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ENVIRONMENTAL EFFECTS OF FLOW REGULATION ON THE LOWER RIVER MURRAY, AUSTRALIA

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ABSTRACT

Before regulation flows in the lower Murray were highly variable, as for most rivers in semi-arid regions. Major floods promoted large-scale recruitment of flora and fauna in riverine and floodplain communities, and seasonal floods maintained lower levels of recruitment. The regime changed with the construction of 10 low-level weirs in 1922–35, supplemented by the effects of dams in upstream areas. Flows remain variable but are much reduced in volume (about 44%). Low flows (100–300 Gl per month) have decreased five-fold and moderate flows (500–1500 Gl per month) have increased two-fold. Although the magnitude of peak seasonal flows has been diminished, the timing of flows is unaffected. The effects differ in the Valley and Gorge sections of the river, depending on local development of the floodplain and associated wetlands. The weirs have flooded once-temporary wetlands and contributed to problems of salinization. Weir operations cause daily stage fluctuations that diminish downstream, and the channel is developing a stepped gradient as a consequence of active deposition and erosion. Regulation has limited exchanges between the river and its floodplain, changed the nature of the littoral zone and generally created an environment inimical to many native species, notably fish. The key to rehabilitation may be to restore a more natural balance of low and medium flows, but this may be unrealistic, given the needs of irrigators and other water users. Despite its evolutionary history of wide spatial and temporal variation, the Murray river–floodplain ecosystem evidently cannot accommodate these forms of disturbance.

KEY WORDS Floods Floodplains Weirs Water levels Channel changes Littoral zone Wetlands Fish Management Ecology Murray–Darling river system

INTRODUCTION

Flow is a governing influence in rivers. Depending on local geomorphology, it may affect all parts of the physical environment, from the particles of sediment in the channel to the form of the surrounding landscape. It is a key element of a river's physical 'habitat template' (e.g. Southwood, 1988), a prescription for the life-history attributes required of resident plants and animals and hence for the variety of ecological responses following disturbance (Poff and Ward, 1990).

The significance of flow is further accentuated in the rivers of semi-arid regions because their spatial and temporal flow variations are more extreme and less predictable than those of rivers in humid regions (e.g. Beckinsale, 1969; Poff and Ward, 1989). The physical effects of variability are exemplified in the complex cross-sectional shape of the channel, with benches representing adjustments to different modes of the water and sediment transport regimes (Graf, 1987). The biological consequences are evident in plants and animals that are opportunistic in their response to floods and eurytopic in their capacity to endure conditions between floods. High mobility is another adaptive trait that enables the animals to disperse towards secure areas, away from adversity. Floods maintain the rhythm of the ecosystem, as in the seasonal and perennial rivers of humid regions (Junk *et al.*, 1989), but the pulse is erratic.

The water resources of semi-arid regions throughout the world are heavily exploited, and virtually all large river systems are subject to control via dams and weirs (e.g. Davies and Walker, 1986). In these rivers the

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regulated regime might be compared with an electronic signal subject to amplitude modulation—the signal (consumer demand) is superimposed on a carrier wave (natural flows) whose frequency remains unchanged, but whose amplitude is varied with the amplitude of the input signal. The modulated flood pulse changes the habitat template, and the biological character of the ecosystem must change accordingly. These changes are augmented by other human impacts related to urban and agricultural development. It is arguable whether the effects of flow regulation are greatest for semi-arid rivers, reflecting the disparity between the natural and regulated regimes (Walker, 1992), or comparatively minor because the ecosystem has an exceptional capacity to absorb the effects of change (Poff and Ward, 1990).

In this paper the effects of flow regulation on the lower River Murray, part of the Murray-Darling river system in south-east Australia, are reviewed. The lower Murray formerly behaved as a typical semi-arid river, with highly variable flows, but the regime changed following construction of a series of low-level weirs in 1922-35, supplemented by the effects of dams further upstream. Although there are few historical data, the effects of regulation are apparent in continuing changes to the biophysical environment. The new regime has changed the balance of processes involved in the maintenance of the channel and floodplain environments (Thoms and Walker, 1989; 1992a, 1992b; in press), and its ecological effects have been to limit exchanges between the river and its floodplain, to change the nature of the littoral zone and generally to create an environment inimical to many native species (Walker, 1992; Walker *et al.*, 1992).

PERSPECTIVES

The Murray-Darling river system drains the inland slopes of the Great Dividing Range in south-east Australia. The catchment area is $1{\cdot}073 \times 10^6$ km^2, but most is arid or semi-arid land and only a small part contributes significant run-off. The Murray itself rises in south-east New South Wales (NSW) and the Darling in north-east NSW and south-east Queensland, and the two rivers join at Wentworth (NSW), 827 river km from the sea in South Australia (Figure 1). Their combined length is a remarkable 5500 km, but

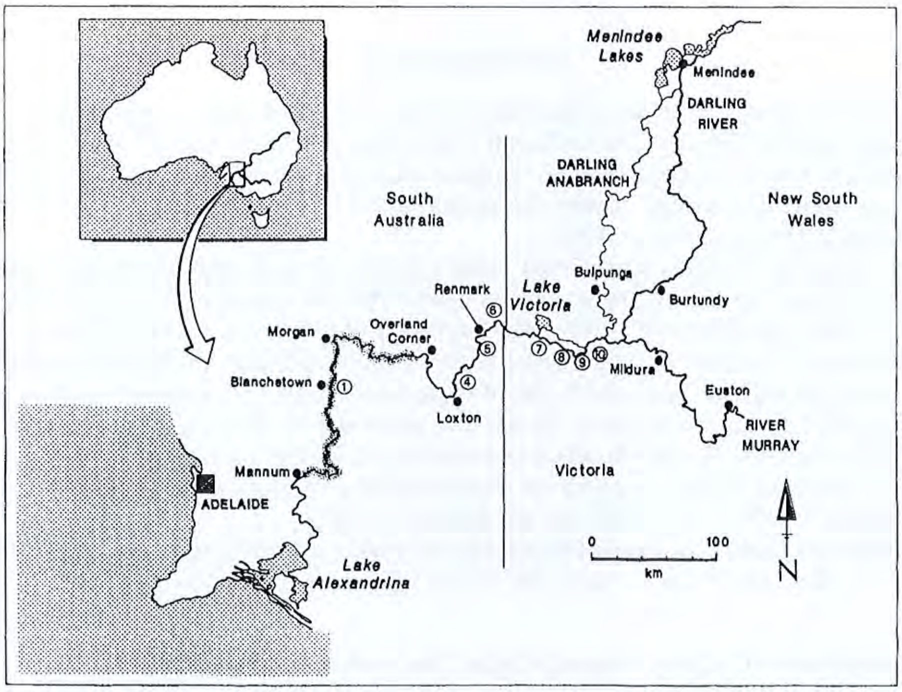

Figure 1. Sketch map of the lower River Murray. The Valley Section extends from the Murray-Darling confluence to about Overland Corner, and the Gorge Section (stippled) extends from there to about Mannum. Numerals refer to Locks 1-10

their combined average annual discharge is an equally unremarkable 10 035 gigalitres (Gl). Most of the discharge originates near the source of the Murray, and the Darling contributes roughly 10%. Further information is provided by Walker (1992) and Mackay and Eastburn (1990).

Fluvial history

The Murray and Darling rivers are trunk remnants of a more extensive system that originated in the Tertiary. The basin began as a region of subsidence, accentuated by the gradual uplift of the Great Dividing Range along the eastern and southern margins. The sea invaded the region six million years ago, and retreated two to four million years ago as the climate became steadily drier. The present Murray-Darling junction was inundated by a vast freshwater lake, Lake Bungunnia, that persisted for about two million years, leaving extensive clay deposits (Gill, 1973). With the disappearance of the lake 500–700 thousand years ago there began a series of major oscillations between wet and dry conditions, reflected in the structure of dunefields and lunettes that are typical of the present landscape (Bowler, 1990). The climatic instability was accompanied by changes in the salinities of surficial soil and water; these have again increased following extensive vegetation clearance in the past 200 years (Macumber, 1990).

Environmental units

The Murray–Darling confluence is within the Mallee Plains tract of the Murray, extending from Swan Hill (Victoria) to Overland Corner (South Australia) (976 river km), and named for an association of eucalypts that was the dominant vegetation before agricultural development. The regional climate is semi-arid, with annual rainfall 200–500 mm and evaporation 1500–2400 mm. Irrigated agriculture and grazing are the main forms of land use, and the largest townships (Figure 1) have populations < 50 000. The surface soils are calcareous, being the products of weathered marine sediments. The prevailing south-westerly wind has been the main agent of contemporary landforms, rather than fluvial or tectonic influences. Other environmental data are provided by Gill (1973).

