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ECOLOGICAL PERSPECTIVES ON REGULATION AND WATER ALLOCATION FOR THE ORD RIVER, WESTERN AUSTRALIA

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ABSTRACT

Water management agencies throughout Australia are attempting to find a balance between the water requirements of ecological and socio-economic environments as part of a holistic approach to managing flow-dependent river ecosystems. Environmental water provisions are under consideration for the Ord River in far northern Western Australia. This river has been regulated for irrigation and there are plans for substantial expansion. Like other semi-arid and tropical rivers, however, the hydrology of the Ord River is highly variable and unpredictable, and therefore, proportionate water release strategies for the environment that are based on average monthly flows are unsuitable. Regulation continues to produce pronounced ecological changes throughout the river system as the impacts of flow regime are negated. There is a dichotomy in optimal flow regimes for the contrasting management aspirations of ecological restoration based on low seasonal flows, and the dilution flows required for the drainage of agricultural effluent. Whilst current agricultural land and water management practices continue, the two cannot coincide, and consequently, a decision should be made regarding which environmental water allocation holds the primary value. Such a decision would guide the appropriate dry season flow regime on the lower Ord River. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: river regulation; flow variability; flow regimes; environmental water provisions; irrigation

INTRODUCTION

In many parts of the world, management for multiple use of limited environmental resources, including water, has been actively pursued as a means of commodity rationalization, and to increase their total economic value (Ward and Lynch, 1997), although the latter is often poorly defined in short-term ways. Kingsford (2000) contended that Australian wetland policies dealt poorly with the importance of river flows because they failed to identify trade-offs between diversions to humans (socio-economic values) and flows to wetlands (ecological values), which for this paper, we define as the broader fluvial system incorporating the channel and its floodplain in a longitudinal and lateral sense (after Semeniuk, 1987). An attempt to rectify this lack of integration is in the form of a holistic approach to the maintenance of flow-dependent ecosystems (Arthington *et al*., 1992), and is based on current scientific understanding of the processes governing the wider river ecosystem (*sensu* Lewis *et al*., 1990) and the effects of disturbance (Resh *et al*., 1988; Sparks, 1992). Simply, the holistic approach promotes a hydrologic management regime where water release strategies use the coefficients of variation for daily flows in each month to guide when releases should occur.

To achieve a balance between the water requirements of ecological and socio-economic environments, water management agencies throughout Australia are attempting to adopt a holistic approach to the management of regulated river systems and their wetlands (e.g. Water and Rivers Commission, 1999a). This hydrologic management model represents a shift from prevailing assertions that water returning to the oceans was 'wasted' (e.g. Kingsford, 2000). At least two factors impede the allocation of appropriate environmental water to rivers that display high flow variability. First, Walker *et al*. (1997) demonstrated that for rivers displaying highly variable flow patterns, skewed flow distributions make the detection of trends difficult, even where 50 years

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of data are available. Average flows become rather meaningless, and monthly flow allocations based on measures of central tendency are probably unrepresentative of the historic hydrograph. Second, experimental determination of appropriate environmental flows on Australia's largest and most regulated semi-arid river, the Murray, has been made within the pre-existing (and increasing) constraints of irrigation requirements (Blanch *et al*., 1996).

