AQUATIC CONSERVATION: MARINE AND FRESHWATER ECOSYSTEMS, VOL. 7, 63–73 (1997)

VIEWPOINT

Irrigation development on Cooper Creek, central Australia—prospects for a regulated economy in a boom-and-bust ecology

KEITH F. WALKER[1], JIM T. PUCKRIDGE[1] and STUART J. BLANCH[1,2]
[1]*River Murray Laboratory, Department of Zoology, and* [2]*Department of Botany, The University of Adelaide, South Australia 5005, Australia*

ABSTRACT

1. We take issue with a proposal to irrigate cotton crops from Cooper Creek, as the development would be in sharp contrast to the 'boom-and-bust' character of the local environment. In dryland rivers the flow regime is influenced by aseasonal climatic phenomena like the Southern Oscillation, so that patterns are highly variable and averages are virtually meaningless. Some irrigation developments on dryland rivers have been planned during periods that were unusually wet and, as a result, present levels of water use are not sustainable.
2. Long, dry periods are the norm in dryland rivers. The biota tolerate drought and respond to occasional floods that may have long-enduring effects (riparian trees, for example, may live for centuries). All are sensitive to the rates of rise and fall and the amplitude, duration and frequency of floods. Where the flood pulse is erratic, as in Cooper Creek, species with opportunistic traits are likely to dominate. Base flows and seasonal variations imposed by irrigation use present a very different physical environment for these species. The plan to tap the Cooper headwaters would amplify the impacts because this region is a refuge for flora and fauna.
3. In general, we contend that the Cooper Creek ecosystem could not accommodate a competitor for water that is vital for its own maintenance, and that the irrigation proposal could be rationalized only in the sophistry of short-term economics. © 1997 by John Wiley & Sons, Ltd.

INTRODUCTION

Industrialists and conservationists often are portrayed in the media as natural adversaries, and the same is true of their professional colleagues, economists and ecologists. It may surprise some on both sides, and not a few politicians, to know that economics and ecology have a common root. The words are from the Greek *oikos*, meaning house or habitat, *nemein*, to manage, and *logos*, to study. The two disciplines therefore have a common interest in the environment, even if they do not share the same traditional values. If they can be reconciled, our record of managing both economic and ecological systems would surely improve.

Within economics and ecology, of course, there are conflicting ideas. Economists will recall the classic doctrine of *laissez faire*, suggesting that an economic system provides most well-being for individuals and communities when it is undisturbed by artificial stimulus or regulation. The idea is by no means discredited, but many regard it as a prescription for 'boom-and-bust' cycles, where the economy oscillates between times of plenty and hardship. Among ecologists there is a broad parallel in the division between those who see people ideally living in harmony with the ecosystems they inhabit, and those who believe that the environment should be open to regulation, or transformation, for the benefit of people.

CCC 1052–7613/97/010063–11$17.50

Received 28 November 1996
Accepted 30 December 1996

Ecological systems in desert regions behave like the boom-and-bust model in economics. Pattern and process are governed by a capricious climate; species of plants and animals dependent on *seasonal* resources are comparatively few and the biota is dominated by opportunists able to endure harsh conditions and to respond quickly when favourable conditions return. In contrast, the ecosystems of higher-rainfall regions support more biological diversity, and interactions between species (competition, parasitism, predation) play a greater role in determining patterns of distribution and abundance. Thus, the rigours of a harsh, changeable climate and the relative comforts of a more benign, regular climate produce ecosystems of quite different character. The distinction is expressed by *predictability*, from a seasonal or annual standpoint.

In 1995 a consortium of cotton growers presented to the Queensland Department of Primary Industries a proposal for irrigated cotton farming at Currareva, on the headwaters of Cooper Creek in the Queensland part of the Lake Eyre Basin. The growers proposed to withdraw 42 000 ML of water from the Cooper each summer to irrigate 3600 ha of cotton, and to construct two offstream storages (total capacity 15 000 ML) as reservoirs for low-flow years. They pointed out that the diversion would represent only 2.5% of the median annual flow (1.7 million ML).

The proposal drew concern from wetland ecologists throughout Australia, and at INTECOL's Fifth International Wetlands Conference (Perth, Western Australia; September 1996) a resolution was passed unanimously recommending rejection of the proposal. Similar recommendations came from a scientific workshop on the ecology of arid zone rivers (Windorah, Queensland; September 1996), hosted by members of the local community, and from the 35th Congress of the Australian Society for Limnology (Berri, South Australia; September 1996).