In this paper the term 'lower Murray' is applied to the river below the Darling confluence (Figure 1). Although this region includes only part of the Mallee Plains tract, it is distinctive from the viewpoint of management:

(a) The aquatic environment is strongly influenced by flows from the Darling, and hydrologically distinctive because the Murray receives no significant tributaries below the Darling. Further, the Darling's influence is disproportionately increased by regulation. Since 1968, when the Menindee Lakes storage was completed, Darling water has been diverted to Lake Victoria pending release to the Murray for irrigation in summer and autumn. Average daily irrigation flows in the lower Murray (7000 Ml) now contain more water from Lake Victoria (5000 Ml) than from the Murray above the confluence (Mackay *et al.*, 1988).
(b) Water from the Darling is turbid owing to its high suspended load, so that the lower Murray is also turbid. The average turbidity in the lower Murray at Overland Corner (83 NTU, range 15–380, $n = 387$, 1978–86: Mackay *et al.*, 1988) is about three times the level in the Murray above the confluence.
(c) The lower Murray is impounded by a series of weirs that form contiguous pools along the river. The concentration of weirs and the nature of their effects reinforce the distinctiveness of the region (Walker *et al.*, 1992).
(d) Most of the lower Murray region is in South Australia, so that it has a certain degree of political and economic integrity. The river is managed by state government departments in collaboration with the federally-constituted Murray–Darling Basin Commission.

The lower Murray includes four sections (Figure 1; Pressey, 1986):

Valley. This is part of the Mallee Plains tract, extending from the confluence to Overland Corner (906 river km). The floodplain is 5–10 km wide, with remnants of up to four broad terraces (Gill, 1973; Cole, 1978) formed by fluctuations in previous water and sediment transport regimes (Woodyer, 1978; Graf, 1987). The river meanders freely, with a wavelength of about 4 km near the South Australia border (Rutherfurd, 1990) and a sinuosity index (ratio of channel length to valley length) of 2·1. There are many irregularly shaped

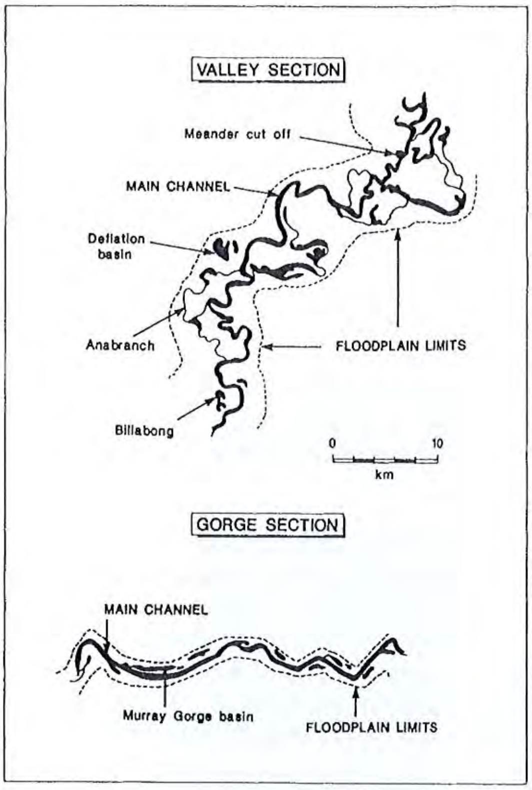

Figure 2. Wetland forms associated with the Valley and Gorge sections of the lower Murray

wetlands (Figure 2) including anabranches, billabongs (oxbows), deflation basins and the large expanse of Lake Victoria (11 180 ha). The Valley Section includes Locks 3–10.

Gorge. Near Overland Corner the Murray enters a 30 m deep limestone gorge where the floodplain is constrained to 2–3 km. The gorge was incised during a period up to 900 000 years ago when the sea retreated 130 m below its present level (Twidale *et al.*, 1978). The river's course is structurally controlled, in contrast to the Valley Section, although it may show some inclination to meander within the gorge. The channel includes long, straight reaches (up to 8 km) and angular reaches where the river abuts limestone cliffs, and the sinuosity index is a comparatively low 1·08. The morphological diversity of wetlands is much less than in the Valley Section (Figure 2). The Gorge Section includes Locks 1–2.

Swamplands. The Murray emerges from the gorge below Mannum (although there are isolated limestone bluffs downstream) and flows through a section flanked by once-extensive swamplands, most of which have been drained and reclaimed for farmland. Earthen levees, stabilized by exotic willows (*Salix* spp.), have been constructed to keep the river from the reclaimed areas. There are no weirs, but the region has been affected by a rise in river level associated with barrages across the Murray mouth.

Lakes. The Murray enters Lake Alexandrina (2015 Gl) at Wellington before flowing to the Southern Ocean. The seaward margins of the lake are impounded by barrages constructed in 1940 to keep sea water from the lower river. The difference in water elevations across the barrages is 750 mm; their closure flooded the lake shoreline and caused a 450–600 mm rise in the level of the lowermost reaches of the river.

Together the Valley and Gorge sections occupy more than 80% of the lower Murray. At this scale the environment has been shaped by forces operating over a much longer time span than the two centuries of European occupation in Australia. Within the last 100 years, however, the Murray has been transformed by flow regulation and other effects of urban and agricultural development.

IMPACT OF REGULATION

Impoundments

Flows in the Murray-Darling system are controlled by dams on tributaries in New South Wales and Victoria (e.g. Jacobs, 1990). The first significant diversions were in 1922–40, with completion of Hume Dam (near Albury) and barrages, weirs and other small storages. Capacities increased sharply during the 1950s and have since maintained that trend (Close, 1990). The principal offstream dams include Dartmouth (Mitta Mitta River, 4000 Gl), Eildon (Goulburn, 3390 Gl) and Hume (Murray, 3038 Gl), and there are many smaller storages (to 1700 Gl). The Murray itself is impounded by Hume Dam, a diversion weir at Yarrawonga (118 Gl) and 13 locked weirs, including those below the Darling junction. The Darling is comparatively unregulated, apart from the Menindee Lakes storage (1682 Gl), although there are storages on tributary rivers. As noted, Darling water is transferred to Lake Victoria (680 Gl) for release to the lower Murray during the irrigation season. The operating rules (administered by the Murray-Darling Basin Commission) guarantee a minimum annual entitlement flow of 1850 Gl to South Australia, although average flows are considerably more than this (6650 Gl; Jacobs, 1990).

Ten low-level (3 m) weirs with adjacent lock chambers were constructed on the lower Murray between 1922 and 1935 (Figure 1). The pools are variously 22–98 km long, so that the lower Murray above Blanchetown consists entirely of pool environments. Each weir consists of a navigable pass of movable panels and sluice bays of 'stop logs' that are removed or installed as required. The lockmasters endeavour to maintain an upper pool level within 50 mm of a fixed target, as far as possible. Details of design and operation are given elsewhere (e.g. Jacobs, 1990).

Flow behaviour

Flows in the lower Murray remain variable despite regulation (Close, 1990). Figure 3 shows flows to South Australia from 1901 to 1990, plotted on a logarithmic scale. The largest flood was in 1956, and the most severe drought was in 1967. The 1967 drought does not register as strongly as that in 1914 because 'entitlement' flows following dam and weir construction ensure that the lower river does not fall below weir-pool levels. South Australia's annual entitlement was 1500 Gl until 1979, and subsequently increased to 1850 Gl with completion of Dartmouth Dam in north-east Victoria.

Figure 4 shows daily river heights in the upper and lower pools of Lock 3, Overland Corner, from 1921 to 1989. The commencement of operations is indicated by the first separation of upper and lower pool records (24 March 1925). The data show a basically seasonal pattern subject to erratic floods and droughts.

Table I compares long-term flow records for the Murray and Darling above and below the confluence. The range of extreme flows recorded in the lower Murray (Blanchetown) is from 6 to 491% of the long-term average, and the range for the Darling (Menindee) is 0–911% (Table 2 in Walker, 1986).

