Does flow modification cause geomorphological and ecological response in rivers?

A literature review from an Australian perspective

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Summary

Many large rivers throughout the world are subjected to some form of water resource development, resulting in river regulation and altered flow regimes. The widespread concern about the environmental effects of river regulation is based on the logical assumption that the biota and ecological functioning of river systems depend on the volume and timing of flows and the longitudinal, lateral and vertical connections they facilitate.

This report reviews a subset of refereed and unrefereed Australian and international literature to assess the evidence for ecological responses to flow modifications in rivers. The studies we examined produce overwhelming evidence that both river ecology and river geomorphology change in response to flow modification. Specifically,

- 87% of the studies reviewed demonstrate an ecological and/or geomorphological effect(s) of flow modification
- 83% of variables demonstrate an ecological and/or geomorphological effect(s) of flow modification
- all the studies in which the change to flow was measured or could be determined from gauge data (*n* = 30) demonstrated an ecological and/or geomorphological effect(s) of flow modification
- all of the 9 studies investigating geomorphological responses to flow modification recorded geomorphological changes, and
- 56 of 65 (86%) studies investigating ecological responses to flow modification recorded ecological changes.

Despite the unequivocal evidence for ecological responses to flow change, the relationship between these two measures was not simple. Small flow changes could produce large ecological responses and no simple thresholds were detected. However, only a few studies provided quantified information on flow change and ecological response that could be compared between studies and included in analyses of relationships and thresholds. A larger dataset is required before the nature of the relationship between flow change and ecological response can be properly described and used for prediction.

Clear directions for future research are highlighted from this review:

1. To be able to compare regions and river types, floodplains and wetlands, we need a consistent characterisation of flow change.
2. Much of the data generated in the studies reviewed needs to be re-analysed, to provide robust and comparable measures of ecological change.

To improve our understanding of the geographic and time scales of hydrological and ecological changes we will need a better conceptual framework for dealing with mismatches of scale in the various analyses and interpretations of flow–ecology relationships.

1. Introduction

Many large rivers throughout the world have been subjected to water resource development. Australia has made a substantial public investment in water 'development' for a variety of social objectives — for instance, to settle the inland, to provide farms for returning soldiers, to drought-proof cities and to assist rural economies. Low rainfall, high rates of evapotranspiration, low conversion of rainfall to runoff and highly variable stream flow regimes have promoted the construction of large dams and other extensive water regulating infrastructures. Since 1857, Australians have constructed many thousands of small dams, weirs (3,600 in the Murray-Darling Basin alone) and floodplain levee banks, 446 large dams (>10 m crest height) and over 50 intra- and inter-basin water transfer schemes.

There remain only a few major Australian rivers (e.g. the Paroo River and Cooper Creek in Queensland, the Ovens River in Victoria, rivers of the World Heritage Area in Tasmania, the Fitzroy River in Western Australia and various Northern Territory systems) that are not regulated for irrigation, public water supply, navigation, flood mitigation or electricity supply purposes.

Flow modification resulting from water resource development may have serious repercussions for the geomorphological and ecological condition of downstream river systems (Petts 1996, Ward *et al*. 1999). Without doubt, regulation of flows is a major cause of deteriorating conditions in many Australian river and floodplain ecosystems (Cullen and Lake 1995, Kingsford 2000, Bunn and Arthington 2002). For example, reduced summer flows were a major factor in the development of a severe bloom of toxic cyanobacteria in the Barwon-Darling River, covering hundreds of kilometres, and resulting in water becoming unsuitable for drinking and swimming as well as causing stock deaths (Bowling and Baker 1996).

Australian rivers suffer mainly from reduced flows resulting from abstraction, alterations in flood frequency, duration and extent, and seasonal reversal of flows as a result of water being stored in dams in the wet season and released for irrigation in the dry season. In a detailed analysis of flow data from rivers in southeastern Australia, Growns and Marsh (2000) found that regulated rivers experienced a loss of short-term variation and an increase in predictability of flows. In addition, drought or dry phases have been reduced as a consequence of flow releases during the dry season.

Several authors have reviewed aspects of river regulation and water resource development. Ward (1976), Ward (1982), Ward and Stanford (1982) and Baxter and Glaude (1980) have reviewed the early literature on the effects of dams, especially in North America. Giles *et al.* (1991) discussed the ecological effects of low flows on chalk streams. Kingsford (1995) reviewed ecological changes in wetlands of NSW. Horwitz (1999) reviewed the ecological effects of large dams in Australia and included some discussion of modified flow regimes. Kingsford (2000) described changes over time in four Australian wetlands: Macquarie Marshes, Chowilla Floodplain, Gwydir wetlands and the Moira marshes of Barmah forest. Sheldon *et al.* (2000) reviewed the impacts of river regulation and flow modification in the Murray-Darling Basin. Lemly *et al.* (2000) discussed the effects of irrigation on wetland systems, namely water abstraction and return of polluted water, although their review covered mainly unrefereed reports from Europe, North America, Africa and Australia. Despite the wealth of literature on various aspects of flow regulation and ecological responses, there is no current synthesis of these issues for Australian rivers.

In a recent review on the consequences of altered flow regimes for aquatic biodiversity, Bunn and Arthington (2002) suggest that four important principles link hydrology and aquatic biodiversity and can be used to illustrate the consequent impacts of altered flow regimes. These principles are:

1. Flow is a major determinant of physical habitat in streams, which in turn is a major determinant of biotic composition.
2. Aquatic species have evolved life history strategies primarily in direct response to their natural flow regimes.
3. Maintenance of natural patterns of longitudinal and lateral connectivity is essential to the viability of populations of many riverine species.
4. The invasion and success of exotic and introduced species in rivers is facilitated by the alteration of flow regimes.

The objective of the present review is to examine the literature and summarise the responses of ecological components of river systems to the effects of flow change. Studies included in this review range from peer-reviewed literature (Australian and international) to unrefereed reports predominantly from Australia. The focus of the review is the effect of flow modification *per se* rather than the impacts of other aspects of river regulation, such as thermal pollution or changes in water quality. Major emphasis is given to the common types of flow regulation in Australian river systems. Flow modification as a result of hydroelectric power facilities is not included because it is a relatively uncommon form of flow modification in Australia, despite a few high profile examples (e.g. Tasmania's Mersey and Derwent Rivers).

This review has three main aims:

(i) to determine whether an ecological response to flow modification in rivers is a general pattern;

(ii) to quantify the responses of Australian rivers and wetlands to flow modifications at various time-scales and, if possible, to establish simple relationships or thresholds of flow-related ecological change in terms of aquatic and riparian species richness, community structure and ecosystem processes; and

(iii) to examine whether the impacts of flow regulation on aquatic biodiversity in Australian rivers support the four principles proposed by Bunn and Arthington (2002), and to record any notable patterns of divergence from these principles.

2. Methods

2.1. Reference collection

Abstracts and citations were collected by searching databases for the following terms:

- Flow modification
- Flow alteration
- Flow reduction
- Water abstraction
- Flow regime + alteration
- Flow regime + reduction
- Flow regime + modification
- Hydrological regime
- Hydrological threshold
- Hydrological variability
- Flow threshold
- Environmental flow
- Flow regulation + environmental + effect/impact
- Dam + flow + environmental + effect/impact
- Water storage + flow + environmental + effect/impact
- Weir + flow + environmental + effect/impact
- Impoundment + flow + environmental + effect/impact
- Extractive water use
- Consumptive water use
- Environmental water allocation
- Water diversion

The following databases were searched:

- Current contents (1993–2001)
- Biological abstracts (1980–2001)
- CSIRO journals (1983–2001)
- Academic research library (1986–2001)
- Life sciences collection (1982–1999)
- Environmental abstracts (1975–1999)
- Streamline (grey literature database 1982–2001)
- Elixir (grey literature database 1990–2001)
- Environmental science and pollution management (only contained references to oral presentations)
- Wilson general science abstracts (1984–2001).

In addition, reference lists from the following review papers and reports were checked for additional relevant papers: Barmuta *et al*. 1992, Kingsford 1995, Arthington 1998a,b, Arthington *et al*. 1998, Arthington and Zalucki 1998, Reid and Brooks 1998, Arthington *et al*. 2000, Brock and Casanova 2000, Brock *et al*. 2000, Kingsford 2000, Lemly *et al*. 2000, Roberts and Marston 2000, Roberts *et al*. 2000, Chessman and Jones 2001, Young *et al*. 2001, Bunn and Arthington 2002. Also, the reference lists from all the reviews, reports and research papers examined were checked for other relevant publications.

2.2. Selection of papers

Initial evaluation of papers from the database was based on the information contained in their abstracts. If a paper appeared to provide data on:

> any aspect of ecological or geomorphological effects, for in-channel, riparian or floodplain habitats, in response to quantified flow modification as a result of water abstraction or impoundment,

it was included. Papers examining the effects of restoration, rehabilitation or amelioration works (e.g. environmental flow releases), and those concerned with extreme natural variation that mimics the effects of abstraction or impoundments, such as droughts, were also included. Due to limited time and resources, the following were excluded from the review:

- foreign language papers
- salt lakes, reservoirs and estuarine habitats
- effects of hydropower dams
- effects of dam construction independent of flow modification

- predictive models that did not include empirical data
- ecological effects of changes in lateral or longitudinal connectivity (e.g. blocking of fish passage) if changes were not related to a quantified change in flow regime
- river regulation for navigation purposes: e.g. rapid changes in water level causing stranding of fish.

Papers on multiple impacts were only included if the design of the study allowed the effects of flow modification to be separated from other impacts, or if flow modification appeared to be the most serious impact.

A summary of each publication, including location, type of river and flow modification, research design, temporal and spatial scale of measurements, taxa and other variables recorded, ecological responses, and relevance to the principles of Bunn and Arthington (2002) is presented in Appendix 1.

2.3. Types of data available

(i) Ecological and geomorphological data collected from each publication were converted into percentage difference between treatment (i.e. regulated) flow regime and control or reference (i.e. unregulated) flow regime, or differences in flow from one time period to another (e.g. pre- and post-flow modification).

Control sites were defined as sites equivalent to the treatment site(s) in all measurable respects except flow modification, whereas reference sites often differed from control sites but were considered to represent less flow-modified conditions.

In a few cases, ecological and geomorphological data were read from figures rather than directly from the text or tables, and these cases have been labelled in Appendix 1 with a double asterisk (**).

Channel cross-section change (Erskine *et al.* 1999) was measured using image analysis to digitise the image (Logan 2000).

(ii) Some data related to the three temporal scales of flow modification, as used by Thoms and Sheldon (2000), to investigate hydrological changes for rivers of the Murray-Darling Basin:

- Flow regime: long-term statistical generalisation of flow behaviour — macro scale influences that extend over hundreds of years.
- Flow history: the sequence of floods and droughts — meso-scale influences lasting 1 to 100 years.
- Flow pulse: a flow event — micro scale influences that generally last for less than one year.

(iii) Hydrological data were retrieved either from the published paper or from relevant gauge data obtained directly from the National Land and Water Resources Audit database (http://www.nlwra.gov.au).

The Hydrological Index (HI) (Young *et al.* 2001) was calculated for those Australian sites for which there are suitable gauged flow data. The HI describes changes in flow magnitude and pattern by comparing four components: total flow volume, monthly flow variability, seasonal periodicity of flow and seasonal amplitude of flow, for current (post-flow modification) and historical (pre-flow modification) monthly flow data (Young *et al*. 2001). The HI has a range of 0 to 1, where 1 represents no change and 0 represents maximum change.

2.4. Analyses

The data extracted from the papers were used to summarise the degree of ecological change and to analyse associations between hydrological modification and ecological change.

The papers and variables included in particular analyses differed according to the type of data that could be extracted from each paper. For example, some papers reported quantitative changes in ecological variables but not hydrological variables, and such papers could not be included in the analysis of correlations between hydrological change and ecological change. Those papers whose data were used for analyses have been listed in Appendix 1.

The proportion of papers and the proportion of ecological or geomorphological variables demonstrating an impact of flow modification were determined. Many studies recorded more than one ecological or geomorphological variable. For example, Armitage and Blackburn (1990) measured species richness, Shannon diversity and community dissimilarity for chironomid fauna at five sites on the River Tees, UK. If any recorded variables indicated a quantitative or qualitative response to flow modification, then the study was counted as demonstrating an ecological or geomorphological effect of flow modification.

A small number of papers quantified both hydrological and ecological change in a manner that allowed the data to be used in formal analyses. Contingency tables summarise the associations between high and low levels of change (using 50% change as the low–high cut-off for each variable) for ecological and hydrological variables. The null hypothesis that the ecological change category was independent of the flow change category was tested with Fisher's Exact Test. Correlations between quantified ecological change and proportional hydrological change and proportional change in MAF (mean annual flow) and HI were tested using Pearson's correlation coefficient. The null hypothesis was that there was no correlation between ecological and hydrological change.

2.5. Constraints

A number of difficulties and constraints potentially limit the interpretations of the data and analyses in this report.