On 29 October 1996 the Queensland Minister for Natural Resources announced that the Currareva proposal would be rejected by a special Act of Parliament. He cited the 'overwhelming weight' of ecological evidence predicting environmental damage from the development. Efforts are being made to resurrect the proposal, however, and the issue is not fully resolved. This paper is modified after one presented at the meeting in Windorah. It is intended as a contribution to further debate, and as a caution over the implications of irrigated agriculture in arid lands.

The Currareva proposal provoked dismay among ecologists and conservationists because the development would be in sharp contrast to the boom-and-bust character of the regional arid environment. Economists might liken this to the concept of a stable *demand* imposed upon a wildly fluctuating *supply*. In this Viewpoint we outline some of the intrinsic features of dryland rivers and voice our concern that, even if irrigation is technically feasible in the region, it would mean catastrophic changes to the environment. Our perspective is ecological, and we do not pretend to provide an economic analysis, but as the philosophical differences between ecology and economics are more apparent than real, both viewpoints ultimately should lead to the same conclusion. We do not properly address the question of *why* the Cooper Creek environment should be protected, nor do we consider the possible impacts of agricultural chemicals and other side-effects of development. We begin from the premise that the ecological features of the river reflect its flow regime, and argue that hydrological changes would mean ecological changes.

COOPER CREEK

Cooper Creek is part of the arid Lake Eyre Basin in central Australia, one of the world's largest endorheic systems (1.14 million km^2) (Figure 1). Most rivers in the basin have very large floodplains reflecting gentle gradients, low topographic relief and occasional floods that produce complex channel and floodplain forms unlike those of humid zone rivers (e.g. Pickup, 1991). The Cooper itself rises at 230 m altitude in western Queensland, and flows south-westerly for 1523 km through increasingly arid woodland, grassland and desert to meet Lake Eyre (Figure 1). The catchment is 306 000 km^2, of which one-third is floodplain (Graetz, 1980). The gradient is 0.052 from the headwaters to the Barcoo–Thomson junction, and a mere 0.00017 from there to Lake Eyre (Kotwicki, 1986).

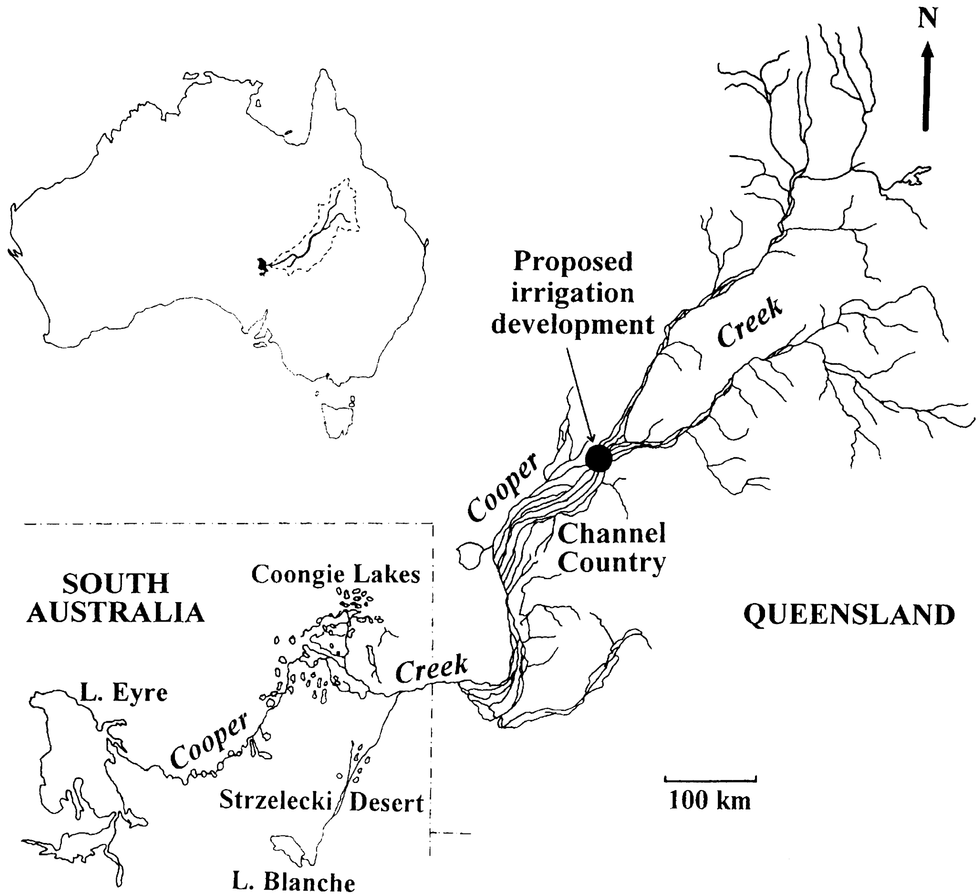

Figure 1. Cooper Creek, showing the site proposed for irrigation development (Currareva).