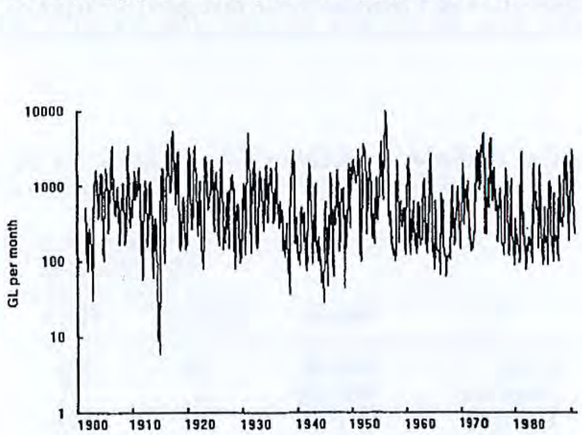

Figure 3. Regulated flows to South Australia, 1901–90. Note that the vertical axis has a logarithmic scale. Based on data from the Murray-Darling Basin Commission

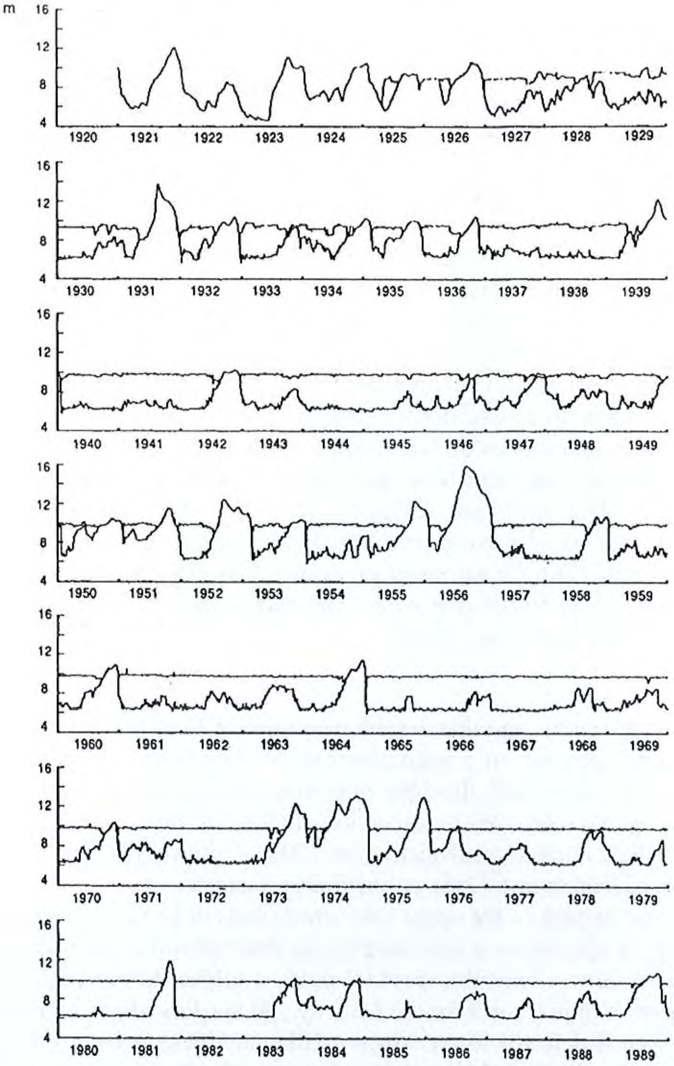

Figure 4. Variation in river heights (metres) at Lock 3, Overland Corner. The upper (Lock 3) and lower pool (Lock 2) levels are 9·8 and 6·1 m, respectively. Based on daily records from the Engineering and Water Supply Department, South Australia

Table I. Long-term discharges at stations above and below the junction of the Murray and Darling rivers (see Figure 1). Data from Murray-Darling Basin Commission, Canberra

			Mean discharge ($m^3 s^{-1}$)		
River	Site	Record	Minimum	Mean	Maximum
Murray	Euston	1941-89	7·4	271	3495
Darling	Menindee	1941-89	0	91	1843
Darling	Burtundy	1941-89	0	59	913
Anabranch	Bulpunga	1955-89	0	9	707
Murray	Blanchetown	1950-80	20	318	1562

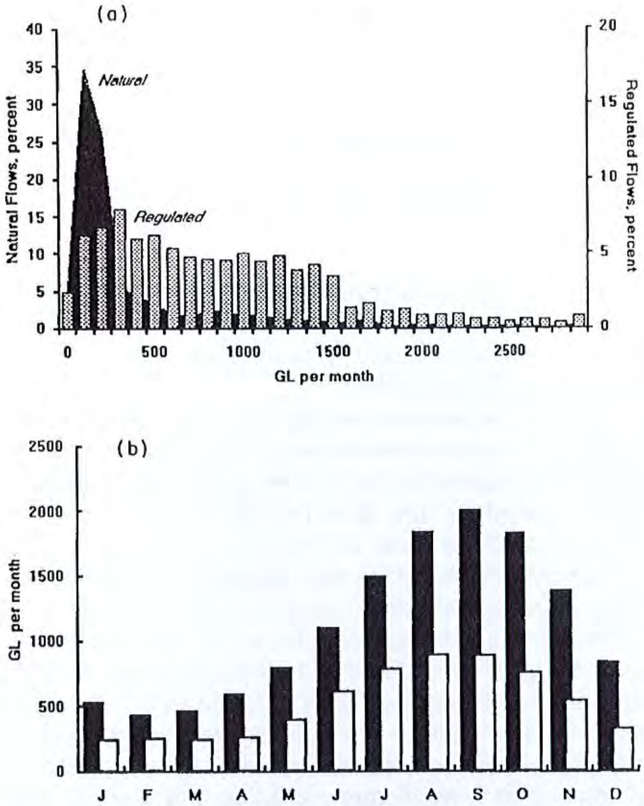

Figure 5. (a) Comparison of the frequency distributions of simulated 'regulated' flows (bars) and 'natural' flows (shaded area) to South Australia, 1892–1972, for levels of abstraction that prevailed in 1988. The horizontal axis is truncated at 3000 Gl; this accounts for 95% of 'natural' flows and 99% of 'regulated' flows. Data from Murray-Darling Basin Commission. (b) Comparison of simulated average monthly flows to South Australia, 1892–1972, for levels of abstraction that prevailed in 1988. 'Natural' flows are shown as shaded bars, and 'regulated' flows are shown as open bars. Data from Murray-Darling Basin Commission

The variability of flows makes it difficult to isolate the effects of regulation. Simulated data, however, suggest striking differences between regulated and unregulated conditions. Figure 5 shows output from a computer model run by the Murray-Darling Basin Commission (e.g. Jacobs, 1989; Close, 1990). The simulation compares 'regulated' and 'natural' flows in the lower Murray, but in an artificial manner: the comparisons demonstrate the effect that levels of water use in 1988 would have had on historical flows (1892–1972). 'Regulated' flows are determined from actual flows corrected for the levels of abstraction (diversions and storage) that prevailed in 1988, and 'natural' flows are estimated from actual flows with abstractions set to zero.

Figure 5a shows that regulation has markedly reduced the frequency of low flows. Thus, flows of 100–300 Gl account for 60% of natural monthly flows but only 13% of regulated flows. The pre-regulation data show that under natural conditions flows up to 500 Gl would be expected in 75% of months, whereas they now occur in only 30% (Close, 1990). Further, the incidence of flows in the range 500–1500 Gl has increased by a factor of roughly two. One operational constraint is that at flows above about 600 Gl per month all the weir pools (13–64 Gl) are filled, so that there is no remaining storage capacity. Another is that bankfull capacities are typically in the range 1100–1300 Gl per month (Thoms and Walker, 1992). At entitlement flows (about 100–200 Gl per month), a large part (40–80%) of the flow entering South Australia is diverted through the Chowilla anabranch system (Murray-Darling Basin Commission, 1991), bypassing Lock 6 where the channel capacity is about 1125 Gl per month. Taking this into account, the data indicate that the river is now generally maintained at or near bankfull levels.

Figure 5b compares average monthly flows. Regulated flows are clearly much reduced (about 44%) compared with unregulated conditions. Outflows at the Murray mouth are 36% of the natural flow (Close, 1990), demonstrating the supplementary effect of diversions within South Australia. Flow through the Murray mouth ceased during a period of low flow in 1981, and this is likely to recur in future. Significantly, the data show no change in seasonality—flows under both regulated and unregulated conditions tend to be at a maximum in late winter and early spring and at a minimum in late summer and autumn. This is in contrast to the Murray below Hume Dam, where there are marked seasonal effects (e.g. Walker, 1980).

Flood behaviour

The ecological dynamics of floods are not adequately described by simple analyses of the magnitudes and frequencies of flows. Although the history of floods in the Murray is well chronicled as river heights, there are very few data relating to their ecological significance. Even so, it is possible to recognize associations between the form of the hydrograph and its biological effects.

A comparison of flows in the Murray at Morgan (see Figure 1) before and after regulation suggests that the magnitude of peak annual flows with return periods up to 2·1 years has been decreased by up to 0·5 m (Thoms and Walker, in press). In this region the river is now maintained at a base pool level of 3·3 m (Lock 1). In the unregulated Murray periods of low flow (<500 Gl, and well below bankfull levels) were commonplace, punctuated by minor floods every 1–2 years and occasional major floods. The regulated regime maintains flows at or near bankfull capacity, and although major floods still occur the magnitude of water level changes associated with the minor floods is significantly reduced.