(i) The links between flow modification and ecological/geomorphological changes can be obscured by multiple impacts occurring at the same time and location. For example, flow modification as a result of dam operations is often confounded by the effects of sediment-trapping by the dam and by thermal pollution, to name just two potential downstream impacts. In addition, processes not directly related to river regulation, such as land use change, or the invasion of exotic species, may result in in-stream or wetland impacts that may be difficult to separate from the effects of flow modification (Bunn and Arthington 2002). Authors' conclusions regarding the cause of ecological or geomorphological changes were accepted if the author(s) provided justification in the discussion of the results or design of the study. Otherwise, the occurrence of alternative or additional impacts has been noted in Appendix 1.

(ii) There are few suitable control or reference sites, and little historical data (ecological, geomorphological and hydrological) suitable for the assessment of flow modification impacts. Flow regulation began in the 1800s in Australia (Kingsford 2000), and large dam building began at the turn of the century (McMahon *et al*. 1998) and pre-dated reliable gauge data in some locations, and detailed ecological and geomorphological studies in most areas. Therefore, the design of most studies was limited in terms of geographic or timeframe comparisons between flow-modified and unmodified rivers.

(iii) Measurement of flow modification is inconsistent, especially for wetlands. In some cases, HI measurements and alternative indices, e.g. change in MAF, were available for a particular location and the two measurements did not indicate the same degree of hydrological change. For example, the Campaspe and Broken Rivers scored HI values of 0.55 and 0.54 respectively, yet water diversion figures for MAF were 50% and 10% respectively (Humphries and Lake 2000).

3. Results

3.1. Frequency of responses

In total, 657 studies were considered for the literature review and 70 of these matched the selection criteria and were therefore included (see Appendix 1). The majority of these were Australian studies (Figure 1a) because of the secondary search technique of reading reference lists from included papers and additional appropriate studies. A wide range of clear geomorphological and ecological effects of flow modification has been documented by these studies:

- 61 of 70 (87%) studies demonstrated an ecological and/or geomorphological effect(s) of flow modification
- 169 of 204 (83%) variables demonstrated an ecological and/or geomorphological effect(s) of flow modification
- 100% (*n* = 30) of all studies that included a quantified flow modification, or for which gauge data were obtainable, demonstrated an ecological and/or geomorphological effect(s) of flow modification
- 100% (*n* = 9) of studies investigating geomorphological responses to flow modification recorded geomorphological changes
- 56 of 65 (86%) studies investigating ecological responses to flow modification recorded ecological changes.

3.2. Flow modification type

Flow modification in the reviewed studies resulted from abstraction, irrigation, augmented flows, flood mitigation, extended inundation and drought (Figure 1b). The majority of studies focused on the effects of abstraction (28 studies) or irrigation (19). Although a wide range of ecological and geomorphological effects was noted, with the exception of studies of extended inundation, effects did not vary according to the type of flow modification. Extended inundation invariably resulted in death of trees (Briggs *et al*. 1997; Froend and Van Der Moezel 1994; Leslie 1995) or reduced diversity (invertebrates: Timms 1992), fecundity (birds: Briggs *et al*. 1997) or abundance (invertebrates: Neckles *et al*. 1990; Timms 1992).

3.3. Scale of flow modification

Studies generally focused on pulse-scale (i.e. flow event, such as a flood or drought) and history-scale flow modification, i.e. the sequence of floods and droughts (Thoms and Sheldon 2000), and responses differed in severity as a result of the scale of flow modification (Figure 1c). In addition, pulse studies were more likely to include some examination of the hydrological factors causing the ecological response and were therefore more likely to support one of the principles of Bunn and Arthington (2002, see below). There was a wide range of ecological responses to both pulse and history-scale flow modification, but there were no general differences between the types of responses recorded for the two scales of flow modification.

The magnitude of ecological effects documented in history-scale studies ranged from <10% to >100% and data were evenly spread across this range (Figure 2). The mean (± SE) magnitude of all quantified ecological responses reported in the papers (Figure 2) was 89.7 % (± 45). The ecological responses documented in pulse-scale studies were less spread, the responses tended to be moderate or severe, and only two of the 10 papers included had a mean ecological response of less than 50% (Table 1: mean = 69.8 ± 14).

3.4. Habitat studied

Most papers studied in-channel or floodplain habitats (Figure 1d). Channel studies, comprising the bulk of the papers reviewed, considered all the variables summarised

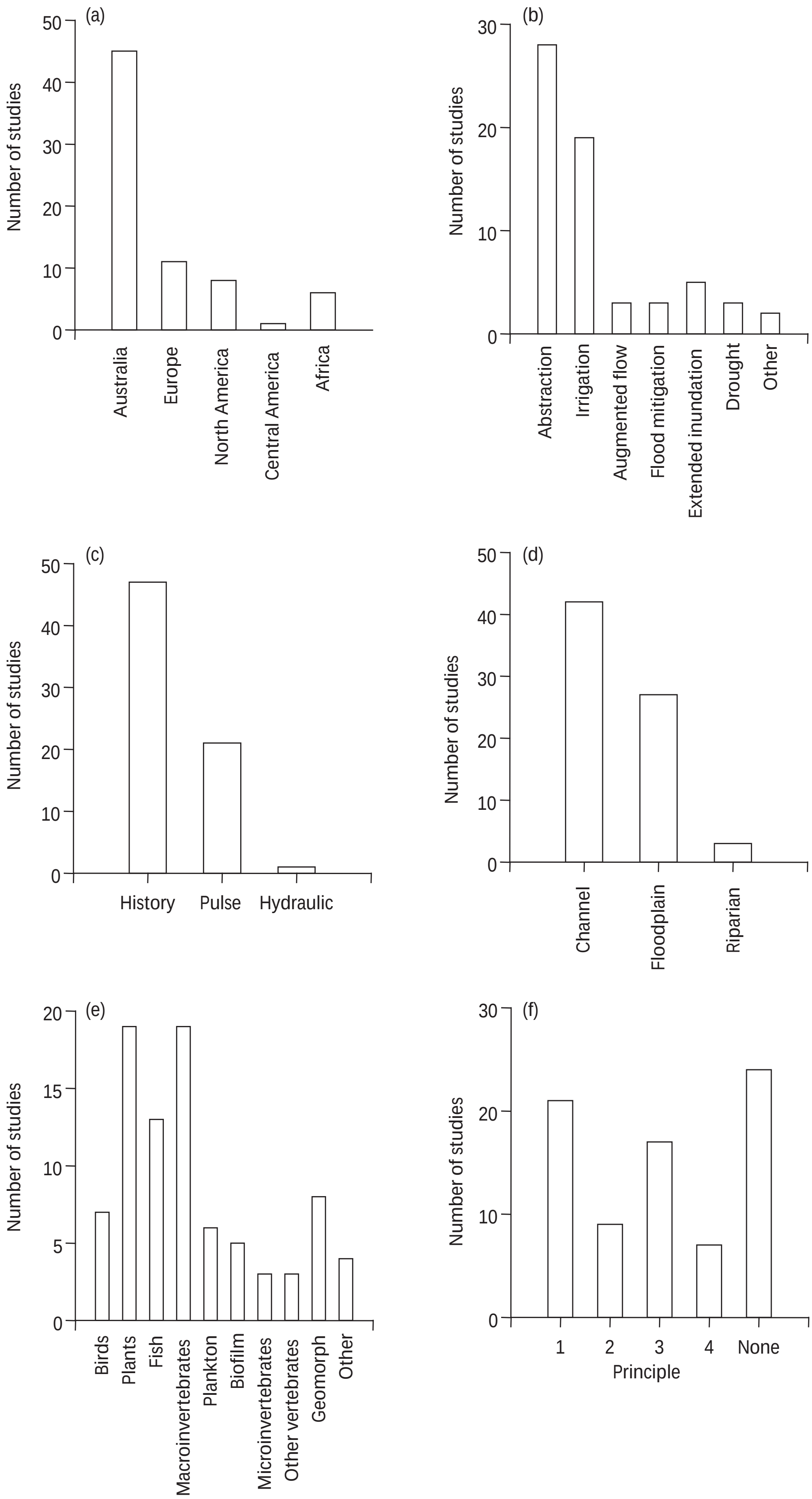

Figure 1. The number of studies included in the literature review, which were conducted for (a) different geographical locations; (b) type of flow modification; (c) temporal scale of flow modification (see p. 4 for definitions from Thoms and Sheldon (2000)); (d) riverine habitats; (e) taxa studied; (f) principles from Bunn and Arthington (2002); see page 2.

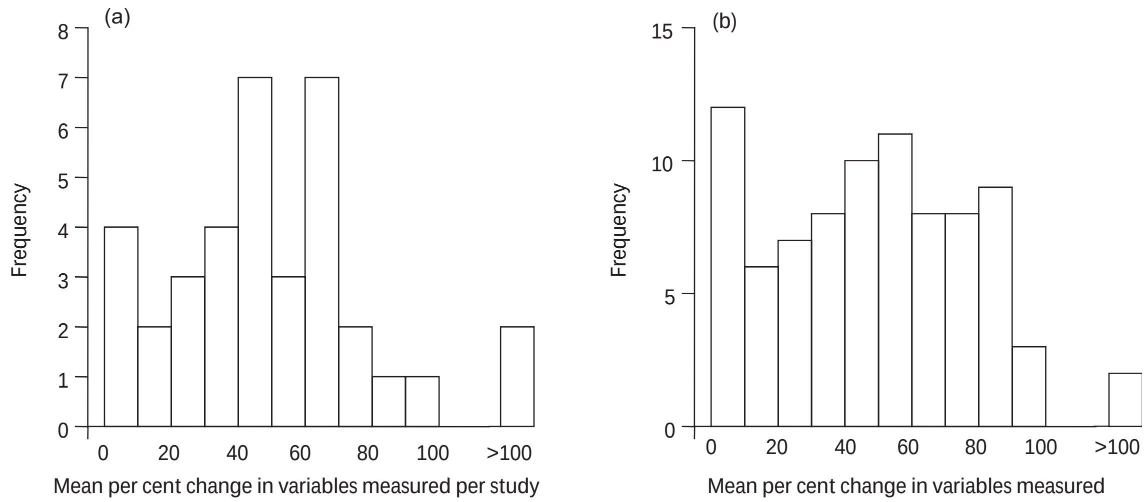

Figure 2. Percentage change for (a) papers (mean for all variables measured) and (b) variables from studies of history-scale flow modification (Sheldon *et al.* 2000).

Table 1. Percentage ecological change for measured variables from studies of pulse-scale flow modification (cf. Thoms and Sheldon 2000): 22 variables from 10 studies were quantified

Percentage change	Number of studies	Number of variables
1–10	0	0
11–20	0	0
21–30	1	2
31–40	0	0
41–50	1	2
51–60	0	3
61–70	3	2
71–80	2	3
81–90	1	7
91–100	1	2
>100	1	1

below. Wetland studies were predominantly concerned with birds and vegetation, but also examined fish and invertebrates. The main differences between the studies on different habitats were the variables studied. For example, all four riparian studies discussed vegetation. All the bird studies were conducted in wetland habitats. Eight of the nine geomorphological papers were concerned with in-channel responses.

3.5. Taxa or variables studied

A wide range of variables was used to measure ecological response (Figure 1e). Not surprisingly, responses differed between variables.

Geomorphology

Geomorphological effects of flow regulation were noted in all studies. Common responses to reduced flow were in-channel morphology changes (Thoms and Walker 1993), especially contraction of the channel (Petts and Greenwood 1985, Walker 1990a, Erskine *et al*. 1999). Armouring of the river bed was recorded in gravel bed rivers where flows lost competence for transporting sediment (Sherrard and Erskine 1991).

Planform adjustments resulted in altered sinuosity in the Kemano River (Church 1995) and the River Rheidol (Petts and Greenwood 1985). Bed stabilisation, formation of islands, benches and bars and vegetation encroachment were common effects of reduced flows (Sherrard and Erskine 1991, Benn and Erskine 1994, Décamps *et al*. 1995, Ligon *et al.* 1995, Serrano and Serrano 1996, Erskine *et al*. 1999).

Phytoplankton

Studies of phytoplankton indicated that flow reduction provides favourable conditions for phytoplankton production (Roy and Messier 1989, Gawne *et al*. 2000) and cyanobacterial growth in particular (Bowling and Baker 1996, Sherman *et al*. 1998). Zooplankton abundance may be reduced (Timms 1992) and zooplankton composition altered by extended inundation in wetlands (Nielsen *et al*. 2000). Similarly, Gawne *et al*. (2000) and Robertson *et al*. (2001) showed that flow regulation dampened biofilm production in lowland rivers and their wetlands, and biofilm composition could also be altered (Sheldon and Walker 1997).

Vegetation

Responses by aquatic, littoral, riparian and floodplain plants to flow modification are varied, because species differ in flood tolerance and dependence. Several studies noted changes in the distributions of particular species (Bren 1992, Zengel *et al.* 1995, Kidson *et al*. 2000a) or community composition (Ladle and Bass 1981, Chesterfield 1986, Walker *et al*. 1994, Leslie 1995) as a result of altered flow regimes.

River red gum (*Eucalyptus camaldulensis*) and other floodplain trees can die if inundated for too long (Froend and Van Der Moezel 1994, Leslie 1995, Briggs *et al.* 1997) and macrophyte species richness may decrease (Nielsen and Chick 1997). The abundance of exotic weed species can be negatively correlated with flood frequency (Bren and Gibbs 1986, Froend and Van Der Moezel 1994, Décamps *et al*. 1995).