In the 'Channel Country' of the middle reaches (Figure 2) the Cooper has two contemporary fluvial forms: deep, narrow, anastomosing channels which transport sand and mud at moderate flows, and a vast network of braided channels that transports clay-rich mud at high flows (Nanson *et al.*, 1986). The braided pattern confers a great variety of 'edge' environments which must promote biotic diversity. Temporary lakes and vegetated sand islands occur across the floodplain.

Near the South Australian border the river is funnelled into one channel as it flows through the Innamincka Tablelands. Beyond, it spreads into the dunefields of the Strzelecki Desert, forming another mosaic of shallow freshwater and saline lakes, internal deltas, deep permanent channel reaches, flooded woodlands and grasslands, samphire claypans and other wetlands (Reid and Puckridge, 1990; Gillen and Drewien, 1993). These ponding areas are likely to act as nutrient traps (cf. Stafford Smith and Morton, 1990), and as drought refugia and sites of high productivity (Briggs, 1992; Morton *et al.*, 1995).

The discharge of the Cooper is influenced by monsoonal rainfall in summer, but is subject to extreme variations (Table 1, Figure 3) (Graetz, 1980; Kotwicki, 1986). Transmission losses are high: only 30% of overbank flows reach Innamincka, hence the Coongie Lakes system, and most is retained in the Channel Country (Knighton and Nanson, 1994). Only in extreme floods (roughly one year in six: Kotwicki, 1986) does water reach Lake Eyre. In times of flood the region supports immense populations of fish, waterbirds and other animals (e.g. Ruello, 1976; Kingsford and Porter, 1993).

Figure 2. Braided channels of the ‘Channel Country’ in the middle reaches of Cooper Creek, Queensland. The floodplain is an oasis of permanent waterholes (top right) and semi-permanent channels in semi-arid desert (top left). [Photo: SJB]

The Lake Eyre rivers presently are unregulated and subject only to minor diversions for stock and domestic consumption. The Currareva proposal, however, would establish a precedent for regulation throughout the basin. Even apparently minor reductions in flow would be amplified by the low gradient and complex channel, reducing the depth and extent of downstream flooding. Claims by developers that vast volumes of ‘surplus’ water exist, only to be wasted in the desert lakes and floodplains, are unsupportable because infrequent, unpredictable flooding is vital for the growth and reproduction of the regional aquatic plants and animals. The Coongie Lakes are listed under the Ramsar Convention for Protection of Wetlands of International Importance and, with Lake Eyre, have World Heritage value (Morton *et al.*, 1995).

Table 1. Statistics (ML) for a gauge at Currareva (Cooper Creek, Queensland), operated from 1939–1986. Yearly and monthly data are based on 39 years of complete records and 536 monthly records, respectively. Original data from Queensland Department of Primary Industries.

	Yearly	Monthly
Minimum	0	0
Maximum	13 140 391	6 536 422
Mean	2 955 828	256 485
Median	1 701 788	753
Mode	(none)	0
Skew	1.45	4.98

WHAT MAKES ARID-ZONE RIVERS DIFFERENT?

Hydrology and water resource management

Some dryland rivers, including Cooper Creek, flow entirely in arid or semi-arid catchments; others rise in well-watered areas and flow for long distances through catchments that contribute little runoff. Notwithstanding their diversity, these rivers have a number of unifying hydrological features (Molles *et al.*, 1992). For example, responses to variations in rainfall in xeric catchments tend to be non-linear,