The rate of passage (duration) of a flood is significant because it influences the recruitment success of fish and other species that breed on rising floods. At less than bankfull discharge the speed of flow waves (changes in flow-rate) has greatly increased in the locked sections of the Murray (Jacobs, 1990), and some effect on overbank flows would be anticipated because the weir pools represent a significant loss of floodplain storage capacity (Archer, 1989). Perhaps for this reason, the recession limb of the typical flood stage hydrograph now appears to be significantly steeper than it was before regulation. For example, the recession time of a 3-m flood at Overland Corner in 1885 was 59 days and the recession of a 2-m flood in 1986 was only four days (Thoms and Walker, 1989). A comparable attenuation is reported for the Murray at Corowa (NSW) (Jacobs, 1989). If these figures are representative, they suggest that floods now do not persist as long as they did formerly; this probably has been a factor in the decline of native fish populations (see later). These changes presumably owe more to the operation of dams rather than weirs.

Role of weirs in salinization

Higher river salinities, exacerbated by land salinization, are a major economic and environmental problem in the Murray Valley (Murray–Darling Basin Ministerial Council, 1987). The salt load entering South Australia is 1·1 million tonnes annually, and a further 0·5 million tonnes is added within the state. Salinities in the Murray at Morgan (Figure 1) in 1978–86 were 146–723 mg l^{-1}, varying with discharge (Mackay *et al.*, 1988). The ultimate source of the salt is groundwater associated with relictual marine sediments, but accession to the river has been increased by irrigation, vegetation clearance and the hydraulic effects of the weir pools. Although structural modifications of the weirs have been contemplated as a means to increase the area of temporary wetlands (Ohlmeyer, 1991), they may not be a popular option for salinity mitigation given the likely impact on other forms of water use. Changes to Lock 6 have been considered, however, as part of investigations at Chowilla, near Renmark (Figure 1).

The Chowilla area is a 1650 km^2 area of floodplain with many associated wetlands. In 1930 water impounded by the newly constructed Lock 6 flooded the anabranch system, rendering permanent many temporary wetlands. The main effluent, Chowilla Creek, now contributes about 43 tonnes of salt daily to the lower Murray, and up to 145 tonnes in the aftermath of large floods (Murray–Darling Basin Commission, 1991). Additional salt inputs are associated with nearby Lake Victoria, where the level was artificially raised in 1928; these are now <5 tonnes per day, but are expected to double in the next 40 years. The growth and regeneration of floodplain trees are adversely affected by salinity and the regulated flow regime (O'Malley and Sheldon, 1990). One of the favoured engineering options, despite strong opposition, is to construct further weirs to isolate part of the anabranch system as salt interceptors (National Environmental Consultancy, 1988; Murray-Darling Basin Commission, 1991). An earlier proposal to install tube wells to intercept inflowing groundwater has been regarded as too expensive, but still retains some credibility. Another proposal to lower the weir pool level was rejected partly because of a claim that it would initiate a 30 year period of hydrological re-adjustment in which salt inputs could exceed present levels.

Variations in stage

The lower Murray weirs have important effects on water levels in floodplain and river environments (Walker *et al.*, 1992). In some respects, river stages are a more appropriate currency for studies of environmental effects than discharges.

Routine weir operations maintain close control over upper pool levels, but cause levels below each weir to fluctuate. The few data available for the river before locking suggest that changes in the river level then were more sustained. To illustrate, Figure 6 shows rates of changes in the lower pool of Lock 3 during 1990, superimposed on the upper and lower pool levels. The pattern of daily changes is largely an artefact of the 50 mm 'tolerance' that governs upper pool levels. The large fluctuations recorded in April were not related to routine weir operations, but were part of an attempt to flush saline water from nearby Lake Bonney. Over the long term, daily changes in the lower pool are typically within ±200 mm and occasionally ±500 mm. Greater changes do occur, but these cannot be attributed solely to weir operations. The fluctuations are progressively diminished in the approach to the next weir, so that there are gradients between weirs. Their effects are most noticeable in regard to channel changes and the development of littoral communities.

Channel changes

The lower Murray has a complex cross-section typical of semi-arid rivers, with in-channel benches reflecting adjustments to variable flow and sediment regimes (Thoms and Walker, 1992a, in press). The generally low channel slope (mean $5{\cdot}5\ \mathrm{cm\ km^{-1}}$) indicates that the channel has been stable for a long time. Within the normal span of flows water may take 10–100 days to travel from the Darling confluence to the sea.

Although the channel configuration has remained essentially stable since regulation began, there have been significant changes in internal dimensions and slope (Thoms and Walker, 1992a, in press; cf. Rutherfurd, 1990). Their extent depends on the sequential position of the weir and the time of construction, and local factors including floodplain width and variations in the bank material. In effect, the channel is developing a stepped gradient. The river banks (silt and clay) are prone to failure after rapid flood recessions but are less affected by routine changes in level, although these may contribute incrementally. Width-depth ratios have been increased by erosion by an average of 32% between Locks 3 and 4 (Valley Section) and decreased by deposition by 22% between Locks 2 and 3 (Gorge Section). The benches have been eroded in the lower pools and flooded to depths of >2 mm in the upper pools. In the middle reaches they are largely

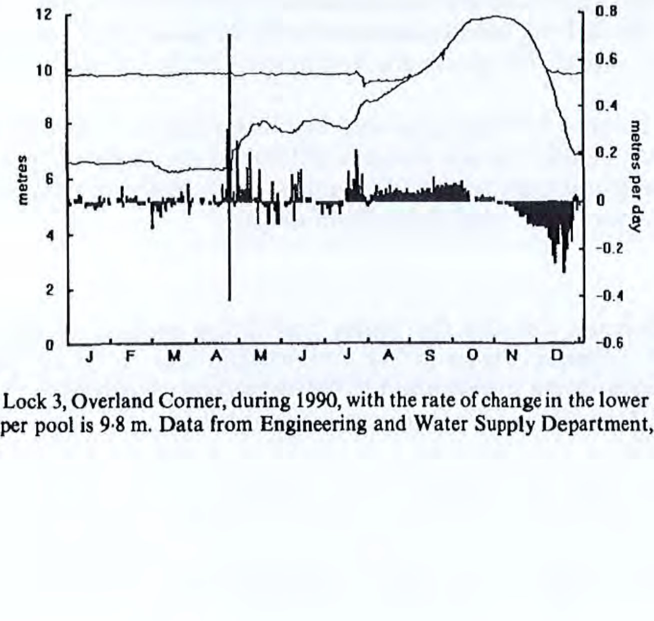

Figure 6. Daily pool levels at Lock 3, Overland Corner, during 1990, with the rate of change in the lower pool superimposed. The design level for the upper pool is 9·8 m. Data from Engineering and Water Supply Department, South Australia

intact, and provide shelving banks that encourage the development of littoral plant and animal communities (Walker *et al.*, 1992). Although flow variations (and rapid drawdown) will ensure that the shape of the channel is never completely stable, the channel slope is likely to attain a quasi-equilibrium in about 40 years (Thoms and Walker, in press). It is likely that the weir systems in the Valley Section will attain stability before those in the Gorge Section.

Sediment cores from the weir pools show an abrupt transition to regulated conditions: before regulation the sediments were predominantly coarse sands, whereas they are now fine silts and clays. This represents a decrease in median grain size of about 30%. The significance of this change for the river benthos is being investigated in studies of diatoms and other material recovered from sediment cores (Thoms *et al.*, unpublished data).

There are interesting similarities and contrasts between the channel changes associated with the Murray weirs and those reported for navigation dams on the Upper Mississippi River (Grubaugh and Anderson, 1988; 1989). In both instances the short-term (about 50 years) impacts have been increases in mean river stage and water surface areas, and increased rates of sedimentation and erosion. The increased variance of river stages in the Upper Mississippi, unlike the Murray, has brought increases in the recurrence and duration of floods. The difference may arise from a greater reduction of reservoir capacity due to sedimentation in the Upper Mississippi, whereas the sediment supply to the lower Murray is comparatively small, reflecting its position in the fluvial system (cf. Thoms and Walker, 1992). Ultimately, the conditions of sediment supply to the lower Murray suggest that its adjustment time will be much longer than that of the upper Mississippi.