Invertebrates

Alteration of community composition was the most common response of macro- and microinvertebrates to modification of flow regimes (Extence 1981, Ladle and Bass 1981, Petts and Greenwood 1985, Neckles *et al*. 1990, Timms 1992, Bickerton *et al*. 1993, Castella *et al*. 1995, Growns and Growns 2001). However, increases and decreases in secondary productivity (Extence 1981, Roy and Messier 1989, Neckles *et al*. 1990, Timms 1992) and decreases in richness of invertebrate taxa (Marchant 1989, Timms 1992, Bickerton *et al*. 1993) were also noted.

Fish

The fish faunas of highly flow-modified rivers tend to have low diversity (Gehrke *et al*. 1995), low abundances of native species (Leslie 1995), low breeding success for native species (Harris 1988, Humphries and Lake 2000) and different community structures (Gehrke *et al*. 1999) compared to less flow-modified rivers. They also tend to have low abundance ratios of native to alien species (e.g. Gehrke 1997).

Waterbirds

Similarly, bird breeding and abundance are affected by flow modification. Wetlands that flood and dry naturally tend to have higher values for breeding records (number of nests or offspring) (Briggs *et al.* 1997), adult abundance (Kingsford and Thomas 1995), species richness (Leslie 1995) and number of species breeding (Briggs *et al*. 1994) than do wetlands where the area and duration of inundation have been altered. Inter-annual variations in bird abundance have been correlated with both the area of wetland flooded and in-channel annual flow (Kingsford and Thomas 1995, Kingsford and Johnson 1998).

3.6. Principles suggested by Bunn and Arthington (2002)

There was some evidence to support the four principles of Bunn and Arthington (2002, see below, Figure 1f, Table 2). Particularly conclusive was the evidence for principles 1 and 4.

Overall, the majority of papers could not be assigned to any principle (Figure 1f, Table 2). This was not because the principles were not relevant to the taxa studied, but rather because the author(s) reported ecological changes but did not investigate the mechanisms behind those ecological changes, so the support or otherwise for the principles could not be determined

Principle 1: Flow is a major determinant of physical habitat in streams, which in turn is a major determinant of biotic composition

All geomorphological studies investigated the first argument of principle 1, and all nine studies provided support for this principle. Components of physical habitat affected by flow modification include wetted area (Roy and Messier 1989, Froend and Van Der Moezel 1994, Humphries *et al*. 1996), the development of bars, benches and islands (Ligon *et al*. 1995), retention of organic matter (Gawne *et al*. 2000), presence of pool habitat (Erskine *et al*. 1999), availability of woody debris (Humphries *et al*. 1996) and substrate composition (Sherrard and Erskine 1991). It is also important to acknowledge the role of sediment transport as a co-determinant of physical habitat in river systems. Many of the geomorphological studies note that change to the sediment transport regime is a factor in river channel changes in regulated rivers.

The literature reviewed also produced evidence for links between physical habitat and the biota. Riparian or dryland plants invade dry ground and in-channel islands (Sherrard and Erskine 1991, Décamps *et al*. 1995, Serrano and Serrano 1996). Salmon populations in the Mackenzie River, Oregon, have decreased by 50% as a result of lack of spawning habitat (Ligon *et al*. 1995). Macroinvertebrate community composition has altered in conjunction with sedimentation and changes to channel morphology (Petts and Greenwood 1985). A substantial reduction in the area, depth and volume of aquatic habitat resulted in a 54% increase in

Table 2. Number of papers investigating different taxa, habitats and scale of flow modification whose findings reflected the four principles of Bunn and Arthington (2002). Number of papers covering each category in parentheses. Note that 'Habitat' is the only principle that applies to geomorphological processes. Some papers supported more than one principle.

	1. Habitat	2. Life history	3. Connectivity	4. Exotics	Not assigned
Geomorphology (9)	9	—	—	—	0
Phytoplankton and biofilm (5)	5	0	0	0	0
Biofilm (5)	2	1	0	0	1
Vegetation (19)	4	1	11	4	4
Invertebrates (19)	4	0	1	0	15
Fish (13)	2	5	0	3	4
Birds (7)	0	1	6	0	1
Hydraulic (1)	1	0	0	0	0
Pulse (21)	3	5	8	3	8
History (48)	17	4	9	4	17
Riparian (4)	3	0	0	1	1
Channel (41)	18	6	0	3	17
Floodplain (27)	2	5	17	3	7

primary production and a 2400% increase in secondary production (Roy and Messier 1989). An increase in secondary production was also recorded as a result of increased water temperature and algal growth (Extence 1981). Baker *et al*. (2000) found that the slow flowing conditions in the lower River Murray favoured the growth of *Anabeana circinalis* rather than the diatom *Aulacoseira granulata*.

Principle 2: Aquatic species have evolved life history strategies primarily in direct response to their natural flow regimes

Few studies directly examined the evolution of life history strategies, but indirect support for principle 2 was provided by the reliance of aquatic taxa on natural hydrological triggers such as flood size and timing. For example, three of four environmental releases in the Groot River of South Africa, which is regulated for flood mitigation, triggered spawning in the redfin minnow (Cambray 1991). Flow volumes in winter in the Sydney Basin were correlated with initial cohort abundance for the Australian bass (Harris 1988). The timing of inundation affects wood growth in floodplain vegetation, macrophyte richness and biofilm production (Robertson *et al*. 2001). Where flow has been reduced, the floodplain mussel of south-eastern Australia has extended its range to the detriment of the river mussel which is adapted to fast flowing water by its large muscular foot and small streamlined shell (Walker 1990b).

Principle 3: Maintenance of natural patterns of longitudinal and lateral connectivity is essential to the viability of populations of many riverine species

There is a substantial body of literature on the importance of connectivity, both longitudinal and lateral. Longitudinal connectivity is affected by many factors other than flow, including in-stream barriers that restrict fish movement (Harris 1984). A number of papers did not quantify the effect of flow, and they therefore could not be included in this review (e.g. Junk *et al*. 1989; Tockner *et al*. 1999; Ward *et al*. 1999 and references within). However, a number of studies indicated that flow modification affects the amount and timing of water reaching the floodplain (e.g. Kingsford and Thomas 1995) and that the biota, especially vegetation and birds, respond to inundation patterns. Insufficient water on the floodplain resulted in reduced bird nest numbers (Kingsford and Johnson 1998) and abundance (Kingsford and Thomas 1995). Vegetation cover dropped by 70% in wetlands after a two-month water diversion (Zengel *et al*. 1995). River red gum growth, survival (Kidson *et al*. 2000b), health (Bacon *et al.* 1994) and quality (Bren and Gibbs 1986) are related to flooding patterns. Community composition of floodplain vegetation also responds to flooding patterns (Bren and Gibbs 1986), and insufficient floods can result in the invasion of plants such as river red gum (Bren 1992), weeds (Bren and Gibbs 1986) and dryland tree species (Kidson *et al*. 2000a).

Similarly, too much water, particularly inundation for extended periods, results in ecological changes. Thornton and Briggs (1994) documented the death of 570 ha of river red gum forest as a result of extended inundation (see also Froend and Van Der Moezel 1994, Briggs *et al*. 1997). Similarly, Leslie (1995) noted the death of river red gums and the decline of macrophytes when summer drying was prevented in the Moira Marshes. Lack of summer drying also reduced bird breeding at Lake Merrimajeel, Murrumbidgil Swamp (Crome 1988) and Tombullen Wetland (Briggs *et al*. 1994). Invertebrate abundance decreased and community composition altered as a result of extended inundation (Neckles *et al*. 1990). Inundation timing and length affected richness, diversity and community composition in macrophytes (Nielsen and Chick 1997), and community composition of the microinvertebrate egg bank (Nielsen *et al*. 2000).

Principle 4: The invasion and success of exotic and introduced species in rivers is facilitated by the alteration of flow regimes

All studies that assessed the responses to flow modification of native species compared to exotic species found that exotic species were more successful where the flow had been modified. Australian studies found that exotic fish were more abundant relative to native fish in rivers with modified flow regimes (Leslie 1995, Gehrke 1997, Humphries and Lake 2000, see also Gido and Brown 1999). In Lower Putah Creek, California, the abundance of species exotic to that environment showed a negative correlation with flow at the site scale, whereas the correlations for native species were positive (Marchetti and Moyle 2001). Similarly, exotic plants invade native vegetation (Bren and Gibbs 1986; Décamps *et al*. 1995) and are more successful than native species at invading the main channel or wetlands (Décamps *et al*. 1995; Erskine *et al*. 1999; Froend and Van Der Moezel 1994) when high flows are reduced in size or frequency. Unfortunately, none of the studies included in the review examined the differential success of native and exotic species of invertebrates, birds, biofilm or phytoplankton; therefore the application of this principle to those taxa is unknown.

3.7. Flow–ecology relationships

Contingency tables were only calculated for ecological change versus proportional change in MAF and proportional hydrological change, because HI values obtained for most sites with quantified ecological data were clustered and ranged only from 0.52 to 0.67. There was no evidence to reject the null hypothesis that ecological change was independent of hydrological change, using a 50% change cut-off for each variable (Tables 3 and 4). The correlation analyses also indicated that there were no simple linear relationships between the size of ecological change and the size of the hydrological change (Figure 3).

Table 3. Contingency table for proportional hydrological change and mean per cent ecological change. The division between low and high is 50% for each variable. Fisher's exact test demonstrated (P = 1.0 with 1 df) that proportional hydrological change and ecological change were independent for the studies included (see Table 5 for list of studies).

Proportional hydrological change	Ecological change		
	1 (low)	2 (high)	Marginal totals
1 (low)	4	6	10
2 (high)	1	3	4
Marginal totals	5	9	Grand total n = 14

Table 4. Contingency table for percentage change in mean annual flow (MAF) and mean per cent ecological change. The division between low and high is 50% for each variable. Fisher's exact test demonstrated (P = 1.0 with 1 df) that change in MAF and ecological change were independent for the studies included (see Table 5 for list of studies).

Proportional MAF change	Ecological change		
	1 (low)	2 (high)	Marginal totals
1 (low)	3	6	9
2 (high)	2	2	4
Marginal totals	5	8	Grand total n = 13

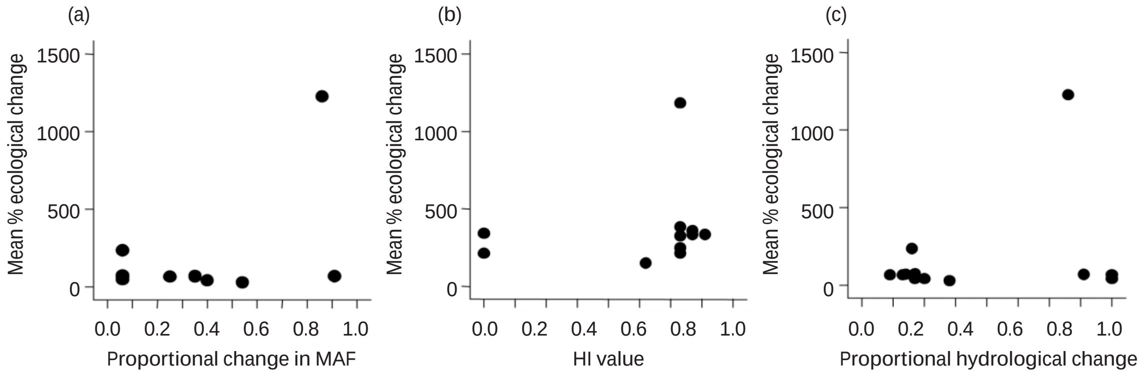

Figure 3. (a) Correlation between proportional change in MAF (mean annual flow) and mean % ecological change. Full data set: Pearson's $r = 0.481$, $n = 12$, $p = 0.113$. Excluding Roy & Messier's (1989) extreme ecological change: Pearson's $r = -0.350$, $n = 11$, $p = 0.291$. (b) Correlation between HI value and mean % ecological change. Full data set: Pearson's $r = 0.189$, $n = 11$, $p = 0.578$. (c) Correlation between proportional change in MAF and mean % ecological change. Full data set: Pearson's $r = -0.166$, $n = 13$, $p = 0.589$. For all, see Table 5 for included studies.

Table 5. Summary of ecological and hydrological data from papers that quantified hydrological change and ecological responses. Mean ecological change is the mean of all ecological variables quantified in each study. Proportional hydrological change is a combination of indices, either proportional change in MAF or 1 – HI. Note that the HI value is subtracted from 1 because an HI value of 0 indicates maximal change and HI value of 1 indicates no change (Sheldon et al. 2000), whereas the opposite is true for proportional hydrological change.