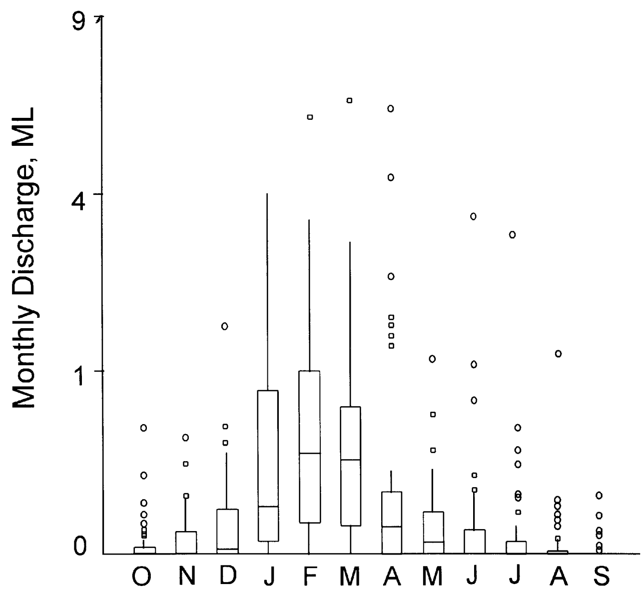

Figure 3. The hydrograph of Cooper Creek at Currareva, Queensland, from 1939–1986 (see also Table 1). The data are ML passing the gauge each month ($n = 536$); the axis is square-root transformed so that the actual variability appears considerably diminished. The temporal axis corresponds to a 'water year' (Oct–Sep), often used in Australian water resource statistics where irrigation is concerned.
These are Box whisker plots (cf. Wilkinson, 1990). Each monthly complement of data appears as a box defined by upper and lower *hinges*. The median divides the data into halves, and the hinges (cf. quartiles) again split the remainder into halves. The difference between the upper and lower hinges is the *Hspread* (cf. inter-quartile range). The *whiskers* indicate the range of values within 1.5 (Hspread) of the hinges. Inner and outer *fences* are defined by zones within 1.5 and 3 Hspreads of the hinges, respectively. *Outside values* are beyond the inner fences, and *far outside values* (open circles) are beyond the outer fences.

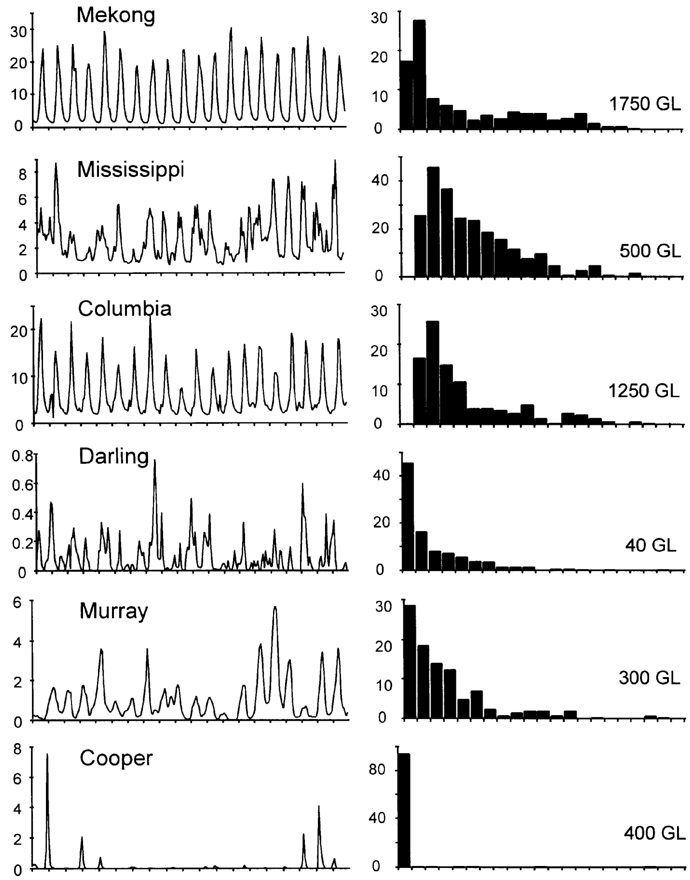

Figure 4. Hydrographs and relative flow-frequency distributions (peak monthly flows, GL) for rivers in various climatic regions over 20-year intervals that, so far as possible, are from periods before intensive flow regulation commenced. Note that the vertical scales are not similar, and that some small registrations are not distinguishable (the frequency data for the Cooper, for example, do not appear to sum to 100 per cent). The data are from gaugings published by UNESCO, and are described more fully by Walker *et al.* (1995).

compared with the more nearly linear responses of mesic catchments, so that the effects of climatic changes may be disproportionate. Further, the annual discharges of xeric basins tend to decrease with increasing basin area, whereas those of mesic basins tend to increase (cf. Finlayson and McMahon, 1988). In dryland rivers the dominant rhythms are not wholly seasonal or annual but are related, at least in part, to weather anomalies associated with the El Niño Southern Oscillation (ENSO). The ENSO signal appears in the rainfall patterns of Australia, India and North and South America, and there have been perhaps 20 significant episodes in the past century (Quinn and Neal, 1987; Ropelewski and Halpert, 1987). In Australia these effects are compounded by other atmospheric phenomena, and by the effects of evaporation on the conversion of precipitation to runoff (McMahon *et al.*, 1992; Simpson *et al.*, 1993).