Flow essentially 'drives' sediment transport and, in fluvially dominated systems, shapes the river channel and consequently the structure of riparian landscapes (Young, 1999). This can result in multiple successional stages (e.g. Malanson, 1993). Timing, frequency and level of flooding disturbance are also important determinants of vegetation dynamics in the riparian zone. How natural flow disturbance shapes community structure can depend on the frequency, magnitude and predictability of the disturbance (Sousa, 1984). The ecological significance of the river flood pulse has been argued by Junk *et al*. (1989) and Bayley (1991) to be where the rate of increase in the rise of the hydrograph concurs with an increase in mean water surface area as the moving littoral zone traverses the land causing an expansion of available food and habitat resources. The importance of fluctuations in river height and breadth (i.e. flooding) is beyond dispute. In dry regions, however, the significance of flooding is at least matched by the importance of flow variability (Walker *et al*., 1995), and the effect of variable flow becomes a prominent feature of the physical habitat (Poff and Ward, 1990). Variable and often unpredictable hydrologies are characteristic of many Australian rivers, especially in the semi-arid and tropical zones (Mallen-Cooper, 1998; Puckridge *et al*., 1998; Thoms and Sheldon, 2000). In these regions, river flow patterns are neither wholly seasonal nor annual, but are related to a combination of atmospheric phenomena (e.g. monsoonal and/or El Niño Southern Oscillation influences), and the effects of evaporation on the conversion of precipitation to runoff (Walker *et al*., 1997). Consequently, the hydrographs of these watercourses typically display 'flashy' peaks and long periods of little or no flow (Petts, 1984), resulting in the evolution of opportunistic and flexible life history strategies, and irregular recruitment patterns (e.g. Baird *et al.,* 1987; Pettit and Froend, in press).

Relationships between flows and flooding, when combined with historical flow data (usually based on 100 years of information where available), can help determine the impacts of dams and water diversions on rivers and their wetlands (Kingsford and Thomas, 1995). Generalizations of gross environmental changes due to seasonal flow alteration by river regulation are possible, although an understanding of flow-related problems involving spatial and temporal scale remain limited because historical data are often lacking, and sampling is invariably difficult (Walker *et al*., 1995). Ideally, hydrological models should predict flooding and drying patterns of riverine habitats, and be linked to ecological processes and biotic cycles so that management practices are improved (see Walters and Holling, 1990), but the models themselves have been primarily developed for delivering water for human purposes (e.g. irrigation). This results in few opportunities to review the predictive power of hydrologic models (Thoms and Cullen, 1998), or their ecological relevance (Kingsford, 2000).

Junk *et al*. (1989) cautioned that the flood pulse concept might not be easily transferred to regions of high flow variability, because organisms might not be able to adapt to such habitat shifts; however, Walker *et al*. (1995) suggested that a flow-based model would have an implicit capability to measure and predict the effects of river regulation, provided that the concurrence of hydrological and seasonal cycles was qualified. They argued that the effects of flow regulation are largely due to the processes of water supply and demand operating at different scales; daily and seasonal demands on the resource are largely driven by non-seasonal factors. For example, irrigated agricultural water demand may impose a seasonal stability on a river by increasing the frequency of some flows (to meet 'dry season' water demands) and decreasing others (saving 'surplus wet season' water for the next growing season). Moreover, there is often a seasonal reversal whereby dry season flows are augmented for reasons including the transport of agricultural effluent (Doupé *et al*., 1998), and rainy season flows are depleted. The changed hydrologic regime is likely to transform the physical, chemical and biological characteristics of the river (Walker *et al*., 1995).

The Ord River, in the semi-arid tropics of northwestern Australia's Kimberley region, has been twice dammed for irrigated agriculture. The Ord River Irrigation Area (ORIA) is a 'flow-through' irrigation scheme, comprising about 15 000 ha of land on the Ivanhoe and Packsaddle Plains near the township of Kununurra (Figure 1). Irrigation waters are diverted from Lake Kununurra and delivered by a gravity feed system of