Paper	Mean ecological change (%)	HI value	Proportional change in MAF	Proportional hydrological change
Briggs *et al*. (1997)	68.5	0	N/A	1.00
Bren (1992)	67.0	0.71	0.25	0.29
Brereton (1994)	65.0	0.63	0.06	0.37
Briggs *et al*. (1994)	42.8	0	N/A	1.00
Crome (1988)	72.0	0.67	0.35	0.34
Church (1995)*	16.0	N/A	1.00	1.00
Humphries and Lake (2000)	42.5	N/A	0.40	0.40
Kidson *et al*. (2000a)	49.9	0.63	0.06	0.37
Kidson *et al*. (2000b)	236.5	0.63	0.06	0.36
Kingsford and Johnson (1998)	76.7	0.63	0.06	0.37
Marchant (1989)	43.0	0.63	0.40	0.37
Roy and Messier (1989)	1227.0	N/A	0.86	0.86
Shaikh *et al*. (1998)	67.0	0.67	0.35	0.33
Thoms and Walker (1993)	30.2	0.52	0.54	0.48
Zengel *et al*. (1995)	70.0	N/A	0.91	0.91

* Not included in figures or analyses because only geomorphological change quantified.

4. Discussion

This review highlights very strong evidence for both ecological and geomorphological changes in response to flow modification. Specifically, 87% of studies demonstrated that where flow is modified there are ecological and/or geomorphological effects. Of the variables examined, 83% demonstrated ecological and/or geomorphological responses to flow modification. All of the 30 studies in which flow or flow change were quantified demonstrated ecological and/or geomorphological effects of flow modification. All of 9 studies investigating geomorphological responses to flow modification recorded geomorphological changes and 56 of 65 (86%) studies investigating ecological responses to flow modification recorded ecological changes.

While the review found indisputable evidence for ecological effects of flow modification, the relationship between the degree of flow modification and ecological or geomorphological change was not simple. One might expect a monotonic relationship between flow modification and ecological response, indicating that small flow modification resulted in small ecological changes. However, this review finds that severe ecological changes can occur in response to even small alterations to flow regime. For example, the lowest proportional hydrological change recorded, 0.29 (HI = 0.71) in Table 5, was associated with a 67% loss of grassland in the Barmah Forest War Plain (Bren 1992).

Similarly, other relatively small hydrological changes were associated with large percentage changes in ecological variables. There were 72% fewer birds' nests at Murrumbidgil Swamp and Lake Merrimajeel in years when the wetland had not dried out, compared to years when it had (Crome 1988). Water levels in these wetlands are controlled by Booligal Weir, which has a proportional hydrological change of only 33% (HI = 0.67), yet where the wetlands were once intermittent, they may now remain inundated for several years in a row (Briggs and Maher 1983, Maher 1984). Conversely, the area and/or time spent inundated may be reduced for other floodplain areas, also resulting in considerable ecological changes. Shaikh *et al*. (1998) found that the area covered by river red gum and *Phragmites* reed was correlated with the area inundated by flood events. Mean inundated area time (haD) was 67% less than the maximum recorded during the study despite a proportional hydrological change of only 33% in the main channel (HI = 0.67). Four times more river red gums died in the Macquarie Marshes, and tree growth rate was 56% less, in years with lower annual discharge than in wetter years (Shaikh *et al*. 1998; see also Kidson *et al*. 2000b). These figures were recorded for an area that has a proportional hydrological change of 0.37 (HI = 0.63).

A threshold model might of the relationships found between flow modification and ecological response. In a threshold model, a population or system can remain viable until conditions such as flow volumes or physical habitat deteriorate beyond a threshold. At that point, the population ceases to reproduce or ecological processes are fundamentally altered. This type of model explains some geomorphological processes, whereby flows of certain size can be designated habitat-forming floods. For example, discharges of a given magnitude are responsible for the construction of in-channel bars. The results of a study of 15 regulated rivers (Petts 1979) support the suggestion of a threshold response to flow changes. There, morphological changes were observed downstream from dams until the regulated catchment area had been reduced on average to 40% of the total catchment draining to the river. This would suggest that a change in discharge character of 40% would be required to produce river channel changes in regulated rivers, but that depends on the relationship between catchment area and discharge.

Three of the studies reviewed here document flow threshold values below which population or ecosystem function was not normal. Sherman *et al.* (1998) demonstrated that flows of less than 1000 ML/day resulted in thermal stratification of Maude Weir pool on the Murrumbidgee River; thermal stratification was a requirement for exponential growth of the cyanobacteria *Anabaena* spp. to occur. Australian bass failed to spawn in 1979 and 1980 in the Hawkesbury and Colo Rivers; in these years, mean discharge for the Colo River in July and August was less than 400 ML/day (Harris 1988); mean discharge for these months over the entire study period was approximately 700 ML/day (Harris 1988). Similarly, no breeding was recorded for intermediate egrets, rufous night herons, glossy ibis, strawnecked ibis, Australian white ibis and royal spoonbills when annual flow in the Macquarie River was less than 200,000 ML; mean annual flow over the 12-year study period was approximately 280,000 ML (Kingsford and Johnson 1998).

The effects of flood mitigation in the MacKenzie River (USA) may also be seen as a threshold response (Ligon *et al.* 1995). Floods no longer overtop the bank and consequently gravel is no longer transported from the floodplain into the main river channel. In response, new islands are not developing and the reduced availability of salmon spawning habitat has resulted in a 50% reduction of salmon abundance (Ligon *et al*. 1995).

Despite these examples of individual thresholds, contingency table associations in this review do not find simple threshold relationships, probably because of the wide range of variables studied. The mechanisms or driving processes behind the viable function of a population or ecosystem are likely to be different for different taxa and habitats. For example, habitat-forming flows that produce in-channel benches, which trap organic matter and provide refuge in flood events, may be necessary to provide physical habitat for macroinvertebrate communities (Thoms and Sheldon 1997), but water temperature and chemical conditions seem to be more important in regulating the community composition of phytoplankton communities.

This review only tested for simple linear relationships or simple thresholds, because few of the reviewed studies quantified both flow modification and ecological response, and the data did not permit more complex analyses. While it is very likely that any relationship will be much more complex, such complexity could only be explored in this review if the dataset had been larger and if other potentially causal factors (riparian modification, water quality, in-stream habitat availability) had also been considered in the modelling.

There are three opportunities for increasing the size of the dataset. First, further literature searches, especially of the international and unrefereed literature, may provide more studies that have quantified hydrological change and ecological response. Second, it is apparent that many Australian studies probably have the necessary quantifiable information on hydrological change and ecological response but did not report either or both of these in their papers. Obtaining and re-analysing the original data from these research projects would be very rewarding. Finally, existing datasets, particularly from various environmental surveys and audits (e.g. National Land and Water Audit, Sustainable Rivers Audit), may also provide relevant information for further analyses of the relationships between flow and ecological response, although the constraints on interpretation discussed below will be particularly important.

As outlined above, rivers respond to three scales of hydrological behaviour: the flow regime, the flow history, and the flow pulse. The initial impact of water resources development will be a change in the nature of the flood pulse. Then, continued development will result in a change in flow history leading eventually to change at the scale of the flow regime. The time-scale of ecological change through this sequence, from organism-level responses, through population and community changes to ecosystem-level change, will depend on the organism or group of organisms or ecosystem component in question. This suggests that for any hydrological change there will be a lag time before the ecological response can be detected, and the extent of this lag time will depend on the component in question. For many of the long-lived organisms, such as large fish or riparian trees, there would be a considerable lag time, with recent hydrological development taking decades to be transferred into detectable environmental impact. For example, Thoms and Walker (1993) have demonstrated that the physical responses of the lower River Murray to weir construction upstream are still incomplete after 70 years.

In contrast to the apparently specific responses of taxa and habitats to flow change, the four principles of Bunn and Arthington (2002) appear to apply equally to different taxa and habitats. The exceptions, rather than contradicting the four principles, occur because studies have not examined these concepts for particular taxa. For example, none of reviewed studies measured whether there was differential success of exotic and native invertebrate, avian, phytoplankton or biofilm taxa in flow-modified rivers.

Three factors can hamper the demonstration of general relationships between flow and ecological responses even if they do exist: (i) lack of consistency between studies; (ii) scale mismatches between hydrological change and ecological response; (iii) time lags between cause and effect. The studies reviewed here investigated widely different geographic locations, spatial and temporal scales, types of habitat and taxa. For example, Thornton and Briggs (1994) reported that 570 ha of dead red gum forest (*E. camaldulensis*) was a 1% effect because the spatial extent of the study was 174,700 ha (not all of which was red gum forest), whereas a loss of 596 ha of grassland due to invasion by red gum constituted a 67% loss as the spatial extent of the study was 2,412 ha (Bren 1992).

Mismatching between the scale of hydrological change (both timescale and spatial scale) and scale of ecological response may also occur within studies. For example, hydraulic patterns are known to be very important to macroinvertebrate distribution and community composition (Statzner and Higler 1986) and local factors are sometimes the most important in regulating such communities (Doisy and Rabeni 2001), yet all invertebrate studies in this review examined flow modification at much larger spatial and temporal scales.

Time lags between hydrological events and the ecological responses may prevent researchers from identifying flow–ecology relationships. Geomorphological studies frequently comprise long-term changes and recognise a period of adjustment, but ecological studies vary widely in timescale, and snapshot-type studies may not detect responses that occur over a longer time period. For example, in long-lived species, such as river red gum or Murray cod, the population may be persisting but comprise only adult individuals that are unable to reproduce due to lack of hydrological triggers.

Small modifications to in-channel flows can have considerable ecological effects through the resulting large changes to wetland flooding patterns, which consequently affect the biota. Pressey (1990) found that 30% of total wetland area in the Murray-Darling Basin is now permanently flooded. Similarly, Growns and Marsh (2000) found that the loss of a drought or drying phase is a common result of flow modification in south-eastern Australia. There are often severe effects when intermittent wetlands become permanent waterbodies because of flow modification, because wetland function is related in part to a drying phase. This has been documented for mature trees, which die in permanent water (Froend and Van Der Moezel 1994), macrophyte, macro and microinvertebrate community structure and productivity (Neckles *et al*. 1990, Nielsen and Chick 1997, Timms 1992 respectively), and availability of organic debris (Glazebrook and Robertson 1999). These changes in turn affect resources available for consumers such as fish and birds (Crome and Carpenter 1988, Boulton and Lloyd 1992).

In-channel fauna can also be affected by relatively small hydrological change. Sheldon *et al*. (2000) modelled taxa responses to flow modification and found that even slight modification led to the loss of several taxa.

Moderate to severe ecological effects have been recorded in pulse-scale studies, possibly because the studies examined major hydrological modification, e.g. major drought (Extence 1981), and very extended inundation (Froend and Van Der Moezel 1994). This review could not analyse these studies because a general hydrological index for these flow modifications has not been developed.

Although the magnitude of ecological change has been documented in many studies, it is much harder to quantify the importance of a particular ecological effect in relation to the viability of a population, e.g. a fish species, a bird species, or the functioning of an ecological process such as nutrient cycling within the river ecosystem. For example, does a 20% change in primary productivity matter to the ecology of a particular wetland, or is it within the natural range of variability? For how long can such a change be tolerated without significant effects on aquatic biota or food web structure? Understanding the significance of ecological responses, especially in terms of sustainability of populations, communities and ecosystems, is one of the most important research challenges for ecologists in the coming decade.

4.1. Future directions for desktop research

- Development of a hydrological index of interannual variability in flow modification, or adaptation or use of the 32 indices of interannual hydrologic alteration devised by Richter *et al.* (1996), so that pulse-scale studies can be analysed. There are some existing methods. Décamps *et al*. (1995) compared the ratio between the mean daily flow per year and the long-term average, to find the relative abundance of water for each year of the study. Alternatively, the coefficient of variation of the MAF for a particular year could be compared to the long term MAF. See also Ladson and White’s (1999) amended index of annual proportional flow deviation as used by Marchant and Hehir (2002) in their study of the impact of dams in south-east Australia on macroinvertebrates. In a more complex approach to river flow characterisation, Thoms and Parsons (2003) used 340 regime, history and pulse-scale flow variables in a multivariate statistical analysis. They were identifying river reaches with similar hydrological character and determining the association between different temporal flow variables and river reaches.
- Development of a hydrological index to quantify changes in the spatial and temporal patterns of wetland inundation, or use of the Brownlow *et al*. seven classes of wetland inundation patterns (Brownlow *et al*. 1994). The latter method is based on water depth data through time for locations within wetlands and can be adapted to obtain a percentage change at the whole wetland scale. Important ecological factors for wetland biota and processes appear to be duration, timing, frequency and area of inundation and the occurrence of a drying phase. The HI used in this review does not incorporate these

variables and is therefore not really suitable for wetlands. Hydrological data for wetland inundation may not be as readily available as main channel gauge data, but data are available for some areas, e.g. Menindee Lakes (Gawne 2001), Macquarie Marshes (Kingsford and Thomas 1995), Great Cumbung Swamp (Shaikh *et al*. 1998).

- Comparison between ecological effects attributed to natural flow variation and those attributed to flow modification. Differences in ecological responses to natural and anthropogenic sources of disturbance are of considerable interest. It is thought that biota have evolved strategies to deal with natural disturbances, whereas they may be less resistant to much more recent human-induced disturbances.
- Development of links between a quantified ecological response and the viability of a species and the functioning or integrity of a community or ecosystem. Ecological literature often implies such links, but to date these implications have not been integrated for freshwater environments or taxa.
- Increasing emphasis on floodplain studies. Most Australian lowland rivers have floodplains (Thoms and Sheldon 2000), and ecosystem processes such as the transport of organisms, nutrients and carbon are very important to river functioning (Baldwin and Mitchell 2000).
- Examination of the hydrological factors causing ecological change, i.e. identifying the components or combinations of components of flow modification that are causing ecological and geomorphological impacts. The sub-indices of the HI may be a useful way to break up the flow regime into key components and examine relationships between those components and ecological change. For example, research on macrophytes and other plants has focused on the mechanisms by which flow modification, or at least inundation pattern, affect the biota, and this approach should also be adopted by those investigating invertebrates etc.

