specific hypotheses for this valley

Priority	No.	Short description	Rationale
1	7	Replenishing wetlands	Wetland contraction and reductions in flooding frequency are major environmental concerns in the Gwydir valley. Replenishing wetlands is the primary focus of the present flow rules
2	8	Enhancing fish communities	The rehabilitation of native fish populations is a major environmental concern in the Gwydir valley. Increased water supply to the wetlands may create improved conditions for breeding and recruitment of native fish, which may then colonise the river system
3	2	Improving low-flow habitat	This hypothesis relates to habitat enhancement through the maintenance of wetted area and the breakdown of stratification that has led to deoxygenation of bottom waters. It may be applicable to a small section of the Gwydir River between Tareelaroi Weir and the wetlands
4	4	Conditioning stony beds	Stony beds are not widespread in areas affected by the flow rules but do occur patchily downstream of Copeton Dam and in the vicinity of Moree (The Rocks). No unregulated reference river is available for comparison with the section near Moree, but the Horton River may be suitable for comparison with the Gwydir upstream of Gravesend. The release of environmental contingency water may affect biofilms in this section, but its release is not currently slated for this purpose
5	5	Wetting terrestrial organic matter	Sections of the river, affected by environmental flow rules, where flow change might result in additional wetting of terrestrial organic matter are very limited
6	6	Resetting lowland biofilms	Sections of the river, affected by environmental flow rules, where flow change might result in more frequent biofilm resetting are very limited
Not applicable	1	Suppressing blooms	The main site of algal and cyanobacterial blooms in the Gwydir River is the Moree weir pool. This pool is below the point at which environmental flows are diverted to the wetlands
Not applicable	3	Flushing blooms	The main site of algal and cyanobacterial blooms in the Gwydir River is the Moree weir pool. This pool is below the point at which environmental flows are diverted to the wetlands
Not applicable	9	Restoring natural drying	Current flow rules do not address the RFO of restoring natural drying patterns
Not applicable	10	Reducing bank erosion	Implementation of the flow rules does not change present rates of rise and fall in river levels. Operational procedures ensure that from Copeton Dam are stepped down gradually at the end of the irrigation season

Table 7. Priority of generic and valley-specific hypotheses for the Hunter Valley

Priority	No.	Short description	Rationale
1	11	Maintaining estuarine productivity	The Hunter estuary supports major commercial and recreational fisheries. The hypothesis has support in previous scientific research (Ruello 1973; Loneragan and Bunn 1999)
2	8	Rehabilitating fish communities	Native fish conservation is a critical issue for the Hunter River. Increased wetting within the channel may create improved conditions for breeding and recruitment of native fish
3	4	Conditioning stony beds	Stony beds occur in the Hunter River downstream of Glenbawn Dam (to below the Glennies Creek confluence) and in Glennies Creek downstream of Glennies Creek Dam. The Hunter River shows a pronounced accumulation of silt, biofilms and macrophytes immediately downstream of Glenbawn, but receives substantial flushing a short distance downstream as a result of unregulated tributary inflows from Rouchel Brook, the Pages River and Dart Brook. Unscoured beds show a much greater longitudinal persistence downstream of Glennies Creek Dam. Suitable unregulated reference streams occur nearby
4	14	Phasing in temperature changes	This issue is being addressed by an associated project
5	3	Flushing blooms	Planktonic diatom blooms in the Hunter River downstream of Glenbawn Dam are almost certainly unnatural and are an issue of concern for the local community. The source of the blooms is not known, but it is likely that environmental releases from Glenbawn could reduce cell densities
6	5	Wetting terrestrial organic matter	The Hunter River comprises mostly unstable gravel and sand beds and is not retentive of organic matter. In addition, much of the natural riparian vegetation has been destroyed. The lack of natural terrestrial inputs cannot be remedied by environmental flows; river stabilisation and restoration are needed
7	12	Restructuring habitat	The dominance of unstable sand beds in the Hunter River is mainly a consequence of geomorphological changes resulting from removal of the original riparian vegetation, desnagging and catchment clearing. It needs to be addressed by physical rehabilitation works rather than the provision of environmental flows. While large floods may greatly restructure the channel, the smaller environmental flows probably play only a minor role
Not applicable	1	Suppressing blooms	Regulated low flows are generally higher than those that would have occurred naturally. In addition, the current flow rules deal mainly with protection of a portion of high flows
Not applicable	2	Improving low-flow habitat	Regulated low flows are generally higher than those that would have occurred naturally. In addition, the current flow rules deal mainly with protection of a portion of high flows
Not applicable	6	Resetting lowland biofilms	Stable subsrata for the attachment of biofilms, such as snags, are scarce in the lower Hunter River
Not applicable	7	Replenishing wetlands	The Hunter River lacks major wetlands (other than estuarine wetlands)
Not applicable	9	Restoring natural drying	The Hunter River lacks temporarily flowing anabranch systems
Not applicable	10	Reducing bank erosion	Rates of rise and fall are not addressed by the current rules