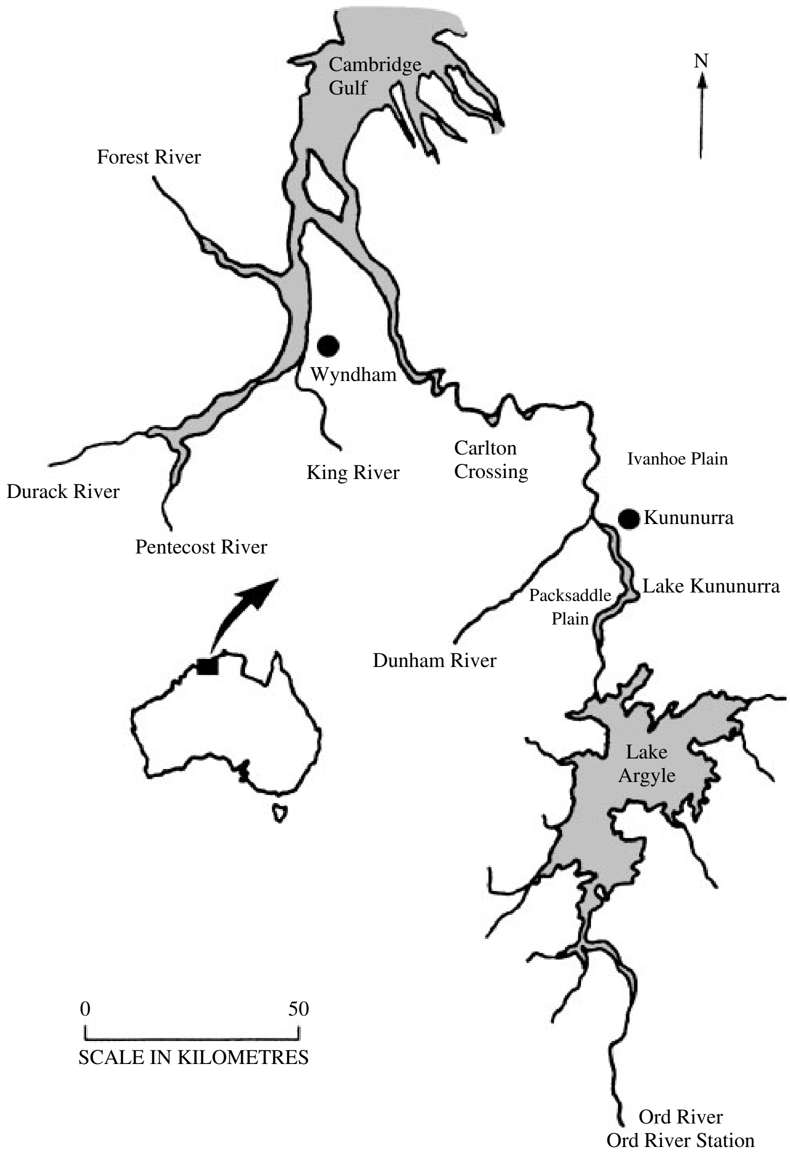

Figure 1. Locality plan of the Ord River district

channels. Agricultural effluent returns to the lower Ord River (i.e. below the Lake Kununurra diversion dam) via a drainage network. Maintenance of the hydraulic head necessary for the delivery of irrigation water restricts variation in downstream flow patterns (Doupé and Bird, 1999). A fourfold expansion of irrigated land is proposed (Anon., 1997a). The expansion will increase irrigated water demand from present levels of about 160 Gl per annum (Doupé *et al*., 1998) to between 1200 and 1500 Gl per annum (Anon., 1997b; Water and Rivers Commission, 1999b). Determination of appropriate environmental water flows for the Ord River is yet to be decided, and provides the focus of this paper.

A SHORT HISTORY OF THE ORD RIVER IRRIGATION PROJECT

Forrest's (1880) speculative report of favourable country for 'pastoral and agricultural experiments' focused much attention on northwestern Australia; however, it was some years before Despeissis (1913) pursued the possibility of irrigated agriculture on the Ord River. Walker (1992) contends that despite many decades of agronomic investigation, political indecision and broader than usual public discussion, the best policy decisions were not made for the Ord scheme. For example, Durack (1945) cautioned that substantial sheet and gully erosion in the 46 000 km^2 Ord River catchment would probably lead to the subsequent sedimentation of any irrigation water reservoir, and Jenkins (1945) warned of the potential for insect, bird and climatological problems if crops were grown in the region.

The Lake Kununurra irrigation diversion dam was constructed on the Ord River and farming (predominantly cotton) began on the ORIA in 1963. Despite the predictions of Thomson (1962) that the application of chlorinated hydrocarbons would alleviate any insect pest problems, and the optimistic agronomic forecasts of Cannegeiter (1964), agricultural production on the Ord collapsed entirely in 1974 (Whitaker, 1979). The Ord River Dam (subsequently named Lake Argyle), the main irrigation supply dam, had only just been completed following protracted argument by the Western Australian Government that it was integral to the project's success (Graham-Taylor, 1982). This dam regulated a further 55 km of the Ord River to form Lake Kununurra, and inundated the confluence of several significant rivers in the formation of Lake Argyle (Figure 1).