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Appendix 1

Summary of contents of all studies included in this review

For those papers that included appropriate statistical analyses, statistically significant or non-significant results are marked (*) or (NS), and results or assertions that were not tested statistically are marked (NT). Remaining papers did not present appropriate statistical analyses. 'Principle' refers to principles 1 to 4 from Bunn and Arthington (2002). Summary/Analysis refers to the following components: 1: Included in the calculation of the proportion of variables and studies demonstrating impact of flow modification; 2: Figure 1; 3: Figure 2; 4: Table 2; 5: Table 3 (contingency table analysis); 6: Figure 3 (correlation analysis). ** indicates cases where ecological and geomorphological data were read from figures rather than directly from the text or tables.

Paper	**Armitage and Blackburn 1990**	**Armitage and Petts 1992**	**Bacon et al. 1994**
Geographic location	River Tees, UK	UK	Macquarie Marshes, Macquarie River, NSW
Habitat	Channel	Channel	Floodplain
River type	Upland	Various	Inland
Experimental study	No	No	No
Flow modification type	Industrial water supply (similar flow pattern to irrigation) NB temperature regime also modified	Abstraction	Abstraction
Flow modification scale: hydraulic, pulse, history, regime	History, dam closed in 1971	History	History
Flow modification degree	• Discharge 0.45–4m^3s^{-1} from dam • Control site discharge 0.07–23m^3s^{-1}	Various	HI at Oxley gauging station = 0.63
Study design	4 treatment sites, 1 control site on tributary	Snapshot survey, upstream reference sites, RIVPACS model	Comparison of sites with healthy and unhealthy trees
Temporal scale of study	Sampling four times per year 1972–1975	One sampling event	Unknown
Spatial scale of study, Number of sites	5 sites within 1.5 km	51 sites on 22 rivers NB may be the same data as Castella *et al.* (1995)	7 pairs of sites
Variables measured	Ecological structure: community	O/E scores	Ecological function: tree health
Ecological effect	Richness 9% lower at site immediately below dam than control site (NT), however impact sites further from dam had higher richness than control site (23%, 27% and 17%) (NT). Overall (1972–1975) Shannon diversity lowest at site closest to dam, highest at control site (NT), however annual values show no consistent pattern. Taxon accretion curves for three of four treatment sites closer to dam plateau more than those of control site and treatment site furthest from dam. Dissimilarities between fauna in 1972 and 1975 were highest for control site, lowest for site adjacent to dam	O/E scores could not consistently distinguish between control and impact sites or between differing degrees of flow modification	Health of trees primarily related to soil moisture content, which is a result of flooding frequency and duration
Taxa studied	Chironomids	Macroinvertebrates	Red gum (*Eucalyptus camaldulensis*)
Principle	Could not assign	Could not assign	3
Summary/Analysis	1, 2, 3	1, 2	1, 2

Paper	**Baker *et al*. 2000**	**Benn and Erskine 1994**	**Bickerton *et al*. 1993**
Geographic location	Australia: lower Murray, SA	Cudgegong R below Windamere Dam: NSW	Wissey, Rhee, Pang Rivers, UK
Habitat	Channel	Channel and riparian	Channel
River type	Lowland / Inland	Lowland	Upland
Experimental study	No	No	No
Flow modification type	Abstraction	Irrigation	Groundwater abstraction
Flow modification scale: hydraulic, pulse, history, regime	History	History dam closure 1984	History
Flow modification degree	• Discharge 3000–5000 ML/day • HI at Lock 1 is 0.5	Mean Pc is 32%	• Moderate–severe • Not quantified
Study design	Repeated measurements of 17 'parcels of water'	Surveys in 1984 and 1991, comparison of 1965 and 1989 aerial photographs	Downstream reference sites (abstraction affects headwaters only
Temporal scale of study	Up to 4 samples of each parcel (7–10 days travel time) Oct 1994 – January 1995	See above	One sampling event
Spatial scale of study, Number of sites	8 sites over 544 km	9 sites over 13 km river section	6 sites on 3 rivers NB this data is a subset of Armitage and Petts (1992)
Variables measured	Population of *Anabeana circinalis*, *A. flos-aquae f. flos-aquae, Aulacoseira granulata* (diatom)	Geomorphology	• Community composition • Family richness • ASPT (organic pollution index equivalent to SIGNAL)
Ecological effect	• *A.circinalis* population growth rate 0.176 ($\pm$ 0.436) • *A. flos-aquae f. flos-aquae* (0.132 $\pm$ 0.233) • *A. granulata* -0.015 $\pm$ 0.184 i.e. conditions favour cyanobacterial growth	• Increased density in riparian trees (*Casuarina cunninghamiana*) • No planform changes due to lateral confinement by bedrock • Cross section alteration has occurred at 5 of 9 sites • 5 of 9 sites have decreased mean particle size • Vegetation encroachment by *Vallisneria*, *Phragmites*, *Juncus*, *Rubus*, *Casuarina* occurred at 5/9 sites	Richness was 19% (Wissey R), 17% (Rhee R), 44% (Pang R) lower at impact sites than reference sites (NT). ASPT was 23% (Wissey R) and 14% (Pang R) lower at impact sites than reference sites (NT). However, the Rhee River impact site had an ASPT score 2% higher than the reference site (NT). Macroinvertebrate responses may be related to reductions in macrophyte cover at impact sites Community composition differed between upstream and downstream sites (NT)
Taxa studied	Phytoplankton	Geomorphology	Macroinvertebrates
Principle	1	1	Could not assign
Summary/Analysis	1, 2	1, 2, 5	1, 2, 3

Paper	Bowling and Baker 1996	Bren and Gibbs 1986	Bren 1992
Geographic location	Barwon-Darling R	Barmah forest, Victoria	War Plain, Barmah Forest, Victoria
Habitat	Channel	Floodplain	Floodplain
River type	Inland	Inland	Inland
Experimental study	No	No	No
Flow modification type	Abstraction	Irrigation	Irrigation
Flow modification scale: hydraulic, pulse, history, regime	History	History	History
Flow modification degree	• HI at Wilcannia is 0.60, • HI at Mungindi is 0.63	• Categorical flood frequency for 1963–1985. NB: Bren *et al*. (1987) found that flow at Tocumwal was correlated with % forest flooded at Barmah • Tocumwal HI is 0.71	• Seasonal reversal • HI at Tocumwal is 0.71
Study design	Descriptive	• Examination of flood maps and vegetation map Chesterfield (1986) to produce correlation between flood frequency and vegetation community parameters • Historical data for red gum quality	Analysis of historical photos
Temporal scale of study	Weekly sampling over 2 months	Annual flood maps 1963–1985	1945, 1957, 1970, 1985
Spatial scale of study, Number of sites	24 sites	0.5 km grid over 28,900 ha forest	0.2 km grid over 2,412 ha
Variables measured	Ecological process: Cyanobacterial (*Anabaena circinalis*) bloom	Population status, community composition	Community composition
Ecological effect	Severe toxic bloom for 8 weeks, resulting in stock deaths and a state of emergency in NSW	• Red gum 'quality' (mature tree height) positively correlated to flood frequency. • Distribution of 13 distinct understorey plant associations related to flood frequency. • Weed species negatively related to flooding frequency	Invasion of *E. camaldulensis* into grassland. Area without trees (1945) reduced by 67% (1985).
Taxa studied	Phytoplankton	• River red gum (*Eucalyptus camaldulensis*) • Plants	Grassland plants
Principle	1	3, 4	3
Summary/Analysis	1,2, 5	1, 2, 5	1, 2, 3, 3, 6

Paper	**Brereton 1994**	**Briggs *et al*. 1994**	**Briggs *et al*. 1997**
Geographic location	Macquarie Marshes, Macquarie River, NSW	Tombullen wetland, Murrumbidgee R	Australia: Murrumbidgee R NSW
Habitat	Floodplain	Wetland	Floodplain
River type	Inland	Inland	Lowland / Inland
Experimental study	No	No	No
Flow modification type	Abstraction	Permanent inundation	Extended inundation of wetlands
Flow modification scale: hydraulic, pulse, history, regime	History	History (10 yrs)	Pulse
Flow modification degree	HI at Oxley gauging station is 0.63	HI given nominated value = 0 for conversion to permanent wetland	Could not assign HI for Boggy Ck, Bulls Run, Dry Lake, Uri, Wowong wetlands. HI = 0 for Talbot, Gogeldrie, Tombullen (converted to permanent inundation)
Study design	Comparison of cross-section surveys in 1968 and 1992/3	descriptive	Treatment vs reference
Temporal scale of study	1968–1992/3	Annual surveys 1981–1991	Annual surveys 1989–1994
Spatial scale of study, Number of sites	Surveys in the southern marshes channels	350 ha wetland	14
Variables measured	Geomorphology	• Ecological structure: population • Ecological function: breeding	• Ecological function: bird breeding • Ecological structure: plant distribution
Ecological effect	Monkeygar Ck upstream of Gibson Way has increased in cross-sectional area by 6–32%. Breakaway enlarged. Mole Marsh and Bora Return have erosional channels developing. Monkeygar reedbed inundation time reduced by 65% . NB primary data not presented	• Decrease in abundance, richness of uncommon spp over time (NT). • Decrease in abundance but not richness of common spp over time (NT) • Decrease in no. of spp breeding over time (NT)	• Percentage of red gum area alive in wetlands with no local control was 99%. Permanently inundated wetlands had mean 26% area of red gum alive. • Heavily controlled wetlands (HI = 0) have 96% fewer breeding records for precocial spp and 30% fewer records for other waterbirds than did wetlands with no local control • Emergent macrophytes cover 74% less proportional inundated area in permanently flooded wetlands than those under local control
Taxa studied	Geomorphology	Birds	• Birds • River red gum
Principle	1	3	3
Summary/Analysis	1, 2, 3, 3, 6	1, 2, 3, 5, 6	1, 2, 3, 5, 6

Paper	**Burns and Walker 2000**	**Cambray 1991**	**Castella *et al.* 1995**
Geographic location	Lower Murray R	Groot River, South Africa	UK
Habitat	Channel	Channel	Channel
River type	Inland	Dryland	Lowland / upland / coastal / inland
Experimental study	No	No	No
Flow modification type	Irrigation	Flood mitigation	Abstraction (ground and surface water)
Flow modification scale: hydraulic, pulse, history, regime	Hydraulic, tailwater levels fluctuate approx 20cm daily	Pulse	History
Flow modification degree	Water level lower pool and tailwater of weir at Lock 1	Eight 3–4 day releases from dam from Oct 1988 to Feb 1989	• 3 categories based on annual discharge reduction (minor, moderate, major) • Ratio between discharge at impact and reference site on day of sampling
Study design	Red gum blocks placed above and below weir	Descriptive	Treatment vs reference
Temporal scale of study	Sampled at 12, 28, 56, 90 days	Sampling during four releases	Surveys during 1989 and 1990
Spatial scale of study, Number of sites	Lock 1	2 sites within approx 40 km	62 sites: 31 pairs (treatment and reference) of sites from 22 rivers throughout UK
Variables measured	Ecological structure: community	Ecological structure: population, spawning	Community composition
Ecological effect	Effect of water level fluctuation obscured by time and depth interactions	Three of the four flows studied initiated spawning	• Community composition altered • Degree of difference between reference and treatment sites larger for moderate/major flow modifications than minor (NT)
Taxa studied	Biofilms	Small-scale redfin minnow (*Pseudobabus asper*)	Macroinvertebrates
Principle	1	2	Could not assign
Summary/Analysis	1, 4	1, 4	1, 4

Paper	**Chesterfield 1986**	**Church 1995**	**Crome 1988**
Geographic location	Barmah Forest, Victoria	Kemano R, Canada	• Lake Merrimajeel • Murrumbidgil Swamp NSW
Habitat	Floodplain	Channel	Floodplain
River type	Lowland / Coastal	Upland	Inland
Experimental study	No	No	No
Flow modification type	Irrigation	Augmented flows	Abstraction
Flow modification scale: hydraulic, pulse, history, regime	History	History, augmented flows began in 1965	Pulse
Flow modification degree	HI at Tocumwal is 0.71	Mean flows 140% greater than preregulation	HI at Booligal weir is 0.67
Study design	Survey 1979 compared with historical data	Aerial photographs in 1938, 1954, 1975 and 1983	Long-term monitoring
Temporal scale of study	50 yrs	1938–1983	Annual surveys 1976–1980
Spatial scale of study, Number of sites	28,900 ha	4 km upstream control reach, 16 km impact reach	2 wetlands comprising 230 ha
Variables measured	Area and location of different plant communities	Geomorphology	Ecological structure: population
Ecological effect	Invasion of grassland, reedbeds by giant rush (*Juncus ingens*), trees (*E. camaldulensis*). Increase in swampy areas dominated by water milfoil (*Myriophyllum propinquum*) and clovestrip (*Ludwigia peploides*), in which forest plants have died.	• Thalweg deflection reduced by 29% in impact reach, 12% control reach (1954–1977) • Channel width increased by 30% (1954– mid 1970s), 15% (1954–1983)	The mean number of stick nests, duck and crake family nests and breeding species were 77%, 84% and 55% lower respectively in 3 years without prior wetland drying compared to one year with prior wetland drying
Taxa studied	Plants	Geomorphology	Birds
Principle	3	1	3
Summary/Analysis	1, 2, 5	1, 2, 3, 5, 6	1, 2, 3