Table 8. Priority of generic and valley-specific hypotheses for the Lachlan Valley

Priority	No.	Short description	Rationale
1	7	Replenishing wetlands	Wetland contraction and reductions in flooding frequency are major environmental concerns in the Lachlan valley. Numerous billabongs (oxbow lakes), backswamps, distributaries (effluents) and anabranches (cowals) occur along the river downstream of Jemalong. Some of these wetlands will be replenished by environmental flows
2	8	Rehabilitating fish communities	The rehabilitation of native fish populations is a major environmental concern in the Lachlan valley. Increased wetting of wetlands and in-channel benches may create improved conditions for breeding and recruitment of native fish
3	3	Flushing blooms	Blooms in weir pools and elsewhere on the lower Lachlan are a frequent occurrence and a major issue for the local community
4	15	Increasing light for water plants	Historical declines of water plants in the Lachlan River are a matter of concern. However, it is uncertain whether the low turbidity of releases from Wyangala Dam will be maintained for the length of the river. Releases from Lake Brewster are likely to be inevitably turbid and may counteract any beneficial effect of Wyangala water
5	5	Wetting terrestrial organic matter	The environmental flow rules are likely to influence wetting of organic matter on banks and in-channel benches. However, measuring this influence is technically demanding
6	6	Resetting lowland biofilms	The environmental flow rules are likely to influence biofilms on snags and shallow sediments. However, measuring this influence is technically demanding
7	4	Conditioning stony beds	Stony beds have a very limited distribution in the Lachlan River, immediately downstream of Wyangala Reservoir
8	9	Restoring natural drying	While the flow rules may result in some trend towards more natural drying patterns, particularly in the lower river and associated wetlands, this can be achieved only to a limited extent unless arrangements can be made to supply stock and domestic needs by means other than continuous run-of-river
9	10	Reducing bank erosion	Bank slumping is restricted to small sections of the river and it is not clear whether this is caused by unnatural rates of rise and fall or by other factors such as prolonged wetting by irrigation releases
10	13	Regenerating riparian regeneration	The condition of riparian zones appears to be much more related to issues of stock access and weed invasion than to wetting
Not applicable	1	Suppressing blooms	Low flows are generally higher than those that would have occurred naturally, because of releases from storage to support stock and domestic water supplies
Not applicable	2	Improving low-flow habitat	Low flows are generally higher than those that would have occurred naturally, because of releases from storage to support stock and domestic water supplies

Table 9. Priority of generic hypotheses for the Macquarie Valley. There are no valley-specific hypotheses for this valley

Priority	No.	Short description	Rationale
1	7	Replenishing wetlands	Wetland contraction and reductions in flooding frequency in the Macquarie Marshes are major environmental concerns. The marshes and some other wetland areas on the lower Macquarie will be replenished by environmental flows
2	8	Rehabilitating fish communities	The rehabilitation of native fish populations is a major environmental concern in the Macquarie valley. Increased wetting of floodplain wetlands, and low-flow habitat enhancement, may create improved conditions for breeding and recruitment of native fish
3	6	Resetting lowland biofilms	The environmental flow rules are likely to influence biofilms on snags and shallow sediments
4	4	Conditioning stony beds	Areas of stony beds occur patchily in the Macquarie River downstream of Burrendong Dam (as far as Dubbo). A suitable study design can be developed comparing these areas with unregulated tributaries (the Bell and Little rivers)
6	2	Improving low-flow habitat	This hypothesis relates to habitat enhancement through maintenance of wetted area and the breakdown of stratification that has led to deoxygenation of bottom waters. Such phenomena may be important in a relatively small sections of the river downstream of the Macquarie Marshes. These sections are regarded as unregulated and will therefore be addressed by the Stressed Rivers program rather than IMEF
7	5	Wetting terrestrial organic matter	For most of the river the channel is deep and incised, and there are few benches and over-bank areas likely to be wetted by environmental flows
Not applicable	1	Suppressing blooms	Algal and cyanobacterial blooms are rare in the Macquarie River. A major bloom did occur during 1998, but was passed downstream from Burrendong Reservoir where it developed under the extreme drought conditions and low water level at the time
Not applicable	3	Flushing blooms	Algal and cyanobacterial blooms are rare in the Macquarie River. A major bloom did occur during 1998, but was passed downstream from Burrendong Reservoir where it developed under the extreme drought conditions and low water level at the time
Not applicable	9	Restoring natural drying	Current flow rules do not address the RFO of restoring natural drying patterns
Not applicable	10	Reducing bank erosion	Implementation of the flow rules will not change present rates of rise and fall in river levels. Slumping is being addressed by other studies