The Ord River irrigation project, like other irrigation schemes in Australia, is heavily subsidized and unable to meet the full costs of establishment (Walker, 1992). A 1993 economic evaluation stated: 'under certain conditions, further development of the ORIA would generate a benefit well beyond the minimum considered necessary to justify a new investment in irrigation' (Anon., 1994). More than 30 years after commissioning, the scheme has diversified in field, fodder and horticultural crops. Buoyed by this 'success', the Western Australian and Northern Territory Governments agreed to proceed with a fourfold expansion of the ORIA (Anon., 1994). The storage capacity of Lake Argyle has subsequently been increased from 5 797 000 Ml to 10 700 000 Ml (Kingsford, 2000) and hydroelectric power is being generated at the outlet. Operational problems continue to hamper the project. High sediment loads due to sheet and gully erosion in the Ord River catchment are reducing the water storage capacity of Lake Argyle (Wark, 1987; Wasson *et al.*, 1994), and inappropriate land and water management practices within the ORIA have resulted in a variety of health and resource management issues (e.g. Rosich and Partridge, 1988; Anon., 1989; Jones, 1997; Doupé, 1997; Doupé *et al.*, 1998).

FLOW VARIATION OF THE ORD RIVER

Natural flows upstream of the dams are highly seasonal. At an unregulated part of the river (Ord River Station; Figure 1), available data show that most large discharges (i.e. 98% of flows >500 m^3 s^{-1}) occur during the wet season (November to March); however, in 1988, highest flows occurred in October (Figure 2). The magnitude of peak flows is highly variable. Maximum discharges exceeding 5000 m^3 s^{-1} have occurred seven times in a 22-year period, particularly January 1980 (23 500 m^3 s^{-1}) and February 1993 (14 600 m^3 s^{-1}). Contrasting with these very large flow events are several years (1984/85, 1989/90 and 1991/92) where flows were low (<500 m^3 s^{-1}), and various times during the 'wet' season (March 1988, November and December 1991, and March and November 1992) when no flows were recorded.

On a worldwide scale, flows on the Ord River are highly variable, with only the arid zone rivers having a higher coefficient of variation (the ratio of standard deviation to mean) for monthly discharges within Australia (Table I). Walker *et al.* (1995) and Puckridge *et al.* (1998) contend that high skewness of monthly flows, as with the Ord River, exaggerates the coefficient of variation because the mean and standard deviation are affected. They argue that measures of variability based on the mean are unrealistic for time series data of less than 50 years, and suggested the median and spread (interquartile range divided by the median) provided a better, but not absolute, indication of variability in a river system. Comparisons with other large rivers show the Ord River has the lowest mean monthly flow and one of the most variable flow regimes (Table I).

Predictability (P), constancy (C) and contingency (M) are also useful indices of seasonal patterns in river flow (Colwell, 1974). Indices vary between zero (unpredictable) and 1 (totally predictable). At the predictable end, there are totally predictable flows ($P = 1$), predictable and identical flows across all months ($C = 1$),

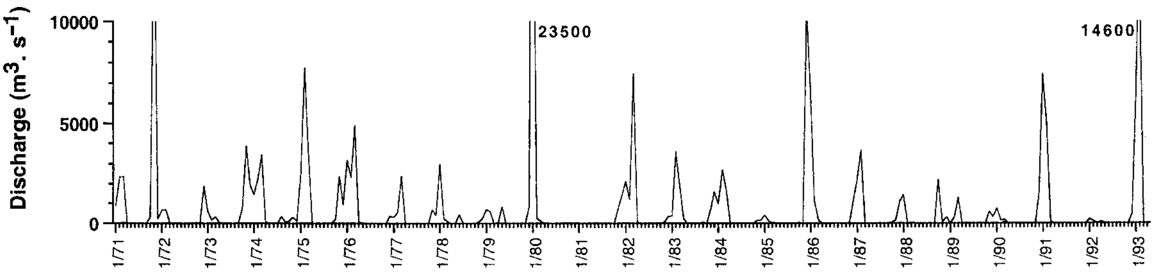

Figure 2. Maximum monthly discharges on the unregulated Ord River between 1971 and 1993 at Ord River Station (Water and Rivers Commission Gauging Station No. 809316). No data were available for 1981