Paper	Décamps *et al*. 1995**	Erskine *et al*. 1999**	Extence 1981
Geographic location	Adour R, France	Snowy R, Victoria	River Roding, UK
Habitat	Riparian	• Channel • Riparian	Channel
River type	Coastal / Lowland	Coastal / Upland / Lowland	Inland / Lowland
Experimental study	No	No	No
Flow modification type	Drought	Water diversion	Drought
Flow modification scale: hydraulic, pulse, history, regime	Pulse	History	Pulse 1975–1976
Flow modification degree	The relative abundance of water for dry year was 0.55 ± 0.4. Preceding year was 1.01 ± 0.4.	HI at Windamere is N/A, Jindabyne is N/A, Dalgety is 0.57, Basin Ck is 0.55 and Jarrahmond is 0.58	Severe, river reduced to pools
Study design	Before versus after: interannual comparisons	Survey in 1990, comparison with historical records	Before vs after
Temporal scale of study	Annual sampling over 3 yrs	30 yrs	Monthly sampling for two years
Spatial scale of study, Number of sites	5 along 2 km stretch of river	352 km river length, below Jindabyne Dam	4 sites, spatial extent not documented
Variables measured	Ecological structure: population, community	Geomorphology	Ecological structure: population, community
Ecological effect	Riparian plant invasions into the channel were higher in dry year than average year, exotics invade faster than natives. Exotic abundance increased by 6%, native by 28% (NT) in dry year. Richness of exotic and native plants increased by 50% and 8% respectively (NT) in dry year. Proportion of exotic plants increased by 32% (individuals) and 50% (species) in a dry year (NT).	Channel contraction (5–95%), lichen growth 1.6–2.15m below pre-dam closure level, vegetation encroachment: river bed colonised by willows in 1971, changed bedforms incl. loss of pool–riffle sequence Channel contracted by 7% and 9% at cross-sections surveyed in 1949 and 1990 (data from Figure 6)	Water temp, organic enrichment, algal growth increase lead to increase in production of macroinvertebrates (*), change in community composition (NT)
Taxa studied	Plants	• Geomorphology • Willow	Macroinvertebrates
Principle	1, 4	1	1
Summary/Analysis	1, 2, 3, 5, 6	1, 2, 3, 5, 6	1, 4

Paper	**Froend and Van Der Moezel 1994**	**Gawne *et al*. 2000**	**Gehrke *et al*. 1995**
Geographic location	Coomalbidgup Swamp, WA	Albury, Barmah, Hattah: Murray R Australia	Darling River, Murrumbidgee River, Murray River, Paroo River
Habitat	Floodplain	Channel	Channel / Floodplain
River type	Lowland	Lowland / Inland	Inland / Dryland
Experimental study	No	No	No
Flow modification type	Prolonged flooding	Irrigation	• Abstraction • Irrigation • Irrigation • None
Flow modification scale: hydraulic, pulse, history, regime	Pulse	History	History
Flow modification degree	6 year inundation of ephemeral wetland	HI at Barmah is 0.66, Euston is 0.59 and Albury is 0.65	• APFD R = 0.74 • R = 1.47 • R = 1.98 • R = 0
Study design	Descriptive	Measurement of carbon metabolism	Correlation: 4 rivers with different flow modification
Temporal scale of study	Sampling in 4th and 6th years of inundation	10 measurements from 1998–1999	Sampled twice over 1 year 1992–1993
Spatial scale of study, Number of sites	4 littoral sites, 1 transverse transect of 75 ha wetland	3 sites along 1800 km of river	4 sites for each river (= 16 sites)
Variables measured	Ecological process: plant death, recruitment	Ecological function	Ecological structure: diversity, community
Ecological effect	• 45% trees dead or moribund • 50% reduction in width of dryland vegetation fringe • Invasion of bare drying ground by weeds	• Disappearance of submerged macrophyte beds. Transition from benthic and floodplain production dominance to phytoplankton production dominance • Decreased retention of organic matter	• Diversity negatively correlated with APFD (*) H'= 1.08 Darling (22% less than Paroo) • H'= 0.76 Murrumbidgee (45% less than Paroo) • H'=0.63 Murray (55% less than Paroo) • H'=1.39 Paroo R (native to alien ratio correlation with APFD, NS)
Taxa studied	Plants	• Primary productivity • Phytoplankton • Biofilms	Fish
Principle	3, 4	1	Could not assign
Summary/Analysis	1, 2, 3, 4	1, 4	1, 2, 3, 5, 6

Paper	**Gehrke *et al*. 1999**	**Gehrke 1997**	**Golladay and Hax 1995**
Geographic location	Hawkesbury-Nepean	NSW	Sister Grove Ck, Texas, USA
Habitat	Channel	Channel	Channel
River type	Upland / Lowland / Inland	Lowland / Coastal or inland	Upland
Experimental study	No	No	Yes
Flow modification type	Public supply NB: some dams have hypolimnetic releases resulting in thermal pollution	Various	Water diversion resulting in artificial flood
Flow modification scale: hydraulic, pulse, history, regime	History	History	Pulse
Flow modification degree	Moderate–severe	"substantial"	Near-bankfull discharge for 2 weeks
Study design	Treatment vs reference	Treatment vs reference (separate rivers)	BACI
Temporal scale of study	3 samples in 6 months (1994–1995)	Summer and winter sampling over two years	2 samples before, 2 after 2 week discharge
Spatial scale of study, Number of sites	38 sites within 1 basin	1 reach from each of 40 rivers	2 treatment, one control site within 10 km stretch of river
Variables measured	Ecological structure: community	Ecological structure: population, community	Ecological structure: community
Ecological effect	Altered community composition	• Community composition differed between regulated and unregulated rivers(*) and between regions(*) • Within 3 of 4 regions regulation accounted for more variation than inter-river variation • The proportion of native : exotic fish caught was different for regulated and unregulated rivers (*), but there was no difference for Shannon diversity, species richness or total abundance (NS) • 10 out of 27 abundant spp showed differences in abundance between regulated and unregulated rivers (as either a main effect or an interaction including river type) • Population size structures differed between regulated and unregulated rivers for 17 of 23 spp tested (*). Five spp showed positive effects of regulation, 13 (native) spp showed negative responses to regulation, 5 spp (including 2 alien) showed a combination of positive and negative responses, 5 spp (including 1 native) showed positive responses, 6 spp showed no effect. There was insufficient data for a further 22 spp	Community composition altered. Densities reduced by 98–99% (sediment fauna), 83–90% (wood fauna)
Taxa studied	Fish	Fish	Meiofauna
Principle	Could not assign	2, 4	Could not assign
Summary/Analysis	1, 4	1, 4	1, 2, 3, 4

Paper	**Growns and Growns 2001**	**Harris 1988****	**Hax and Golladay 1998**
Geographic location	Hawkesbury-Nepean River,	Hawkesbury R, Colo R	Sister Grove Ck, Texas, USA
Habitat	Channel	Channel / Floodplain	Channel
River type	Lowland	Lowland / Coastal	Inland / Upland
Experimental study	No	No	Yes
Flow modification type	No flow, public supply (= Decreased flow)	Multiple regulation	Water diversion producing unseasonal artificial flood
Flow modification scale: hydraulic, pulse, history, regime	History	Pulse: annual flow pattern related to annual fish recruitment	Pulse
Flow modification degree	HI for 212210–213200 not available	HI for Upper Colo, North Richmond N/A	Mean discharge 408 times greater than baseline, for mean 11 days
Study design	Treatment vs reference	Correlation	BACI
Temporal scale of study	5 sampling occasions from 1995–1997	Cohort estimates for 12-year period 1969–1980 calculated from 3 yrs sampling	5 samples for each of 3 floods 1990–1992
Spatial scale of study, Number of sites	23 sites on 7 rivers within 1 basin	17 sites within Sydney basin	1 treatment, 1 control site within 10 km
Variables measured	Ecological structure: community	Ecological function: breeding success	Ecological structure: density
Ecological effect	Macroinvertebrate and diatom community composition altered. 40% and 23% reduction in taxon richness at regulated sites for riffle fauna and pool/rock fauna respectively	• Correlation between winter discharge and initial cohort abundance • Recruitment threshold: no spawning in 1979 or 1980 • Mean relative initial year–class abundance 27% less than that of the wettest year	Mean reduction in density 76% (sediment), 53% (woody debris). Recovery occurred within 2 mo for 3 of 6 cases
Taxa studied	Macroinvertebrates Diatoms (biofilm)	Australian bass (*Macquaria novemaculeata*)	Macroinvertebrates
Principle	Could not assign	2	Could not assign
Summary/Analysis	1, 2, 3, 5, 6	1, 2, 3, 4	1, 2, 3, 4

Paper	Humphries *et al*. 1996	Humphries and Lake 2000	Kidson *et al*. 2000a
Geographic location	Macquarie R, Mersey R: Tasmania	Campaspe R	
Broken R	Macquarie Marshes, Macquarie River		
Habitat	Channel (littoral)	Channel	Floodplain
River type	Mersey: coastal		
Macquarie: inland	Inland	Inland	
Experimental study	No	No	No
Flow modification type	Macquarie: irrigation		
Mersey: abstraction	Abstraction/diversion	Abstraction	
Flow modification scale: hydraulic, pulse, history, regime	History	History	History: Burrendong dam closed 1967, Marebone weir closed 1977
Flow modification degree	HI at Kimberley is 0.44, Morningside is unavailable	Campaspe 50% MAF diverted	
Broken 10% MAF diverted			
HI at Campaspe weir is 0.55, Casey weir is 0.54	HI at Oxley gauging station is 0.63		
Study design	Descriptive	Treatment vs reference	Comparison of 1949 with 1991 aerial photographs
Temporal scale of study	Dec 1991, Feb 1992, Apr 1992 sampling	Adult Bimonthly sampling Oct 1995 – Feb 1998 (Campaspe only) Larval sampling monthly Aug–April, June	1949–1991
Spatial scale of study, Number of sites	2 reaches in each of two rivers	10 sites from Campaspe R (adults) 8 sites, 6 sites larval sampling from Campaspe, Broken R respectively	1:5000 resolution maps covering 200,000 ha
Variables measured	Ecological structure: community	Ecological structure: community	Ecological structure: community
Ecological effect	• Wetted area for riffles decreased sharply below values of between 1 m^3s^{-1} and $4m^3s^{-1}$. Wetted area for coarse woody debris declined slowly at the two Mersey R sites and sharply at $0.5m^3s^{-1}$ and $2m^3s^{-1}$ at the Macquarie R sites. • Richness differed significantly by reach, mesohabitat (pool run riffle) month (*) for sites at both rivers (some interaction terms significant also)	• Campaspe R: larvae of 3 of the 8 native spp present as adults found Broken R: larvae of 9 of the 10 native spp found as adults (historical records 15 spp for each river) • Native : alien larvae Campaspe 9.1, Broken 12.5	• Area occupied by dryland species has increased. • *E. populnea* increased by 20% • *A. pendula* by 46% • *Casuarina cristata* by 73% • *Geijera parviflora* by 32% • *Callitris glaucophylla* by 141% • Area occupied by flood-dependent species has contracted. *E. camaldulensis* area contracted by 7%. *E. largiflorens* box contracted by 38%. *E. coolabah* by 16%. Note that reduction of area occupied by flood dependent species is partially due to land clearing • Area occupied by *Acacia stenophylla* increased by 76%. This species is an opportunistic coloniser in cleared areas
Taxa studied	Macroinvertebrates	Fish	9 tree species
Principle	1	2, 4	3
Summary/Analysis	1, 2	1, 2, 3, 5, 6	1, 2, 3, 5, 6