Table 10. Priority of generic and valley-specific hypotheses for the Murrumbidgee Valley

Priority	No.	Short description	Rationale
1	7	Replenishing wetlands	Wetland contraction and reductions in flooding frequency are major environmental concerns in the Murrumbidgee Valley. Numerous billabongs (oxbow lakes) occur along the river between Wagga Wagga and Hay. Flow-to-fill levels calculated for several of these wetlands indicate that they will be replenished by environmental flows
2	8	Rehabilitating fish communities	The NSW Rivers Survey indicates that native fish conservation is a critical issue for the Murrumbidgee River. Increased wetting of wetlands and in-channel benches, and low-flow habitat enhancement, may create improved conditions for breeding and recruitment of native fish
3	4	Conditioning stony beds	Areas of stony beds occur patchily in the Murrumbidgee River downstream of Burrinjuck Dam (as far as Wagga Wagga). A suitable study design can be developed comparing these areas with regulated and unregulated tributaries
= 4	1	Suppressing blooms	Cyanobacterial blooms occur mainly in the weirs on the lower Murrumbidgee River (Hay, Maude, Redbank and Balranald). Protection of end-of-system flows during the summer and autumn period, when blooms commonly develop, may reduce the frequency of bloom development. IMEF studies can complement an operational algal / cyanobacterial monitoring program that is already in place
= 4	3	Flushing blooms	Cyanobacterial blooms occur mainly in the weirs on the lower Murrumbidgee River (Hay, Maude, Redbank and Balranald). Contingency allocations may sometimes be used to disperse such blooms, although it is hoped that bloom suppression can be achieved mainly through weir manipulations (e.g., pulsing flows from weir to weir) rather than by using additional water. IMEF studies can complement an operational algal / cyanobacterial monitoring program that is already in place
5	16	Reducing temperature depression	This issue is not specifically addressed by the flow rules, and is covered by other studies
6	5	Wetting terrestrial organic matter	The environmental flow rules are likely to influence wetting of organic matter on banks and in-channel benches. However, measuring this influence is technically demanding
7	6	Resetting lowland biofilms	Biofilms are abundant on snags and sediments in the lower Murrumbidgee River and are likely to be influenced by environmental flow rules. However, measuring this influence is technically demanding
8	2	Improving low-flow habitat	This hypothesis relates to habitat enhancement through the breakdown of stratification that has led to deoxygenation of bottom waters. Such deoxygenation might be expected in the weirs on the lower Murrumbidgee River (Hay, Maude, Redbank and Balranald). However, monitoring data suggest that bottom-water release from weirs creates a current through the lower parts of the weir pools, preventing serious oxygen depletion
Not applicable	9	Restoring natural drying	Current flow rules do not address the RFO of restoring natural drying patterns
Not applicable	10	Reducing bank erosion	Implementation of the flow rules will not change present rates of rise and fall in river levels

Table 11. Priority of generic hypotheses for the Namoi Valley. There are no valley-specific hypotheses for this valley

Priority	No.	Short description	Rationale
1	7	Replenishing wetlands	Wetland contraction and reductions in flooding frequency are major environmental concerns in the Namoi valley. Low-level floodplain areas occur along several parts of the river. The degree of wetting of these areas is likely to be affected by management of off-allocation flow events
2	8	Rehabilitating fish communities	The restoration of native fish populations is a major environmental concern in the Namoi valley. Increased wetting of wetlands and in-channel benches may create improved conditions for breeding and recruitment of native fish
3	5	Wetting terrestrial organic matter	The environmental flow rules are likely to influence wetting of organic matter on banks, in-channel benches and floodplains, especially below Boggabri where major off-allocation use commences
4	3	Flushing blooms	Algal and cyanobacterial blooms occur periodically in the lower Namoi River, Gunidgera Creek and Pian Creek, and are likely to be flushed by off-allocation flow events
5	6	Resetting lowland biofilms	The environmental flow rules are likely to influence biofilms on snags and shallow sediments. However, measuring this influence is technically demanding
Not applicable	1	Suppressing blooms	Current flow rules have little effect on low flows in the areas where cyanobacterial blooms occur
Not applicable	2	Improving low-flow habitat	Current flow rules have little effect on low flows in the areas where loss of habitat occurs
Not applicable	4	Conditioning stony beds	Although stony substrata occur in a short segment of the Namoi River downstream of Keepit Dam, this segment is above the major irrigation areas, and therefore its flow regime will not be altered by the flow rules, which are focussed on off-allocation use. Stony substrata also occur in the Namoi River downstream of Split Rock Dam and in the Peel River downstream of Chaffey Dam, but environmental flow rules have not yet been developed for these storages
Not applicable	9	Restoring natural drying	Current flow rules do not address the RFO of restoring natural drying patterns
Not applicable	10	Reducing bank erosion	Implementation of the flow rules will not change present rates of rise and fall in river levels