Littoral communities

The littoral zones of rivers are ecological boundaries between channel and riparian environments, although their importance varies with bank slope, current velocity, water level changes, sediment type and other factors. In lowland rivers the littoral zone often supports emergent and submergent plants that provide a refuge, feeding area, nursery and a corridor for the dispersal of aquatic and terrestrial vertebrates and invertebrates. In the lower Murray the littoral zone harbours most of the biodiversity associated with the river, whereas the open channel is comparatively sterile (Walker *et al.*, 1992). Emergent plants (e.g. *Phragmites australis*, *Typha* spp.) occur in the uppermost 0·5 m and submergent species (e.g. *Myriophyllum*, *Potamogeton* spp.) down to 2 m. Although in some areas the banks shelve to greater depths, plant growth is discouraged by high turbidities, strong currents and unstable sediments.

The development of the littoral community at any site depends on proximity to the weirs. Immediately below Lock 3 the range of daily water level fluctuations is comparable with the depth of the euphotic zone (cf. mean Secchi transparency 300 mm), so that the water level is changing through most, if not all, of the zone for effective plant growth. In this area erosion has steepened the banks and plant growth is limited. There may be exceptions where snags (usually trees undermined by bank erosion) provide shelter; these represent probably the most stable microhabitat associated with the littoral zone (cf. McArthur, 1988). In the upper weir pools, water levels vary less but the shelving benches associated with the former river bank are inundated by >2 m and plant growth is again limited. The maximum development of littoral plants is generally in the middle reaches of the weir pools.

The weir pool margins harbour a number of animal species normally associated with floodplain wetlands. For example, the freshwater mussel *Velesunio ambiguus* (Hyriidae), the crayfish *Cherax destructor* (Parastacidae) and the shrimp *Caridina mccullochi* (Atyidae) are typically lentic or small-stream species found in sheltered areas along the river banks, often in the lee of snags.

Wetlands

The most striking differences between the Valley and Gorge sections of the lower Murray are in development of floodplain wetlands (Figure 2). The total wetland areas in the two sections respectively are 26 272 ha (15 092 ha excluding Lake Victoria) and 10 970 ha (Pressey, 1986). Many of the wetlands in either section were temporary before weir construction, and connected to the river only in times of flood. Those in the Valley Section are of diverse shapes and appear to follow a morphological succession related to lateral movements of the channel (Amoros and Van Urk, 1989). The wetlands are generally flooded via more than one connection to the river (e.g. meander cutoffs) or via overbank flows, with flooding frequency related to the local river height (i.e. proximity to weirs) and the frequency and magnitude of overbank flows. The potential extent of 'flooded-plain' areas (Breen *et al.*, 1988) is greatest in the Valley Section, although proportionally more of the gorge floodplain is subject to inundation. In the Gorge Section the wetlands are typically elongate 'channel-margin swales' (Pressey, 1986; 1990), connected to the river by a single channel except during overbank flows. Their morphology suggests that channel avulsion has occurred as they are frequently larger than the contemporary river and so may represent channels formed under high energy regimes (Bowler, 1990). Localized sediment deposition (e.g. sills and levees) may modify the dispersal of floodwaters and so cause localized changes in floodplain vegetation and wetlands (Buchholz, 1981). In the absence of overbank flows, gorge wetlands are more prone to sediment blockages than valley wetlands, as they have fewer points of connection to the river.

Pressey's (1986; 1990) hydrological classification of Murray wetlands includes four categories: (1) permanent wetlands connected to the river at minimum regulated flow (weir pool level); (2) seasonal wetlands connected to the river above minimum regulated flow but below maximum flow (typically filled during the irrigation season); (3) wetlands above regulated flows, filled by surplus flows; and (4) wetlands above regulated flows, filled by irrigation return water and surplus flows.

Three-quarters of the wetlands in either section are in category 1, showing the significance of raised water levels associated with the weirs. Category 2 is sparsely represented along the lower Murray. Categories 3 and 4 account for 20 and 5% of wetland areas in the Valley and Gorge sections, respectively.

Pressey (1986) also devised a secondary geomorphical classification:

(a) *Murray gorge basins* are not represented in the Valley Section, but account for 45% of the wetland area in the Gorge Section. They are elongate, with rounded or angular margins, often closely adjacent to the main channel and the valley wall. Many are enclosed by levees.

(b) *Deflation basins* occupy 53% of the wetland area in the Valley Section and 16% in the Gorge Section. Some of the former have associated lunettes, although these may easily be confused with swale and ridge systems. None has been significantly modified by deposition. This category may be misnamed, as some of the basins could be the result of lateral migrations of the channel.

(c) *Lentic channel forms* account for 22% of the wetland area in the Valley Section but only 5% in the Gorge Section. They comprise anabranches, distributaries and abandoned channels, including the familiar oxbow billabongs.

(d) *Impounded wetlands* include 11% of the area in the Valley Section and 25% in the Gorge Section. Most are flooded areas associated with the upper weir pools, and so represent a substantial new habitat introduced by flow regulation. Typically, they are marked by stands of drowned trees (river red gum, *Eucalyptus camaldulensis*). Areas just below the weirs have experienced a reduction of flooding, and the middle reaches are probably least affected. The impact is likely to have been greatest in the Gorge Section, where a larger proportion of the floodplain has been permanently flooded. The flooded areas are probably inferior wetland environments, in terms of diversity and productivity, compared with intermittently flooded wetlands (Breen *et al.*, 1988; Grubaugh and Anderson, 1988), and so represent a degradation rather than an enhancement of the Murray's floodplain environment.

The ecological status of lower Murray wetlands has been surveyed by Thompson (1986), with particular regard for waterfowl. Largely as a result of the work by Thompson and Pressey, some governmental departments are involved in hydrological manipulations of selected wetlands to promote breeding of fish and waterfowl (Jensen, in press). There is great scope for other wetland studies considering, for example, the effects of salinization, habitat modification by introduced carp (*Cyprinus carpio*) and variable flood regimes. It would also be valuable to investigate the ecological integrity of the wetlands defined by hydrological and geomorphological criteria.

Riverine flora and fauna

Declines are apparent in the range and abundance of many native plants and animals associated with the lower Murray, and appear to have intensified in the past 30–40 years, coincident with the rapid expansion of irrigated agriculture. The riparian woodlands, (river red gum, *E. camaldulensis*, and black box, *E. largiflorens*) have been degraded by flow regulation, salinization, grazing, land clearance and logging (Margules and Partners *et al.*, 1990). The aquatic plants and animals have been exposed to a wide range of environmental modifications, including alienation of wetlands, changeable water levels, increased turbidity and salinity, pollution by agricultural chemicals and the activities of carp and other introduced fish. Changes have occurred, for example, in the distributions of riverine and wetland species of crayfish, freshwater mussels and snails (Geddes, 1990; Walker, 1992; Walker *et al.*, 1992).

A parallel decline in the native fish fauna has often been cited, although there are few historical data (e.g. Walker, 1983; Lloyd and Walker, 1986; Pierce, 1989; Cadwallader and Lawrence, 1990; Puckridge and Walker, 1990). There are about 30 native fish species, including some that are commercially valuable; these include Murray cod (*Maccullochella peeli*: Percichthyidae), callop (or golden perch, *Macquaria ambigua*: Percichthyidae), silver perch (*Bidyanus bidyanus*: Teraponidae), bony bream (*Nematalosa erebi*: Clupeidae) and freshwater catfish (*Tandanus tandanus*: Plotosidae). In addition, there are 10 introduced species, including the common carp (*Cyprinus carpio*: Cyprinidae), goldfish (*Carassius auratus*: Cyprinidae), redfin perch (*Perca fluviatilis*: Percidae), gambusia (*Gambusia holbrooki*: Poeciliidae) and trout (e.g. *Salmo trutta*: Salmonidae).

Historically, Murray cod and callop have been the two principally commercial species in the lower Murray, although populations of cod especially have declined (Rowland, 1989) and there is now a moratorium on catches of that species in South Australia. Despite considerable year to year variation, there is a clear correspondence between the decline and the rapid expansion of water storages and diversions (and irrigated agriculture) that occurred after about 1950 (Figure 7). The Murray now has the lowest commercial fish yield per square kilometre of floodplain of any of the world's major rivers, although historical catches were comparable (Murray-Darling Basin Commission, 1991). Part of the historical variation in catches is associated with floods: Figure 8 shows a clear correlation between the callop catch and river levels in part of the lower Murray between 1939 and 1979.