Table I. Summary statistics of Australian and world rivers from different climate zones showing mean monthly discharges (m^3 s^{-1}) over 15–25 year periods (modified from Walker *et al.*, 1995)

Country	River	Climate[a]	Min.	Max.	Mean	CV[b]	Skew	Median	Spread[c]
Australia	Ord	Trop, D	0	1285	53	2.86	5.16	1.42	8.87
Australia	Cooper Ck	W/Temp, A	0	7593	142	4.54	8.51	6	4.3
Australia	Diamantina	W/Temp, A	0	5955	101	4.66	9.04	1	40.66
Australia	Darling	W/Temp, SA	0	764	97	1.27	2.13	47	2.7
Australia	Murray	W/Temp, SA	6	5710	975	1.06	2.06	646	1.48
Thailand	Mekong	Trop, D	1006	30 582	8394	0.94	0.99	4390	2.87
Mali	Niger	Trop, D	30	2658	1161	0.71	0.06	1158	1.4
Romania	Danube	W/Temp	1370	13 300	5121	0.4	0.74	4920	0.6

[a] Trop, tropical; D, dry; W, warm; Temp, temperate; SA, semi-arid; A, arid
[b] Coefficient of variation.
[c] Spread = ratio of interquartile range to the median.

and predictable but different flows every month ($M = 1$). Seasonality can also be indicated by M/P. Flow data obtained from Ord River Station show that predictability of flow (0.67) was mostly attributed to no flow in most months of the dry season (Pettit *et al.*, 2001). As expected, highly variable flows among months resulted in a low constancy (0.44), while contingency was low (0.20), and indicated the high variation of monthly flows among years. The contribution of seasonality to predictability was also low ($M/P = 29\%$), meaning that even the distinction between seasons is unclear. Presently, there are no comparative data for the Ord River below the dams.

SOME ECOLOGICAL EFFECTS OF REGULATED FLOW ON THE ORD RIVER

Riparian vegetation dynamics

For many rivers, establishment of trees is related to past hydrological events (Bradley and Smith, 1986; Baker, 1988; Pettit and Froend, in press). Fluvial regime and river geomorphology are major influences on the spatial and temporal structure of riparian vegetation (Barnes, 1984; Johnson, 1994), and fluctuating water flow determines production of multiple successional stages (Gregory *et al.*, 1991; Malanson, 1993; Nilsson *et al.*, 1993). Timing, frequency and level of flooding disturbance also affect vegetation dynamics in the riparian zone. How natural flow disturbance shapes community structure largely depends on the frequency, magnitude and predictability of the disturbance (Sousa, 1984).

Reproduction of riparian vegetation of the Ord River is closely related to river flows (Pettit, 2000). Seedfall for both *Eucalyptus camaldulensis* and *Melaleuca leucadendra*, the two most common riparian trees, coincides with the recession of water levels, typically March/April (Pettit and Froend, in press; Figure 3). Flowering and fruit maturation occur once a year, and seeds disperse downstream and laterally throughout the riparian zone. In the regulated section, there is limited potential for the dispersal of seed into the riparian zone and onto