Figure 4 compares hydrographs of *unregulated* monthly flows for Cooper Creek and rivers from other climatic regions over periods of 15–25 years. Clearly, the discharges of the arid-zone streams are more variable than those of the other rivers, and the skewness of the distributions indicates that even *median* flow data for dryland rivers may be misleading. The proposal to regularly withdraw 2.5% of the median annual flow from the Cooper is problematic because in dry years this may represent *all* of the flow. In fact, in both hydrological and ecological applications the probabilities of extreme events like flood and drought may have more relevance than measures of central tendency or variability (cf. Gaines and Denny, 1993). The lingering influence of ENSO means that climatic patterns in successive changes may not be independent, but inclined toward flood- and drought-dominated sequences. The proponents for the Currareva development used flow records for the years 1939–1986 (Table 1, Figure 3), which included several major floods. In the decade since there have been three major floods.

The hydrological variability of dryland rivers makes the detection of trends difficult, if not impossible, even when there are good historical records. For the Murray–Darling river system (100-yr median discharge 8489 GL; mean 10 090 GL), even a 50-year record may not be representative (Walker *et al*., 1995). Several large dams were constructed during the 1950s, when there was a series of floods and a corresponding rise in diversions (Close, 1990) associated with Soldier Settlement schemes to develop new irrigation areas. The expansion was underwritten by operational changes as well as engineering works (Jacobs, 1990). Regulation has fundamentally changed the patterns of flow (Maheshwari *et al*., 1995): annual diversions in 1930–1991 increased from 3000 to 11 000 GL, and the median natural flow (10 968 GL) now is exceeded only 8% of the time. Efforts are now being made to prevent further diversions (MDBMC, 1995).

The dilemma is by no means uniquely Australian: in the United States the 1922 Colorado River Compact governs water allocations based on estimates of annual discharge in 1905–1922, but later analyses showed that this was the wettest period for 400 years (Coats, 1984). In both the Colorado and Murray systems it appears that present levels of water use are not sustainable, although demands for water have continued to escalate. In ecology, as in economics, a regulated supply cannot meet an unregulated demand.

Hydrological analyses are not wholly satisfactory in the present context, as the established techniques reflect the concerns of civil engineering (storage and transport of water) rather than environmental science (Walker *et al*., 1995). They tend to emphasize *discharge* as a currency for modelling and comparison, whereas *stage* (water levels) may be more meaningful in ecological investigations (Gustard, 1985; Walker *et al*., 1992). Further, the resolution of hydrologic models often is too coarse to be useful in environmental management: water-level fluctuations of as little as 10 cm may be critical for wetland plants (Blanch *et al*., 1994). On the Cooper these factors are compounded by the geomorphological complexity of the floodplain.

Geomorphology

The emphasis given to rivers as conduits for water often overshadows their significance in the transport of sediments. Rivers with variable flow behaviour tend toward a complex channel geometry, including in-channel benches and floodplain terraces (Graf, 1987). Dam and weir construction typically causes localized erosion and siltation and changes the shape of the channel, and typically 100–200 years are required for a river to regain a balance in the distribution and transport of sediment (Petts, 1987). The physical responses of the lower River Murray to weir construction are still incomplete, however, after 70 years (Thoms and Walker, 1993). Hundreds of years may be an unrealistic time scale for economics and resource planning, but it is the scale on which some geomorphic processes occur in dryland systems.

Biological responses to variability

The biological consequences of flow regulation on the Murray are reasonably well documented (e.g. Walker and Thoms, 1993; Gehrke *et al*., 1995; Blanch *et al*., 1996). In large rivers the relation between biology and hydrology is encapsulated by the *Flood Pulse Concept* which recognizes, *inter alia*, that riverine communities respond to variations in the rates of rise and fall and the amplitude, duration, frequency and regularity of floods (Junk *et al*., 1989). The spatial and temporal parameters of the flood pulse are especially important for the flora and fauna of arid-zone rivers (Walker *et al*., 1995). For example:

- *Variability in timing*: Opportunism and flexibility arguably are adaptations to unpredictable environments (Baird *et al*., 1987). Where the periodicity of the flood pulse is highly variable, species with flexible life cycles are likely to have a selective advantage (e.g. Cambray, 1991).
- *Variability in rates of rise and fall*: Variable rates of rise and fall of discharge and water-levels change the littoral hydraulic environment, affecting fish and invertebrates (Gore, 1994). Oscillations within the channel may maintain biofilms (attached algae, bacteria, fungi) in a productive early stage of succession that may be vital for grazing invertebrates (e.g. Sheldon and Walker, 1993).
- *Variability in frequency*: Rare extreme floods and droughts may have enduring effects on populations of longer-lived species, including trees with life times of hundreds of years (Friedel *et al*., 1993). Species dependent on erratic floods for recruitment are likely to have an irregular population age profile (Quiros and Cuch, 1989). Environments with different flood pulse frequencies are likely to differ in species richness and abundance (Puckridge and Walker, 1996).
- *Spatial variation*: In Cooper Creek and other arid-zone systems transmission losses are so high that flood volumes and frequencies diminish with distance downstream (Knighton and Nanson, 1994), and aquatic faunas show corresponding declines in diversity (Puckridge and Drewien, 1988).

The flood pulse, therefore, is a key variable in organizing, maintaining and sustaining dryland river ecosystems. The pulse is erratic in time and space, and the evolutionary response has been to encourage opportunistic life cycles and broad tolerances among a comparatively low diversity in major groups of native plants and animals. The physical environment is no less a product of the variable flow regime. It follows that changes to the flow regime, through regulation or diversion, will change the ecosystem.

THE IRRIGATION PROPOSAL

We are unaware of any place in the world where a similar proposal has been implemented without cost to the environment. Indeed, irrigated agriculture has a 5000-year tradition of dispoiling its environment and there are abundant examples, *particularly* in modern times, of entire regions laid waste by improper land use. The problems of the Murray–Darling Basin are a case in point, exacerbated by the persistent use of techniques like furrow and overhead irrigation that, whilst least expensive in economic terms, are most expensive in environmental terms. Cotton irrigation developments on the Darling River have changed the river and riparian landscape, but their environmental costs, in terms of flow diversions, chemical use and impacts on the native biota, are yet to be calculated. All such regional industries have grown from 'small-scale' developments like that proposed for Currareva. Throughout the Murray–Darling Basin the demand for irrigation water has increased in the manner of a *ratchet*, increasing but never relaxing, in response to the economic imperative for continued growth. Yet Australia already has paid too high a price for its indifference to the long-term welfare of the environment, and is left with an indelible legacy.

Present techniques and strategies for environmental flow management and monitoring are neither sensitive nor sophisticated enough to provide adequate safeguards. Again, in the Murray–Darling Basin there is some belated awareness that environmental degradation can be halted only by returning substantial amounts of water to the environment. Recent experiments in environmental flow management, however, have been within constraints determined by irrigation requirements (e.g. Blanch *et al*., 1996). If environmental allocations are to be successful an appropriate flow *regime* (as opposed to *ad hoc* allocations) will need to be administered to maintain recruitment in populations of native plants and animals. In the meantime the Murray–Darling ecosystem is demonstrating considerable stress, and changes undoubtedly will intensify and accelerate within the next one or two decades.

In the long term there can be no guarantee that the hydrological regime of systems like Cooper Creek can provide a reliable, seasonal supply of water. Tapping the *headwaters* of the Cooper may marginally increase the prospects for an exploitable supply in some periods, but would increase the impact of development on flows in the system as a whole. As suggested earlier, the headwaters tract is the core of the ecosystem, producing most of the water and harbouring much of the biological diversity.

Storage is problematic because annual losses to evaporation are approximately 3 m (Kotwicki, 1986), and reservoirs in the region must have a high surface area to volume ratio. A fixed allocation is not appropriate because, as pointed out earlier, an apparently small part of the median annual discharge may account for all of the flow in some years. The most sustainable form of water use may be to harvest water during large floods, to allow small floods to pass, and to relax the demand completely during times of drought. However, as no water is truly 'surplus' to environmental needs in rivers like the Cooper, abstractions during even large floods could be detrimental. Considering the irrigation industry's requirements for short-term profitability and a guaranteed water supply, increased demand for access to smaller flows would be inevitable.

CONCLUSION

Just as regulation is the antithesis of a free-market economy, it is alien to a boom-and-bust ecology. Whilst terms like 'sustainable development' and the 'precautionary principle' are part of the rubric of every government agency entrusted with environmental management, it is difficult to see how even such elastic concepts as these could sensibly be applied in arid zone river systems like the Cooper. Our judgement is that such proposals can be rationalized only in the sophistry of short-term economics. Systems like Cooper Creek cannot accommodate a major competitor for water that is vital for maintenance of the ecosystem. It is in the nature of all ecosystems to have some capacity to absorb change, but once that capacity is exceeded the system will change rapidly and irrevocably. The decision of the Minister to reject the Currareva proposal is a sign that we might yet learn to live within those limits. It is also some assurance that public action by ecologists can sway government policy, even against short-term economic values.