In the river system as a whole, arguably 15–16 species of fish are threatened and five are vulnerable. In the lower Murray regional extinctions are well advanced for five species, and another two are in precarious circumstances (Lloyd and Walker, 1986; Lloyd *et al.*, 1991). The underlying causes are related to habitat changes, interactions with exotic species and the impact of fisheries. Flow regulation is particularly

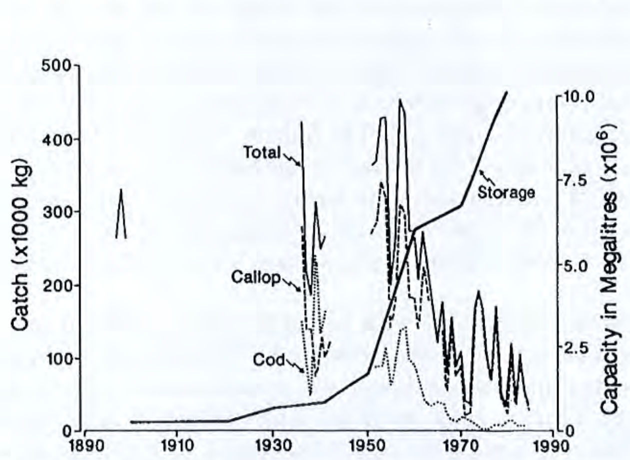

Figure 7. Historical catches of callop and Murray cod from the River Murray in South Australia. The expansion of flow regulation in the river system after 1950 is shown by the trend of water storage capacity. Diagram courtesy of Mr Bryan Pierce, Department of Fisheries, South Australia

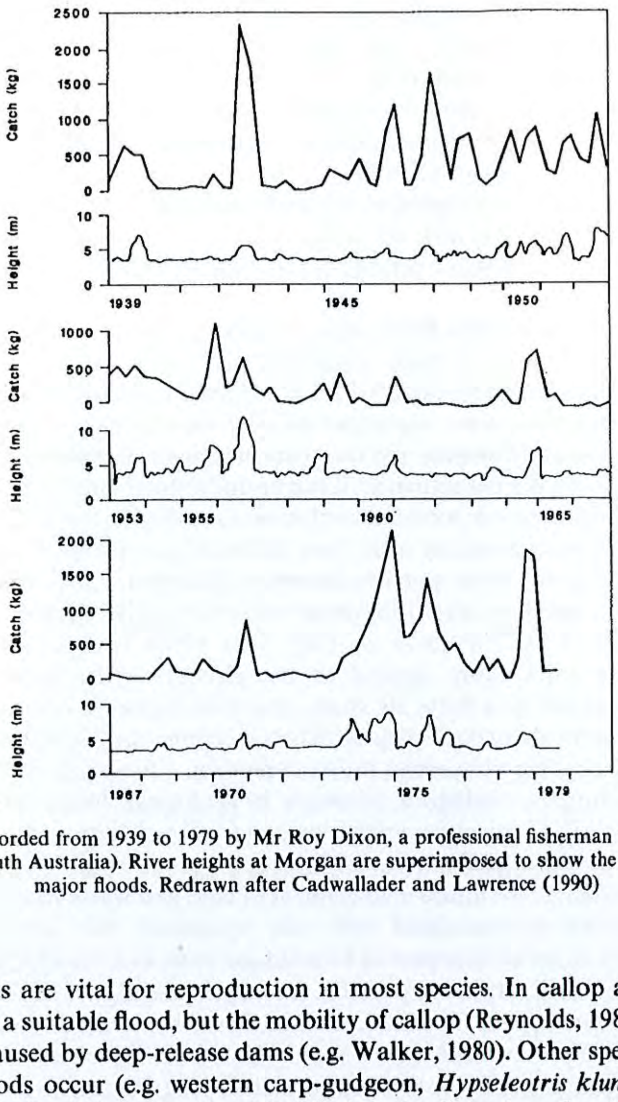

Figure 8. Catches of callop recorded from 1939 to 1979 by Mr Roy Dixon, a professional fisherman working on the Murray between Morgan and Blanchetown (South Australia). River heights at Morgan are superimposed to show the association between catches and major floods. Redrawn after Cadwallader and Lawrence (1990)

implicated because floods are vital for reproduction in most species. In callop and silver perch spawning occurs only when there is a suitable flood, but the mobility of callop (Reynolds, 1983) may have compensated for the decline in range caused by deep-release dams (e.g. Walker, 1980). Other species spawn seasonally, but more intensely when floods occur (e.g. western carp-gudgeon, *Hypseleotris klunzingeri*). Murray cod and catfish also spawn seasonally, independently of floods, but do depend on flooding to supply food for the young. Finally, species like the jollytail (*Galaxias maculatus*) recruit independently of floods, as they rely on marine or estuarine environments for spawning. Earlier work on Murray–Darling fish may underestimate the significance of the smaller (seasonal) floods for recruitment. At least 20 of the 30 native species depend on floods for successful recruitment, and none is independent of the general reliance on flooding of the river–floodplain ecosystem.

DISCUSSION

Floods are a vital factor in the ecology of the lower Murray, as in other floodplain rivers (Sparks *et al.*, 1990). They periodically 'reset' ecosystem processes by promoting recruitment of flora and fauna and by allowing the river and its floodplain to exchange resources. Before regulation the flow regime mirrored its changeable, semi-arid climate; the channel and floodplain were configured to accommodate variable flows and the plants and animals had evolved a variety of appropriate survival strategies. Since then a more stable regime has been imposed and the ecosystem is undergoing a series of compensatory adjustments. Some native species are adapting to the new regime and others, probably a majority, are in decline.

The regulated regime is a major disturbance to the ecosystem not because it is unpredictable (Sparks *et al.*, 1990), but because it is more predictable than the natural regime. Despite 'entitlement' flows that now ensure a minimum pool level, the limits imposed on the magnitude of overbank flows mimic drought conditions because they prolong the isolation of the riverine and floodplain communities. The flooded wetland areas also represent a degraded habitat for riverine animals. For species like Murray cod, which utilize minor seasonal floods to maintain low levels of recruitment and for whom large floods represent opportunities for recruitment on a much larger scale, the regulated regime is clearly hostile. The extent of their decline is such that when big floods do arise, they may lack the numbers to recruit effectively. If recovery is to occur, it will be a slow process dependent on successive periods of recruitment to re-establish a population with a more continuous age structure.

The natural flow regime, and its erratic flood pulse, are keys to understanding the ecology of the Murray and the changes that have occurred as a result of regulation. The same is likely to apply to other semi-arid rivers, yet there is no standard method for describing a flow regime in ecologically relevant terms (Junk *et al.*, 1989; Poff and Ward, 1990). This is an important priority for research, and will require collaboration between ecologists, fluvial geomorphologists and members of cognate disciplines. Part of the problem is that, because flow is inherently a complex phenomenon, it can be understood only with reference to defined spatial and temporal scales. Here there is much potential confusion, as ecologists and other environmental scientists (or environmental scientists and managers) often have different perceptions of space and time. Yet fluvial geomorphology and river ecology have much in common (Schumm, 1988), and many researchers have sought to strengthen their perceptions of environmental units by correlating ecological and geomorphological perspectives (Amoros *et al.*, 1987; Petts *et al.*, 1989; Salo, 1990). Perhaps the salient difference is that concepts of 'recovery' are more easily applied to the physical environment than to the biological environment: plants and animals have finite life spans, and extinctions are not reversible.

The lower Murray, and particularly the Valley and Gorge sections, are distinctive units. They are spatially limited, however, and an ecosystem perspective properly requires a temporal dimension (Ward, 1989). It is useful, for example, to distinguish ecological processes in geological, historical and contemporary time (Schumm, 1988). *Geological* time is an appropriate window for the climate and physiography of the lower Murray landscape. Bowler (1990) argued that an understanding of the climatic and geological history of the Murray–Darling Basin is essential for future management of land and water resources. The same applies to problems of channel maintenance associated with weir operations. For example, the revetments and dredging works below many of the weirs appear to be managed without a broader understanding of why and how the channel is changing in response to regulation. Equally, knowledge of the evolutionary origins of the native flora and fauna is a prerequisite for understanding their present situation and devising appropriate strategies for management. The *historical* time-scale, measured on the order of a few hundred years, is appropriate for an ecological perspective, as it approximates the longevity of the longest lived species (eucalypts) associated with the lower Murray ecosystem. It also coincides with the arrival of Europeans in the Murray–Darling Basin and the changes imposed by flow regulation. The *contemporary* view spans perhaps a few years.

It is in shifting between historical and contemporary time frames that we confront many of the conceptual problems underlying what Cullen (1990) has called 'the turbulent boundary between science and management'. By nature, managers are concerned more with contemporary problems than with those in longer time frames. The extent of temporal variability in the lower Murray ecosystem, however, suggests that we must view the river in a longer time frame than is necessary for rivers in regions of more stable climate. Different spatial scales of perception are another source of confusion. For example, to regard the lower Murray as a single, homogeneous environmental unit may overlook the different impacts of weir construction in the Valley and Gorge sections of the river, reflecting the development of the floodplain and wetlands. Some adopt the broad scale suggested by 'landscape ecology' (Turner, 1989), whereas others argue that scales should be modified to fit the problem at hand (Wiens and Milne, 1989).