Paper	Kidson *et al*. 2000b**	Kingsford and Thomas 1995	Kingsford and Johnson 1998**
Geographic location	Macquarie Marshes, Macquarie River	Macquarie Marshes	Macquarie Marshes
Habitat	Floodplain	Floodplain	Floodplain
River type	Inland	Lowland / Inland / Dryland	Lowland
Experimental study	No	No	No
Flow modification type	Abstraction	Abstraction	Abstraction
Flow modification scale: hydraulic, pulse, history, regime	Pulse: annual flow correlated with tree growth	History	• History • Study at pulse scale: comparison of years with different flow patterns
Flow modification degree	HI at Oxley gauging station is 0.63	HI at Oxley station is 0.63. 51% of water in Macquarie R 100 km upstream reached Oxley 1944–1953, 1984–1993 only 31%	HI at Oxley gauging station is 0.63
Study design	Monitoring of individual tree condition	Long-term correlation, Treatment vs control	Correlation
Temporal scale of study	Sampling four times per year 1995–1999	11 years annual surveys 1984–1993. Hydrological data at Oxley for 50 yrs	Annual surveys in 1978,1986–1996. Weekly surveys of breeding sites
Spatial scale of study, Number of sites	334 trees at 27 sites over 200,000 ha	Aerial survey over 4 wetlands, 1 treatment, 3 controls	Aerial survey over 130,000 ha
Variables measured	Ecological function: tree growth, mortality	Abundance; richness	Ecological structure: population, breeding
Ecological effect	Average growth (%/yr) correlated with annual discharge (NT) mortality negatively correlated with annual discharge (NT). Mean tree growth was 56% less in lower discharge years. Mean mortality was 417% greater in lower discharge years.	• Decrease in treatment richness (*) and abundance (NS) • Increase in water diversion at treatment site (*) • No significant trends at control sites • Abundance correlated with area flooded.(*) • Area flooded related to annual flow at Oxley.(*) • Annual flow at Oxley decreased over 50 yrs • Wetland approx 40–50% smaller than prior to water diversion (i.e. area inundated by major flood)	• Nest no. related to annual flow for all 6 spp. • No breeding for annual flow <200,000 ML. Mean nest number was 85%, 82%, 28%, 85%, 86% and 94% less in drier years than the wettest year for intermediate egrets, rufous night herons, glossy ibis, strawnecked ibis, Australian white ibis and royal spoonbills respectively
Taxa studied	River red gum (*Eucalyptus camaldulensis*)	Birds	Colonial waterbirds: 6 spp (Ciconiidae)
Principle	3	3	2, 3
Summary/Analysis	1, 2, 3, 4	1, 2, 3, 5	1, 2, 3, 4

Paper	Kleynhans 1996	Ladle and Bass 1981	Leslie 1995
Geographic location	Luvuvhu R, S. Africa	Waterston Stream, UK	Moira Marshes, Murray R
Habitat	Channel	Channel	Floodplain
River type	Lowland	Inland	Lowland / Inland
Experimental study	No	No	No
Flow modification type	Abstraction	Drought	Irrigation
Flow modification scale: hydraulic, pulse, history, regime	History, abstraction has increased since 1960	Pulse	History. Hume Dam closed 1936
Flow modification degree	Severe	4 month flow cessation	HI at Tocumwal is 0.71
Study design	Descriptive	Before vs after	Compilation of historical records
Temporal scale of study	Survey in 1991	Monthly sampling for 18 months	N/A
Spatial scale of study, Number of sites	170 km surveyed	50 m study reach	Moira Marshes cover 25,000 ha
Variables measured	Qualitative categories: none, small, moderate, large, serious, critical	Ecological structure: community, population	Ecological structure and function
Ecological effect	Abstraction results in flow cessation during summer. Impact considered serious for all reaches studied	Change in plant and invertebrate community composition	Considerable decline in birds, fish, snakes, leeches and plants. Several species that were abundant and bred in marshes no longer do so. Despite large fishing, feather and leech exploitation, the majority of the declines have only occurred in last 20–30 yrs. Leeches and tiger and brown snakes were extremely abundant until mid 1970s, now extremely rare. Invasion of giant rush along shores of Moira Lake following construction of the Moira Irrigation Channel (1964). Decline of beds of water primrose (*Ludwigia peploides*), river buttercup (*Ranunculus inundatus*) and wavy marshwort (*Nymphoides crenata*) since 1940s due to lack of summer drying. 100 ha red gum forest died from inundation due to development and enlargement of 'the Breakaway', 2000 ha red gum died due to summer inundation at Millewa. Glossy ibis, little egret, great egret and whiskered tern no longer breed in Moira Marshes. Breeding status insecure for intermediate egret, nankeen night heron, great cormorant. Ratio of native:alien fish 1:24. Eight native species found in Moira Lake recently, only gudgeons and smelt have breeding status verified in early 1990s.
Taxa studied	Habitat integrity	Macroinvertebrates Plants	Birds, fish, plants, leeches, snakes
Principle	1	Could not assign	3, 4
Summary/Analysis	1, 2	1, 2	1, 2, 5

Paper	Ligon *et al*. 1995	Marchant 1989	Marchetti and Moyle 2001
Geographic location	McKenzie R, Oregon	Thomson R	Lower Putah Ck, California, USA
Habitat	Channel	Channel	Channel
River type	Coastal	Lowland	Lowland coastal
Experimental study	No	No	No
Flow modification type	Flood mitigation	Irrigation release	Water diversion
Flow modification scale: hydraulic, pulse, history, regime	History	History, dam closure in 1983	• History, over 40 yrs • Study at pulse scale: comparison of years with different flow patterns
Flow modification degree	Reduction of peak flows by 55%, no longer overtop bank	HI The Narrows is 0.63	Moderate, flow cessation occurs during dry years.
Study design	Descriptive	• 1 upstream control vs 3 treatment sites • Before and after data	Comparison of dry years (AF <50% 40 yrs MAF) with wet years (AF >200% MAF)
Temporal scale of study	1945–1989	Sampling during dam construction 1979–1981, post construction 1984–1987	5 yrs 1994–1998 1994–1995 dry years 1997–1998 wet years
Spatial scale of study, Number of sites	Entire river	4 sites over approx 40 km. 2 sites excluded from review due to thermal pollution	8 sites over 37 km stretch
Variables measured	Geomorphology Ecological structure: population	• Ecological structure: community; richness, density	Ecological structure: community
Ecological effect	• Reduction in salmon spawning habitat due to channel stabilisation, arrested development of islands and sidebars. • Mean salmon population size decreased by 50%	• Richness decreased by 43% (from 60 to 46) at treatment site and 1% at control site (from 82 to 81) • No density change for control or treatment site	Community composition changed. Non-native fish showed negative correlation with flow at 4 sites (*) native fish showed positive correlation with flow at 1 site (*)
Taxa studied	• Geomorphology • Salmon	Macroinvertebrates	Fish
Principle	1	Could not assign	2, 4
Summary/Analysis	1, 2, 3, 5, 6	1, 2, 3, 5, 6	1, 2

Paper	**Merron *et al*. 1993**	**Neckles *et al*. 1990**	**Nielsen and Chick 1997**
Geographic location	Phongolo R, South Africa	Manitoba, Canada	Murray R
Habitat	Floodplain	Floodplain	Floodplain
River type	Coastal / Lowland	Inland / Lowland	Lowland / Inland
Experimental study	No	Yes	Yes
Flow modification type	Flood mitigation dam closed 1970 Severe drought 1982–1984	Extended flood duration	Various
Flow modification scale: hydraulic, pulse, history, regime	• History (regulation) • Pulse (2-year drought)	Pulse	Pulse
Flow modification degree	• Most severe drought on record. <5% floodplain area remained inundated. • Dam prevented floods 1982, 1983 and 1984	Duration of inundation extended by 3 months	N/A
Study design	Sampling before during and after drought	Treatment vs control	Experimental mesocosms
Temporal scale of study	• 1974–1976 all major lakes held permanent water • Sept 1983 drought peak • Aug 1984 all lakes full after cyclone in Feb	Weekly sampling during inundation for 2 yrs	6 surveys over 14 months
Spatial scale of study, Number of sites	14 lake sites, 1 river site over 10,265 ha	6 sampling stations within 1 control and 1 treatment impoundment (4.3 and 5.8 ha)	16 mesocosms (diam 4.5 m), 4 per treatment: permanent inundation, spring flooding, summer flooding, unflooded
Variables measured	Ecological structure: community	Ecological structure: community	Ecological structure: community, richness
Ecological effect	• Community composition differed between all three surveys. Species tolerant of a wide range of environmental conditions and/or non-flood dependent spawning species increased relative abundance during the drought. Post drought (and cyclone) sampling found several species had larger ranges. • Of 35 species sampled before drought 34 were sampled after drought	• Invertebrate abundance reduced in 2nd year of flood alteration (*) • Abundance of treatment 70% less than control abundance. • Cladoceran, ostracods, culicids,hydrachnids, turbellarians had reduced densities (*), gastropods increased density (*). • Dityscids and corixids unaffected (NS)	• Richness of permanent inundation treatment 77% of control (*) and summer treatment 85% of control (*) • Diversity lower for permanent treatment than control and spring treatment (*) • All treatments had different community composition
Taxa studied	Fish	Macroinvertebrates	Macrophytes
Principle	2	3	Could not assign
Summary/Analysis	1, 2	1, 2, 3, 4	1, 2, 3, 4

Paper	**Nielsen *et al*. 1999**	**Nielsen *et al*. 2000**	**Ogden 1991**
Geographic location	Murray R	Murray R	Florida, USA
Habitat	Floodplain	Floodplain	Floodplain
River type	Lowland / Inland	Lowland / Inland	Lowland / Coastal
Experimental study	Yes	Yes	No
Flow modification type	Various	Various	Local regulation of wetlands
Flow modification scale: hydraulic, pulse, history, regime	Pulse	Pulse	History
Flow modification degree	N/A	N/A	N/A
Study design	Experimental mesocosms	Experimental mesocosms	Annual survey of natural and altered wetlands
Temporal scale of study	2 yrs	2 yrs	1959–1960,1976–1986
Spatial scale of study, Number of sites	16 mesocosms (diam 4.5 m), 4 per treatment: permanent inundation, spring flooding, summer flooding, unflooded	16 mesocosms (diam 4.5 m), 4 per treatment: permanent inundation, spring flooding, summer flooding, unflooded	45 breeding colonies throughout central and northern Florida
Variables measured	Ecological structure: community	Ecological structure: community	Ecological structure: population
Ecological effect	Seasonal effects overrode treatment effects. No consistent effects between treatments	• No effect for rotifer richness (NS) • Increase in microcrustacean eggbank for permanent treatment (*) • Composition varied between permanent and other treatments (*)	• Altered wetlands contained more nests than natural (*), perhaps due to less variable flooding. • Increase nest no. in altered sites (not tested) over study
Taxa studied	• Macroinvertebrates • Macrophytes	Microinvertebrate egg bank	Wood stork (*Mycteria americana*)
Principle	Could not assign	Could not assign	Could not assign
Summary/Analysis	1, 2, 3, 4	1, 4	1, 4

Paper	**O'Keefe and Uys 1998**	**O'Keefe and Uys 1998**	**Penaz et al. 1992**
Geographic location	Great Fish River, South Africa	Sabie, Mutale, Luvuvhu and Letaba Rivers, South Africa	Rhone R, France
Habitat	Channel	Channel	Channel
River type	Coastal	Inland / Coastal	Lowland
Experimental study	No	No	No
Flow modification type	Flow augmentation from 1977	Luvuvhu and Letaba Rivers: abstraction	Water diversion
Flow modification scale: hydraulic, pulse, history, regime	History	History	Pulse: construction completed 1988
Flow modification degree	River was intermittent before flow augmentation, base flow now 3–5 m^3s^{-1}	• Luvuvhu: was perennial, now intermittent • Letaba: 50% reduction in flow volume in wet months, 90% reduction in dry months.Was perennial, now intermittent	Unknown
Study design	Comparison of separate studies conducted before and after flow modification	Comparison of separate studies conducted on different rivers	Descriptive
Temporal scale of study	Sites sampled 10 times (1960s, 1970s) prior to flow modification, 4 times post modification 1984–1985	• Sabie: 9 sampling times • Mutale: 7 sampling times • Luvuvhu: 7 sampling times • Letaba: 5 sampling times	24 h sampling at each site
Spatial scale of study, Number of sites	6 sites, unknown geographic scale	• Sabie: 2 sites, unknown geographic scale • Mutale: 2 sites, unknown geographic scale • Luvuvhu: 3 sites, unknown geographic scale • Letaba: 2 sites, unknown geographic scale	2 sites with water diversion within 6 km
Variables measured	Ecological function: taxonomic richness	Ecological function: taxonomic richness	Ecological structure: population drift
Ecological effect	Taxonomic richness of stone dwelling macroinvertebrates unchanged over study period	• Sabie: 134 taxa collected • Mutale: 104 taxa collected • Luvuvhu: 150 taxa collected • Letaba: 60 taxa collected • The Letaba River has the most modified flow regime and least taxa, however methods differed between rivers, so results are not directly comparable	• 12 spp found • Drift dominated by chub (*Leuciscus cephalus*) and barbel (*Barbus barbus*)
Taxa studied	Stone dwelling macroinvertebrates	Macroinvertebrates	12 spp fish: larvae and juvenile
Principle	Could not assign	Could not assign	Could not assign
Summary/Analysis	1, 2, 5	1, 4	1, 4

Paper	Penaz *et al*. 1995	Petts and Greenwood 1985	Pressey 1990
Geographic location	Rhone R, France	River Rheidol, Wales	Murray-Darling Basin
Habitat	Channel	Channel	Floodplain
River type	Lowland	Lowland	Lowland / Inland
Experimental study	No	No	No
Flow modification type	Water diversion due to hydropower plant	Flood mitigation	Irrigation
Flow modification scale: hydraulic, pulse, history, regime	Pulse: construction completed 1988	History	History
Flow modification degree	Unknown	Constant release of 0.16 m^3s^{-1}	N/A
Study design	Descriptive	Survey of reach below tributary confluence	Aerial photograph analysis
Temporal scale of study	Snapshot survey 1991	1 week survey during 1982	Survey in 1983
Spatial scale of study, Number of sites	5 sites with water diversion over 10 km	200 m reach mapped, 64 invertebrate samples from impacted reach, 10 reference samples	Floodplain of 2225 km length of River Murray
Variables measured	Ecological structure: population, community	• Geomorphology • Ecological structure: community	Hydrological classification of wetlands
Ecological effect	14 spp found H = 1.8. Fish communities dominated by chub (*Leuciscus cephalus*) and barbel (*Barbus barbus*)	• Main channel width reduced by approx 66%, channel capacity reduced by 70% • Sedimentation produced more sinuous channel form • Community composition altered	35% of total wetland area in basin now permanently flooded
Taxa studied	Young-of-year fish	Geomorphology Macroinvertebrates	Wetland area
Principle	Could not assign	1	Could not assign
Summary/Analysis	1, 2	1, 2, 3, 5	1, 2, 3, 5, 6