REFERENCES

Baird, D. J., Linton, L. R. and Davies, W. 1987. 'Life-history flexibility as a strategy for survival in a variable environment', *Functional Ecology*, **1**, 45–48.

Blanch, S. J., Walker, K. F. and Ganf, G. G. 1994. 'An evaluation of the River Murray Hydraulic Model and its value in environmental flow management', in *Proceedings of the Environmental Flows Seminar*, Australian Water & Wastewater Association, Canberra, 17–21.

Blanch, S. J., Burns, A., Vilizzi, L. and Walker, K. F. 1996. *Ecological Effects of Shallow Winter–Spring Flooding in the River Murray, 1995: Observations on Organic Matter, Plant Growth and Macro-Invertebrate Abundance, with Recommendations for Flow Management*. Report to Natural Resources Management Strategy, Murray–Darling Basin Commission, Canberra.

Briggs, S. V. 1992. 'Wetlands as drylands: a conservation perspective', *Bulletin of the Ecological Society of Australia*, **22**, 109–110.

Cambray, J. A. 1991. 'The effects of fish spawning and management implications of impoundment water releases in an intermittent South African river', *Regulated Rivers: Research & Management*, **6**, 39–52.

Close, A. 1990. 'The impact of man on the natural flow regime', in Mackay, N. and Eastburn, D. (Eds), *The Murray*, Murray–Darling Basin Commission, Canberra, 61–74.

Coats, R. 1984. 'The Colorado River: river of controversy', *Environment*, **26**, 6–13, 36–39.

Finlayson, B. L. and McMahon, T. A. 1988. 'Australia *v* the world: a comparative analysis of streamflow characteristics', in Warner, R. F. (Ed.), *Fluvial Geomorphology of Australia*, Academic Press, Sydney, 17–39.

Friedel, M. H., Pickup, G. and Nelson, D. J. 1993. 'The interpretation of vegetation change in a spatially and temporally diverse arid Australian landscape', *Journal of Arid Environments*, **24**, 241–260.

Gaines, S. D. and Denny, M. W. 1993. 'The largest, smallest, highest, lowest, longest and shortest: extremes in ecology', *Ecology*, **74**, 1677–1692.

Gehrke, P. C., Brown, P., Schiller, C. B., Moffatt, D. B. and Bruce, A. M. 1995. 'River regulation and fish communities in the Murray–Darling river system, Australia', *Regulated Rivers: Research & Management*, **11**, 363–375.

Gillen, J. S. and Drewien, G. N. 1993. *A Vegetation Survey of the Kanowana Wetlands, Cooper Creek, South Australia*. South Australian Department of Environment & Land Management, Adelaide.

Gore, J. A. 1994. 'Hydrological change', in Calow, P. and Petts, G. E. (Eds), *The Rivers Handbook*, Vol. 2, Blackwell Scientific, Oxford, 33–54.

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

Graetz, R. D. 1980. *The Potential Application of Landsat Imagery to Land Resource Management in the Channel Country*, CSIRO Division of Land Resources Management, Perth.

Gustard, A. 1985. 'The characterisation of flow regimes for assessing the impact of water resource management on river ecology', in Lillehammer, A. and Saltveit, S. V. (Eds), *Regulated Rivers*, Universitetforslaget AS, Oslo, 53–60.

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

Junk, W. J., Bayley, P. B. and Sparks, R. E. 1989. 'The Flood Pulse Concept in river-floodplain systems', *Canadian Special Publication of Fisheries & Aquatic Sciences*, **106**, 110–127.

Kingsford, R. T. and Porter, J. L. 1993. 'Waterbirds of Lake Eyre, Australia', *Biological Conservation*, **65**, 141–151.

Knighton, A. D. and Nanson, G. C. 1994. 'Flow transmission along an arid zone anastomosing river, Cooper Creek, Australia', *Hydrological Processes*, **8**, 137–154.

Kotwicki, V. 1986. *Floods of Lake Eyre*, Engineering & Water Supply Department, Adelaide.

Maheshwari, B. L., Walker, K. F. and McMahon, T. A. 1995. 'Effects of regulation on the flow regime of the River Murray, Australia', *Regulated Rivers: Research & Management*, **10**, 15–38.

McMahon, T. A., Finlayson, B. A., Haines, A. T. and Srikanthan, R. 1992. *Global Runoff—Continental Comparisons of Annual Flows and Peak Discharges*, Catena Verlag, Cremlingen, Germany.