The physical environment of the lower Murray will probably approach a partial equilibrium in about 40 years, when adjustments of channel slope and cross-sectional area will have stabilized (Thoms and Walker, in press). The ranges of many native plant and animal species will continue to decline, and inevitably some will disappear from the Murray in South Australia. The limits to overbank flows and the permanent inundation of marginal areas will cause the viable floodplain area to contract, so that the remaining riparian woodlands and wetlands will lie closer to the main channel. Salinization is likely to increase, despite efforts to halt its progress (Murray–Darling Basin Ministerial Council, 1987). The general loss of biodiversity, already low by global standards, may mean an increased role for abiotic factors, as opposed to biotic interactions, in the dynamics of the ecosystem (Sparks *et al.*, 1990). It is not melodramatic, therefore, to consider the lower Murray as a river in crisis. The *Natural Resources Management Strategy* initiated by the Murray-Darling Basin Ministerial Council (1989) is an appropriate general response, but makes little provision for strategic research.

Pressey (1986; 1990) has suggested that maintenance of a natural (or near-natural) environment is merely one of the options for future management. He proposed that the options for Murray wetlands are (1) preservation of the *status quo*, (2) restoration of the natural environment and (3) 'special purpose' management. The first option appears unrealistic, as the present state of the river is a transient phase in which further changes are inevitable. The second cannot be taken literally, but might be developed as a strategy to discover a sustained, more harmonious balance between exploitation and the natural environment. The time-scale for such a strategy, however, must be of the order of tens of years, as opposed to economic and political time-scales. The third option, now finding increasing favour as part of a general regard for 'adaptive management' (Walters, 1986), refers to the prospects for manipulating selected wetlands to promote the breeding of fish or waterfowl. This is a promising approach, at least in principle, but it will require a much greater investment in research to ensure that the basis for management decisions is progressively strengthened and refined.

Given the requirements of irrigators and other water consumers, and the political and economic constraints that abound, it is doubtful whether proposals to restore a more nearly natural distribution of flows in the lower Murray would be seriously regarded, although this may be the only option for restoration of some elements of the natural ecosystem. The metaphor of amplitude-modulated signals used earlier is too simplistic because, in the case of the Murray, the flow regime is subject to both amplitude and frequency modulation. The most damaging component of the change may be the effect on the amplitude of flows, and to change this would require major concessions to environmental flows and ecosystem maintenance, at considerable expense to other users.

It has been suggested that an ecosystem's capacity to resist and recover from disturbance is a function of the biota's experience with natural spatio-temporal variation (Poff and Ward, 1990). If so, semi-arid rivers might be expected to show exceptional resistance to flow regulation. Equally, if the resistance to disturbance (resilience) is inversely related to the magnitude of differences between the natural and regulated regimes, semi-arid rivers might show little resistance to such perturbations. The latter view is more consistent with the physical character of semi-arid rivers, at least within geological and historical time-scales. Semi-arid rivers attain equilibrium for only short periods, due to the sporadic nature of run-off from the catchment (Graf, 1987), and are typically slow to recover from disturbances caused by large floods. Thus, transient forms like channel benches are prominent. Regulation of the Murray has decreased the time for recovery after disturbance, and the channel is developing a morphology that is more resistant to variations in discharge (Thoms and Walker, 1992). In a biological context (and at similar time-scales), the impression of sensitivity is supported by changes in the Murray's fish community, where a small complement of native species has been nearly overwhelmed by exotic species. In floodplain environments too, the prevalence of weed species (Margules and Partners *et al.*, 1990) does little to support the idea that these communities have a high resistance to invasion (McIntyre *et al.*, 1988). These arguments will be difficult to resolve, given the broad spatial and temporal scales on which semi-arid river ecosystems function.

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REFERENCES

Amoros, C. and Van Urk, G. 1989. 'Palaeoecological analyses of large rivers' in Petts, G. E., Möller, H., and Roux, A. L. (Eds), *Historical Change of Large Alluvial Rivers: Western Europe*, Wiley, Chichester. pp. 143–166.

Amoros, C., Roux, A. L., Reygrobellet, J. L., Bravard, J. P., and Pautou, G. 1987. 'A method for applied ecological studies of fluvial hydrosystems', *Regul. Riv.*, **1**, 17–36.

Archer, D. R. 1989. 'Flood wave attenuation due to channel and floodplain storage and effects on flood frequency' in Beven, K. and Carling, P. A. (Eds), *Floods: Hydrological, Sedimentological and Geomorphological Implications*, Wiley, Chichester. pp. 37–46.

Beckinsale, R. P. 1969. 'River regimes' in Chorley, R. J. (Ed.), *Water, Earth and Man*, Methuen, London. pp. 455–472.

Bowler, J. M. 1990. 'The last 500,000 years' in Mackay, N. and Eastburn, D. (Eds), *The Murray*, Murray–Darling Basin Commission, Canberra. pp. 95–100.

Breen, C. W., Rogers, K. H., and Ashton, P. J. 1988. 'Vegetation processes in swamps and flooded plains' in Symoens, J. J. (Ed.), *Vegetation of Inland Waters*, Kluwer, Dordrecht. pp. 223–247.

Buchholz, K. 1981. 'Effects of minor drainages on woody species distributions in a successional floodplain forest', *Can. J. Forest Res.*, **11**, 671–676.

Cadwallader, P. L. and Lawrence, B. 1990. 'Fish' in Mackay, N. and Eastburn, D. (Eds), *The Murray*, Murray–Darling Basin Commission, Canberra. pp. 317–336.

Close, A. F. 1990. 'The impact of man on the flow regime' in Mackay, N. and Eastburn, D. (Eds), *The Murray*, Murray–Darling Basin Commission, Canberra. pp. 61–76.

Cole, P. J. 1978. 'Soils and land use of the River Murray valley in South Australia', *Proc. R. Soc. Victoria*, **90**, 167–176.

Cullen, P. 1990. 'The turbulent boundary between science and management', *Freshwater Biol.*, **24**, 201–209.

Davies, B. R. and Walker, K. F. (Eds) 1986. *The Ecology of River Systems*, W. Junk, Dordrecht. 793pp.

Geddes, M. C. 1990. 'Crayfish' in Mackay, N. and Eastburn, D. (Eds), *The Murray*, Murray–Darling Basin Commission, Canberra. pp. 303–308.

Gill, E. F. 1973. 'Geology and geomorphology of the Murray River region between Mildura and Renmark, Australia', *Mem. Nat. Mus. Victoria*, **34**, 1–97.

Graf, W. L. 1987. *Fluvial Processes in Dryland Rivers*, Springer Verlag, Berlin. 346pp.

Grubaugh, J. W. and Anderson, R. V. 1988. 'Spatial and temporal availability of floodplain habitat: long-term changes at Pool 19, Mississippi River', *Am. Midland Natural.*, **119**, 402–411.

Grubaugh, J. W. and Anderson, R. V. 1989. 'Long-term effects of navigation dams on a segment of the Upper Mississippi River', *Regul. Riv.*, **4**, 97–104.

Jacobs, T. A. 1989. 'Regulation of the Murray–Darling system' in Lawrence, B. (Ed.), *Proceedings of the Workshop on Native Fish Management*, Murray–Darling Basin Commission, Canberra. pp. 55–96.

Jacobs, T. A. 1990. 'River regulation' in Mackay, N. and Eastburn, D. (Eds), *The Murray*, Murray–Darling Basin Commission, Canberra. pp. 39–60.

Jensen, A. 'Conservation-based management: from theory to practice in River Murray Valley wetlands', *Regul. Riv.*, in press.

Junk, W. J., Bayley, P. B., and Sparks, R. E. 1989. 'The flood pulse concept in river-floodplain systems', *Can. Spec. Publ. Fisher. Aq. Sci.*, **106**, 110–127.

Lawrence, B. (Ed.) 1989. *Proceedings of the Workshop on Native Fish Management*, Murray–Darling Basin Commission, Canberra. 174pp.

Lloyd, L. N. and Walker, K. F. 1986. 'Distribution and conservation status of small freshwater fish in the River Murray, South Australia', *Trans. R. Soc. South Australia*, **106**, 49–57.

Lloyd, L. N., Puckridge, J. T., and Walker, K. F. 1991. 'The significance of fish populations in the Murray–Darling system and their requirements for survival' in Dendy, T. and Coombe, M. (Eds), *Conservation in Management of the River Murray System; Making Conservation Count*, Department of Environment and Planning, Adelaide. pp. 86–99.