Paper	Robertson *et al*. 2001**	Roy and Messier 1989	Scott and Grant 1997
Geographic location	Murray R	Eastmain R, Caniapiscau R, Canada	Murray-Darling Basin
Habitat	Floodplain	Channel	Channel
River type	Lowland / Inland	Upland	Lowland / Inland
Experimental study	Yes	No	No
Flow modification type	Flood timing and frequency	Water diversion	Irrigation
Flow modification scale: hydraulic, pulse, history, regime	History	History: diversion began 1980,1981	History
Flow modification degree	N/A	Eastmain 86% MAF diverted Caniapiscau 44% MAF diverted	N/A
Study design	• BACI • Spring, summer, no flood or spring + summer floods annually	Before vs after	Review of literature and historical data, anecdotal reports
Temporal scale of study	6 years	Monitored 1977–1988	Historical data 1900s
Spatial scale of study, Number of sites	3 wetlands (0.5–2 ha) for each treatment	27 sites on 6 rivers	Murray-Darling basin
Variables measured	• Ecological structure: community, population • Ecological function: 1st prod	Ecological structure and function	N/A
Ecological effect	• Wood production greater for summer floods (64%*), spring and summer floods (57%*) than no floods; spring floods equivalent (15% greater) to no floods (NS). • Macrophyte richness 53% higher for spring floods than summer (*). • Community composition different between flood timing (*) but not frequency (NS) in shallow water areas. • Macrophyte production and biofilm accumulation were 83% and 51% respectively higher in spring flood treatments than summer flood (*).	• Drop in water level 1.0–4.0 m (Eastmain R)1.0–3.0 (Caniapiscau R). • "Substantial" reduction in area, depth, volume of aquatic habitat. • 54% increase in phytoplankton production 2400% increase secondary production in Eastmain R but not in Caniapiscau R. • Invertebrate density showed no response. Initial increase in fish yields due to concentration effect. • Change in community composition	• Regulation does not appear to have caused a decline in platypus or water rat distribution, effect on abundance is unknown. • Abundance of invertebrate prey major determinant of platypus abundance. Irrigation bankfull flows flood burrows and may decrease breeding success
Taxa studied	• Biofilms • Macrophytes • Red gum (*E. camaldulensis*)	• Primary production • Secondary production • Macroinvertebrates • Fish	• Platypus (*Ornithorhynchus anatinus*) • Water rat (*Hydromys chrysogaster*)
Principle	2	1	Could not assign
Summary/Analysis	1, 2, 5	1, 2, 3, 5, 6	1, 2

Paper	Serrano and Serrano 1996	Shaikh *et al*. 1998	Sheldon and Walker 1993
Geographic location	Doñana National Park, Spain	Great Cumbung Swamp, Lachlan River	Murray R
Habitat	Floodplain	Floodplain	Channel
River type	Coastal lowland	Dryland	Lowland / Inland
Experimental study	No	No	No
Flow modification type	Groundwater abstraction	Abstraction	Irrigation
Flow modification scale: hydraulic, pulse, history, regime	History	Pulse: area of reed responded at pulse scale to river flow volumes	History
Flow modification degree	Abstraction reduced mean annual water table depth by 1.3 m over 5 yrs	HI at Booligal weir is 0.67	N/A
Study design	Correlation	Landsat MSS images	Historical records, Aboriginal middens, literature review
Temporal scale of study	1989–1994	Images for 14 days over 1985–1994	Records date before 1950
Spatial scale of study, Number of sites	6 sites within 5 km of pumping station	50 m resolution over 4000 ha	Murray-Darling Basin
Variables measured	Water table depth	Ecological structure: community	Ecological structure: population
Ecological effect	Invasion of terrestrial plant species into 3 temporary ponds closest to pumping station	• Inundated area correlated to flow volumes in Lachlan and Murrumbidgee Rivers (*). • Area of reed (*Phragmites australis*) and red gum (*Eucalyptus camaldulensis*) was correlated with flow volumes in the Lachlan and Murrumbidgee Rivers (*). • Mean flow volumes for flood events were 77% less than largest flow recorded during study. Mean inundation area time (haD) was 67% less than that of largest flow recorded during study.	Reduction in abundance and richness of snails NB: some species thought to be extinct locally
Taxa studied	• Water table depth • Plants	Vegetation	Snails
Principle	1	3	Could not assign
Summary/Analysis	1, 2	1, 2, 3, 4	1, 2, 5

Paper	**Sheldon and Walker 1997**	**Sherman *et al*. 1998**	**Sherrard and Erskine 1991**
Geographic location	Murray R, Cooper Ck	Maude Weir pool, Murrumbidgee R	Mangrove Ck, NSW
Habitat	Channel	Channel	Channel
River type	Lowland / Inland	Inland	Inland / Upland
Experimental study	No	No	No
Flow modification type	Irrigation	Irrigation	Public supply
Flow modification scale: hydraulic, pulse, history, regime	History	Pulse	History, dam closed in 1981
Flow modification degree	N/A	Gauge at Maude weir 1993–1995	Pc = –51%
Study design	Comparison of channel biofilms with those of irrigation pipelines	Correlation	Before vs after. 2 cross-section surveys in 1976 and 1989, aerial photographs
Temporal scale of study	1992	Summers of 1993–1994 and 1994–1995	Post-dam surveys in 1989
Spatial scale of study, Number of sites	"Several" sites within approx 30 km of two rivers, 1 pipeline sampled	30 sites over 30 km weir pool	16 km stretch of river
Variables measured	Ecological structure: community	Ecological structure: population	Geomorphology
Ecological effect	Pipeline biofilm had different composition, resulting in higher nutritional quality for snails	• Discharge threshold: <approx 1000 ML/day allowed persistent thermal stratification • *Anabaena* growth exponential (0.37/day) during thermal stratification.	• Channel cross-sections altered, channel width contracted by 50% immediately below dam, slight contraction at bottom of study reach • Benches and bars have formed throughout study reach and plants have colonised. Gravel armouring occurred <10% study reach
Taxa studied	Biofilm composition	Phytoplankton	Geomorphology
Principle	1	1	1
Summary/Analysis	1, 2, 5	1, 2	1, 2, 3, 5, 6

Paper	Thoms and Walker 1993	Thornton and Briggs 1994	Timms 1992
Geographic location	Murray R	Murrumbidgee R	Menindee Lakes
Habitat	Channel	Floodplain	Floodplain
River type	Lowland / Inland	Lowland / Inland	Lowland
Experimental study	No	No	No
Flow modification type	Irrigation and navigation	Irrigation	Increased or permanent inundation
Flow modification scale: hydraulic, pulse, history, regime	History	History	History
Flow modification degree	HI at Locks 3 and 4 is 0.52	• Various categories of local control of wetlands • For conversion to permanent HI = 0	Lake Cawndilla inundation period has increased by 185%, Lake Pamamaroo is now permanent
Study design	Long-term survey	Aerial photograph and ground survey	Treatment vs reference
Temporal scale of study	1906 and 1988 surveys	Survey conducted during 1974 flood	Single sampling visit 1988–1989
Spatial scale of study, Number of sites	99 cross-sections over 154 km stretch of river	174,700 ha	3 treatment, 4 reference wetlands
Variables measured	Geomorphology	Hydrological classification of wetlands	Ecological structure: community
Ecological effect	• Channel morphology altered. • Alterations differed between 2 weir pools: cross-sectional area increased at 47% (pool 2) and 70% (pool 3). Cross-sectional area in erosional zones increased by 8.4 % and 9.0%, decreased by 3.2 % and 11% in depositional zones. Mean bed aggradation was 0.2m and 0.58m. Channel width–depth ratio increased in 43% and 80% of sites. Water transmission efficiencies were reduced by 14%.	• 570 ha river red gum died from inundation (1% red gum area) • 36% of open water wetland area made permanent, 62% open water wetland under some local control	• Decreased zooplankton abundance. Zooplankton and macroinvertebrate richness decreased by 19% and 52% respectively (NT). • Macroinvertebrate composition altered
Taxa studied	Geomorphology	Wetland area	• Zooplankton • Littoral taxa • Macroinvertebrates
Principle	1	3	Could not assign
Summary/Analysis	1, 2, 3, 5, 6	1, 2, 3, 5, 6	1, 2, 3, 5, 6

Paper	**Walker 1990a**	**Walker 1990b**	**Walker *et al*. 1994**	**Zengel *et al*. 1995**
Geographic location	Murray R mouth	Murray R	Murray R	Cienega de Santa Clara, Mexico
Habitat	Channel	Channel / Floodplain	Channel / Riparian	Floodplain
River type	Lowland / Inland	Lowland / Inland	Lowland / Inland	Coastal
Experimental study	No	No	No	No
Flow modification type	Irrigation public supply	Irrigation	Irrigation and navigation	Water diversion
Flow modification scale: hydraulic, pulse, history, regime	History	History	History	Pulse: flow diverted for 8 months
Flow modification degree	HI at Goolwa barrages gauge is N/A	N/A	HI at Locks 3 and 4 is 0.52	Flow reduced from 5.5 m^3s^{-1} to 0.0–0.5 m^3s^{-1} (91% reduction)
Study design	Time series analysis on flow data and mouth restriction	Historical distribution from Aboriginal middens	Correlation with water level variation	Before versus after aerial photography
Temporal scale of study	48 data points from 1980–1984	Unknown	• Single survey in 1988. • Water level data obtained for 1982–1988	4 aerial surveys 1992–1993
Spatial scale of study, Number of sites	1, Murray mouth size	Unknown	99 sites over 154 km stretch of river	12,000 ha
Variables measured	Geomorphological	Distribution	Ecological structure: community	Ecological structure community
Ecological effect	Cross-correlation between flows at Goolwa barrages and mouth restrictions (2 month lag period)	Extended range of floodplain mussel, decreased range of river mussel	Composition and relative abundance of littoral plants were correlated with water level variation as a result of weir operations	70% reduction in cover of above ground vegetation after 2 months of water diversion
Taxa studied	Geomorphological	River mussel (*Alathyria jacksoni*), floodplain mussel (*Velesunio ambiguus*)	Littoral plants	Plants
Principle	1	2	Could not assign	3
Summary/Analysis	1, 2, 5	1, 2, 5	1, 2	1, 2, 3, 5, 6

Appendix 2

Gauging station sites included in Appendix 1 for which Hydrological Index values were generated.

River	Gauge name	Gauge number	Study
Murray	Lock1 lower	412 026	Baker *et al*. 2000
Murray	Tocumwal	409 202	Bren and Gibbs 1986, Bren 1992, Chesterfield 1986, Leslie 1995
Murray	Lock 3	426517	Thoms and Walker 1993, Walker *et al*. 1992
Murray	Lock 4	426 515	Thoms and Walker 1993, Walker *et al*. 1992
Murray	Barmah	409 215	Gawne *et al*. 2000
Murray	Euston	414 203	Gawne *et al*. 2000
Murray	Albury	409 001	Gawne *et al*. 2000
Murray/Lake Alexandrina	Goolwa barrages d/s	426 525B	Walker 1990a
Murrumbidgee	Maude Weir	410 040	Sherman *et al*. 1998
Macquarie (NSW)	Oxley station	421 022	Brereton 1994, Kidson *et al*. 2000a,b Bacon *et al*. 1994, Kingsford and Thomas 1995, Kingsford and Johnson 1998
Cudgegong	Windamere	421 079	Erskine *et al*. 1999
Snowy	Jindabyne	222 501	Erskine *et al*. 1999
Snowy	Dalgety	222 006	Erskine *et al*. 1999
Snowy	Basin Ck	222 219	Erskine *et al*. 1999
Snowy	Jarrahmond	222 20	Erskine *et al*. 1999
Campaspe	Campaspe Weir	406 203	Humphries and Lake 2000
Campaspe	Campaspe Weir head gauge	406 218	Humphries and Lake 2000
Thompson	The Narrows	225 210	Marchant 1989
Broken	Casey Weir	404 217	Humphries and Lake 2000
Colo	Upper Colo	212 290	Harris 1988
Hawkesbury	North Richmond	212 200	Harris 1988
Lachlan	Booligal Weir	412 005	Crome 1988 Shaikh *et al*. 1998
Mersey	Kimberley	316 001	Humphries *et al*. 1996
Macquarie (Tas)	Morningside	318 006	Humphries *et al*. 1996
Darling	Wilcannia total flow/main channel	425 002, 425 008	Bowling and Baker 1996
Barwon	Mungindi	416 001	Bowling and Baker 1996