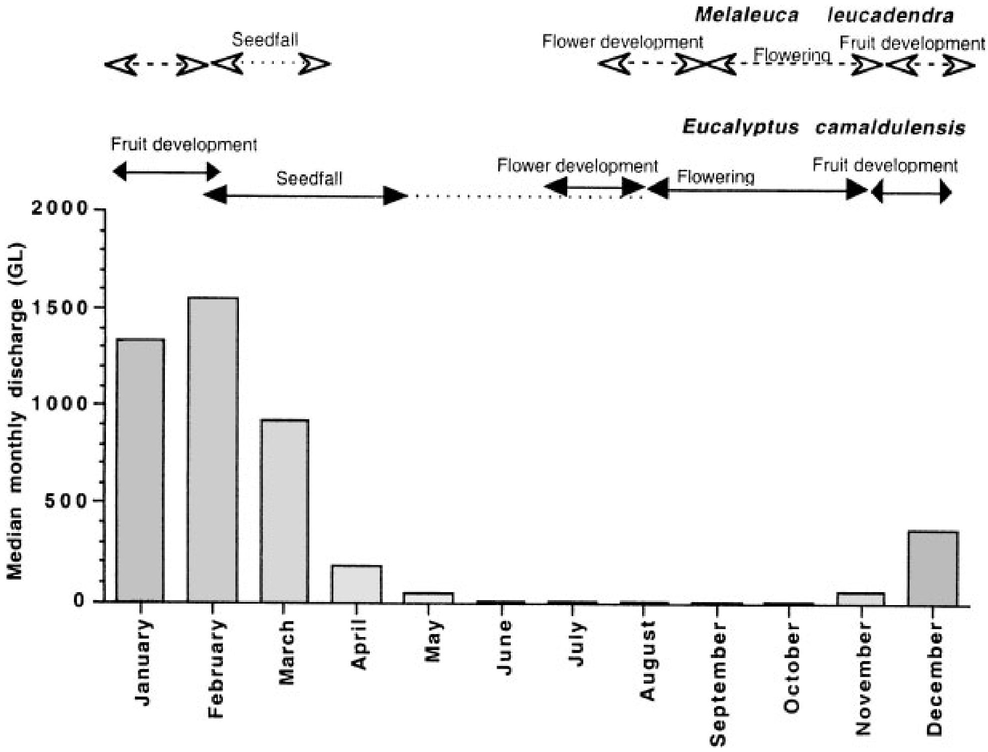

Figure 3. Relationship between median monthly river discharge and reproductive phenology of selected riparian species on the Ord River

the surrounding floodplain because lower wet season flows and continual dry season flows reduce available areas of moist sediment for seed germination and development.

Riparian floristics are related to the frequency and duration of flooding on unregulated, regulated and dammed sections of the Ord River (Pettit *et al.*, 2001). At Ord River station (unregulated), the profile (Figure 4a) shows an abundance of new seedlings (<1 year old) of *E. camaldulensis* and *M. leucadendra* at the lower elevations and an abundance of smaller size classes throughout the profile (Figure 4a). Frequency of larger size classes, especially for *E. camaldulensis*, is greatest at higher elevations and increasing distance from the river. Tree diameter significantly decreases with increased flooding frequency ($r^2 = 0.758$; $p = 0.0001$). High frequency of flooding disturbance probably inhibits seedling development, and restricts large trees to higher elevations protected from flooding. On the regulated lower Ord River upstream of Carlton Crossing (see Figure 1 for location; Figure 4b), dense stands of smaller trees, predominantly *M. leucadendra*, occupy the new riparian zone. These younger trees, determined by the relationship of age to girth for these species (Pettit, 2000), occur within 60 metres of the water, with some relict larger trees occurring at the extent of the original, pre-regulation riparian zone. In the absence of a large flood disturbance thinning out these stands, strong competition may prevent the development of larger size trees and the recruitment of new cohorts of trees. At Lake Kununurra, the riparian zone at the lake now closely mimics a lentic system (Figure 4c). The distribution of tree size classes indicates that recent recruitment of large numbers of seedlings has occurred in a narrow band at the rise and fall of the lake water level. Higher, permanent water levels have resulted in distinct populations of trees; there are relics of larger, older trees of the former riparian system that are no longer flooded, and some large dead trees indicating permanently inundated areas amid a cohort of young saplings developing on the new but narrow littoral zone where fluctuating lake water levels have created a niche of exposed moist sediments that are suitable for seed germination. Given that this area is no longer subjected to disturbance from large floods, the structure of the riparian population would stabilize as saplings mature, and recruitment opportunities disappear.