Mackay, N. and Eastburn, D. (Eds) 1990. *The Murray*, Murray–Darling Basin Commission, Canberra. 366pp.

Mackay, N. J., Hillman, T. J., and Rolls, J. 1988. 'Water quality of the River Murray. Review of monitoring, 1978 to 1986', *Water Quality Report 3*, Murray–Darling Basin Commission, Canberra. 62pp.

Macumber, P. 1990. 'The salinity problem' in Mackay, N. and Eastburn, D. (Eds), *The Murray*, Murray–Darling Basin Commission, Canberra. pp. 111–126.

Magules and Partners, Smith, P., Smith, J., and Department of Conservation, Forests and Lands, Victoria. 1990. *Riparian Vegetation of the River Murray*, Murray–Darling Basin Commission, Canberra. 187pp.

McArthur, J. V. 1988. 'Aquatic and terrestrial linkages, floodplain functions' in Hook, D. and Lea, R. (Eds), *Proceedings of a Symposium on Forested Wetlands of the Southern US*, Forest Service, US Department of Agriculture. pp. 107–116.

McIntyre, S., Ladiges, P. Y., and Adams, G. 1988. 'Plant species-richness and invasion by exotics in relation to disturbance of wetland communities on the Riverine Plain, NSW', *Aust. J. Ecol.*, **13**, 361–373.

Murray–Darling Basin Commission 1991. *Chowilla Resource Management Plan, Community Consultation Program*, Murray–Darling Basin Commission, Canberra.

Murray–Darling Basin Ministerial Council 1987. *Salinity and Drainage Strategy: Background Paper 87/1*, Murray–Darling Basin Ministerial Council, Canberra. 90pp.

Murray–Darling Basin Ministerial Council 1989. *Background Papers: Murray–Darling Basin Natural Resources Management Strategy*, Murray–Darling Basin Ministerial Council, Canberra. 172pp.

National Environmental Consultancy 1988. *Chowilla Salinity Mitigation Scheme, Draft Environmental Impact Statement*, Engineering and Water Supply Department, Adelaide.

Ohlmeyer, R. G. 1991. 'Report on implications of manipulating water levels in the River Murray between Lock 1 and 10', *Murray–Darling Basin Natural Resources Management Strategy, SA River Murray Wetlands Management—Hydrological Management Project S3. Library Reference 91/11*, Engineering and Water Supply Department, Adelaide.

O'Malley, C. and Sheldon, F. (Eds) 1990. *Chowilla Floodplain Biological Study*, Hyde Park Press for Nature Conservation Society of South Australia, Adelaide. 224pp.

Petts, G. E., Möller, H., and Roux, A. L. (Eds) 1989. *Historical Change of Large Alluvial Rivers: Western Europe*, Wiley, Chichester.

Pierce, B. E. 1989. 'Improving the status of our River Murray fishes' in Lawrence, B. (Ed.), *Proceedings of the Workshop on Native Fish Management*, Murray-Darling Basin Commission, Canberra. pp. 7–18.

Pressey, R. L. 1986. *Wetlands of the River Murray below Lake Hume*, River Murray Commission, Canberra, Environmental Report 86/1. 134pp.

Pressey, R. L. 1990. 'Wetlands' in Mackay, N. and Eastburn, D. (Eds), *The Murray*, Murray-Darling Basin Commission, Canberra. pp. 167–182.

Poff, N. L. and Ward, J. V. 1989. 'Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patterns', *Can. J. Fisher. Aq. Sci.*, **46**, 1805–1818.

Poff, N. L. and Ward, J. V. 1990. 'Physical habitat template of lotic systems: recovery in the context of historical pattern of spatiotemporal heterogeneity', *Environ. Manage.*, **14**, 629–645.

Puckridge, J. T. and Walker, K. F. 1990. 'Reproductive biology and larval development of a gizzard shad, *Nematalosa erebi* (Günther) (Dorosomatinae, Teleostei), in the River Murray, South Australia', *Austr. J. Mar. Freshwater Res.*, **41**, 695–712.

Reynolds, L. F. 1983. 'Migration patterns of five fish species in the Murray-Darling river system', *Austr. J. Mar. Freshwater Res.*, **34**, 857–872.

Rowland, S. J. 1989. 'Aspects of the history and fishery of the Murray cod, *Maccullochella peeli* (Mitchell) (Percichthyidae)', *Proc. Linnean Soc. New South Wales*, **111**, 201–213.

Rutherfurd, I. 1990. 'Ancient river, young nation' in Mackay, N. and Eastburn, D. (Eds), *The Murray*, Murray-Darling Basin Commission, Canberra. pp. 17–38.

Salo, J. 1990. 'External processes influencing origin and maintenance of inland water-land ecotones' in Naiman, R. J. and Décamps, H. (Eds), *The Ecology and Management of Aquatic-Terrestrial Ecotones*, UNESCO, Paris and Parthenon, Carnforth. pp. 37-64.

Schumm, S. A. 1988. 'Variability of the fluvial system in space and time' in *Scales and Global Change*', Standing Committee on Problems of the Environment (SCOPE), Wiley, Chichester. pp. 225–250.

Southwood, T. R. E. 1988. 'Tactics, strategies and templets', *Oikos*, **52**, 3–18.

Sparks, R. E., Bayley, P. B., Kohler, S. L., and Osborne, L. L. 1990. 'Disturbance and recovery of large floodplain rivers', *Environ. Manage.*, **14**, 699–709.

Thompson, M. B. 1986. *River Murray Wetlands: their Characteristics, Significance and Management*, Department of Environment and Planning, Adelaide. 172pp.

Thoms, M. C. and Walker, K. F. 1989. 'Preliminary observations of the environmental effects of flow regulation on the River Murray, South Australia', *South Austr. Geogr. J.*, **89**, 1–14.

Thoms, M. C. and Walker, K. F. 1992. 'Channel changes related to low-level weirs on the River Murray, Australia' in Carling, P. A. and Petts, G. E. (Eds), *Lowland Floodplain Rivers: Geomorphological Perspectives*, Wiley, Chichester. pp. 235–249.

Thoms, M. C. and Walker, K. F. 1992b. 'Sediment transport in a regulated semi-arid river: the River Murray, Australia', in Robarts, R. D. and Bothwell, M. L. (Eds), *Aquatic Ecosystems in Semi-arid Regions: Implications for Resource Management*, Environment Canada, WHRI Symposium Series 7, pp 239–250.

Thoms, M. C. and Walker, K. F. 'Channel changes associated with two adjacent weir pools on the River Murray, South Australia', *Regul. Riv.*, in press.

Turner, M. G. 1989. 'Landscape ecology: the effect of pattern on process', *Annu. Rev. Ecol. System.*, **20**, 171–197.

Twidale, C. R., Lindsay, J. M., and Bourne, J. A. 1978. 'Age and origin of the Murray River and gorge in South Australia', *Proc. R. Soc. Victoria*, **90**, 27–42.

Walker, K. F. 1980. 'The downstream effects of Lake Hume on the River Murray' in Williams, W. D. (Ed.), *An Ecological Basis for Water Resource Management*, Australian National University Press, Canberra. pp. 182–191.

Walker, K. F. 1983. 'Impact of Murray-Darling Basin development on fish and fisheries', *FAO Fisheries Rep.*, **288**, 139–149.

Walker, K. F. 1985. 'A review of the ecological effects of river regulation in Australia', *Hydrobiologia*, **125**, 111–129.

Walker, K. F. 1986. 'The Murray-Darling river system' in Davies, B. R. and Walker, K. F. (Eds), *The Ecology of River Systems*, W. Junk, Dordrecht. pp. 631–659.

Walker, K. F. 1992. 'A semi-arid lowland river: the River Murray, Australia' in Calow, P. A. and Petts, G. E. (Eds), *The Rivers Handbook*, Vol. 1. Blackwell Scientific, Oxford, pp. 472–492.

Walker, K. F., Thoms, M. C., and Sheldon, F. 1992. 'Effects of weirs on the littoral environment of the River Murray, South Australia' in Boon, P. J., Calow, P., and Petts, G. E. (Eds), *River Conservation and Management*, Wiley, Chichester. pp. 271–292.

Walters, C. 1986. *Adaptive Management of Renewable Resources*, Macmillan, New York.

Ward, J. V. 1989. 'The four-dimensional nature of lotic ecosystems', *J. North Am. Benthol. Soc.*, **8**, 2–9.

Wiens, J. A. and Milne, B. T. 1989. 'Scaling of "landscapes" in landscape ecology, or, landscape ecology from a beetle's perspective', *Landscape Ecol.*, **3**, 87–96.

Woodyer, K. D. 1978. 'Sediment regime of the Darling River', *Proc. R. Soc. Victoria*, **90**, 139–147.