Molles, M. C. Jr., Dahm, C. N. and Crocker, M. T. 1992. 'Climatic variability and streams and rivers in semi-arid regions', in Robarts, R. D. and Bothwell, M. L. (Eds), *Aquatic Ecosystems in Semi-Arid Regions: Implications for Resource Management*, NHRI Symposium Series 7, Environment Canada, Saskatoon, 197–202.

Morton, S. R., Doherty, M. D. and Barker, R. D. 1995. *Natural Heritage Values of the Lake Eyre Basin in South Australia: World Heritage Assessment*, CSIRO Division of Wildlife & Ecology, Canberra.

MDBMC. 1995. *An Audit of Water Use in the Murray–Darling Basin, June 1995*, Murray-Darling Basin Ministerial Council, Canberra.

Nanson, G. C., Rust, B. R. and Taylor, G. 1986. 'Coexistent mud braids and anastomosing channels in an arid-zone river: Cooper Creek, central Australia', *Geology*, **14**, 175–178.

Petts, G. E. 1987. 'Time scales for ecological change in regulated rivers', in Craig, J. F. and Kemper, J. B. (Eds), *Regulated Streams: Advances in Ecology*, Plenum, New York, 257–266.

Pickup, G. 1991. 'Event frequency and landscape stability on the floodplain systems of arid Central Australia', *Quaternary Science Reviews*, **10**, 463–473.

Puckridge, J. T. and Drewien, M. 1988. 'The aquatic fauna of the Northwest Branch of Cooper Creek', in Reid, J. and Gillen, J. (Eds), *The Coongie Lakes Study*, Department of Environment & Planning, Adelaide, 69–108.

Puckridge, J. T. and Walker, K. F. 1996. *Time-Share Flooding of Aquatic Ecosystems—Coongie Lakes Database*, River Murray Laboratory, Department of Zoology, University of Adelaide and Department of Natural Resources & Environment, Melbourne.

Quinn, W. H. and Neal, V. T. 1987. 'El Niño occurrences over the past four and a half centuries', *Journal of Geophysical Research*, **14**, 449–461.

Quiros, R. and Cuch, S. 1989. 'The fisheries and limnology of the Lower Plata Basin', *Canadian Journal of Fisheries and Aquatic Sciences*, **106**, 429–443.

Reid, J. R. W. and Puckridge, J. T. 1990, 'Coongie Lakes', in Tyler, M. J., Twidale, C. R., Davies, M. and Wells, C. B. (Eds), *Natural History of the North East Deserts*, Royal Society of South Australia, Adelaide, 119–131.

Ropelewski, C. F. and Halpert, M. S. 1987. 'Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation', *Monthly Weather Review*, **115**, 1606–1626.

Ruello, N. W. 1976. 'Observations on some massive fish kills in Lake Eyre', *Australian Journal of Marine & Freshwater Research*, **27**, 667–672.

Sheldon, F. and Walker, K. F. 1993. 'Pipelines as a refuge for freshwater snails', *Regulated Rivers: Research & Management*, **8**, 295–299.

Simpson, H. J., Cane, M. A., Herczeg, A. L., Zebiak, S. E. and Simpson, J. H. 1993. 'Annual river discharges in southeastern Australia related to El Niño Southern Oscillation forecasts of sea surface temperatures', *Water Resources Research*, **29**, 3671–3680.

Stafford Smith, D. M. and Morton, S. R. 1990. 'A framework for the ecology of arid Australia', *Journal of Arid Environments*, **18**, 225–278.

Thoms, M. C. and Walker, K. F. 1993. 'Channel changes associated with two adjacent weirs on a regulated lowland alluvial river', *Regulated Rivers: Research & Management*, **8**, 271–284.
Walker, K. F., Sheldon, F. and Puckridge, J. T. 1995. 'A perspective on dryland river ecosystems', *Regulated Rivers: Research & Management*, **11**, 85–104.
Walker, K. F. and Thoms, M. C. 1993. 'Environmental effects of flow regulation on a semi-arid lowland river: the River Murray, South Australia', *Regulated Rivers: Research & Management*, **7**, 103–119.
Walker, K. F., Thoms, M. C. and Sheldon, F. 1992. 'Effect of weirs on the littoral environment of the River Murray, South Australia', in Boon, P. J., Calow, P. A. and Petts, G. E. (Eds), *River Conservation and Management*, John Wiley, Chichester, 270–293.
Wilkinson, L. 1990. *SYGRAPH: The System for Graphics*. SYSTAT Inc., Evanston, Illinois.