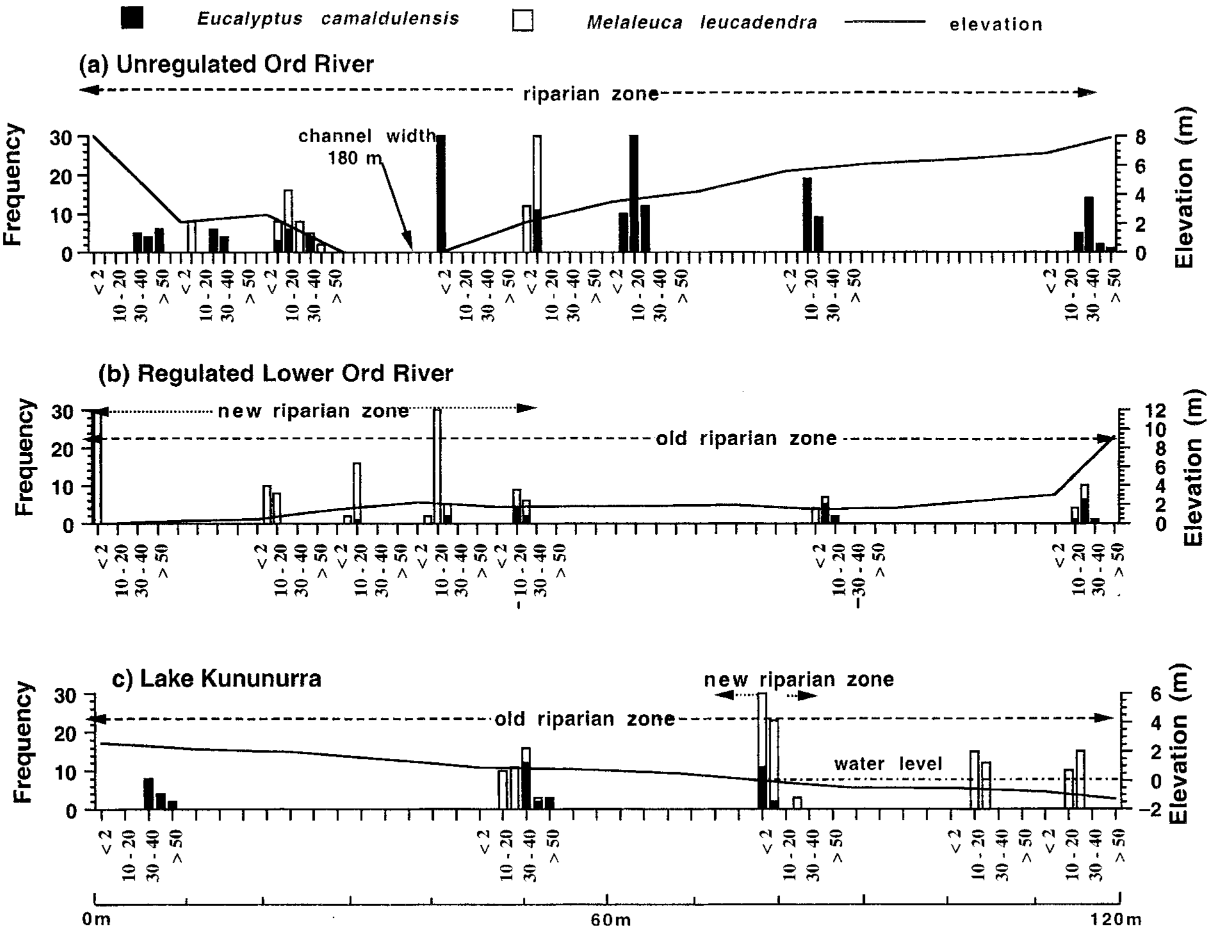

Figure 4. Size class frequency (<2 m to >50 m) and distribution of the two main overstorey species along a transverse profile on the (a) unregulated, (b) regulated and (c) reservoir sites on the Ord River. Frequencies are from combined 100 m^2 plots. Histograms show tree size classes (diameter at breast height, cm) by species for each plot and each distance along the profile

In-stream fauna

No records of the aquatic fauna from the unregulated Ord River are known. Since damming, work involving soil chemistry for crop irrigation, and the transmission of diseases by mosquitoes associated with irrigation and large water storages, have been undertaken (Anon., 1976), and Lane and McComb (1988) have speculated on the ecological impacts of water diversions on downstream wetlands of the Ord. Published information remains scarce.

Work elsewhere has demonstrated that disrupted flooding regimes, and spatial and temporal changes in inundation patterns, have pronounced effects on the composition of aquatic macroinvertebrate (Neckles *et al.*, 1990) and terrestrial vertebrate communities (Nilsson and Dynesius, 1994), and on downstream floodplains and estuaries (Stanley and Warne, 1998; Kowalewski *et al.*, 2000). Construction of dams and weirs can often rearrange the distribution and abundance of the riverine biota (Middleton, 1999). On the Ord, the Ramsar treaty listing of Lakes Argyle and Kununurra, and the lower Ord River floodplain, suggest that hydrologic changes have actually improved bird habitat. For the fishes of the Ord River, however, there is evidence that impoundments have had a pronounced impact on the life histories of many species. The dams divided populations of grunter species (e.g. *Amniataba percoides* and *Hephaestus jenkinsi*) and perches (e.g. *Leiopotherapon unicolor*), and have dramatically reduced the distribution and abundance of barramundi (*Lates calcarifer*) to about one-quarter of its former range in the river (Doupé and Lenanton, 1998). Favourable conditions in the absence of competitors like barramundi, have shifted the fish community composition in Lake Argyle toward the super-abundance of catfishes (*Arius* spp.), and the lake now supports a commercial catfish fishery, tourism, and a 50 tonne per annum cultured barramundi grow-out operation (Doupé and Lenanton, 1998; Doupé and Lymbery, 1999). Allen and Leggett (1990) found very high endemism (38%) in the 48 freshwater fish species known from the Kimberley, a region they describe as an important biogeographical province. We do not know what effects regulation may have had on restricted or unknown species in the Ord catchment.

Fish kills thought due to toxic agricultural residues have been recorded in the ORIA environs since 1973 (Anon., 1976). A series of fish kills in 1997 received widespread attention and renewed interest in methods to disperse agricultural effluent (Doupé, 1997). The construction of some form of fishway was proposed to provide the dual benefit of removing detained farm wastewaters, and recruiting barramundi into Lake Kununurra (Doupé and Bird, 1999). No fishway has yet proven adequate for significant barramundi recruitment, such is the importance of seasonal flow variations for the migration of this species (Doupé and Lenanton, 1998).

Too often, an irony of landscape and resource development for human benefit is the subsequent desire for 'improvement' in the form of restoration or enhancement projects. Wetland alteration is no different (Zedler, 2000). For example, Lake Kununurra is an expansive wetland habitat, with suggestions for introductions of exotic tropical species including flamingos (*Phoenicopterus* spp.) and pygmy hippopotamus (*Hexaprotodon liberiensis*) that would enhance tourism (R. G. Doupé unpublished work). The latter was advocated as a method of controlling the invasive aquatic macrophyte, cumbungi (*Typha domingensis*). Exotic species including the aquatic weed *Salvinia molesta* and redclaw crayfish (*Cherax quadricaranatus*) have recently been recorded in Lake Kununurra (R. G. Doupé unpublished work). Other enhancement proposals have included the introduction of the exotic Nile perch (*Lates niloticus*) to compensate for the absence of barramundi since damming (Williams, 1982; Doupé and Bird, 1999), but the escape of cultured barramundi from Lake Argyle threatens the genetic and ecological integrity of the wild fishery (Doupé and Lymbery, 1999).

BALANCING WATER PROVISIONS IN A REGULATED HYDROLOGICAL ENVIRONMENT: THE MANAGEMENT DILEMMA

Walker (1992) argued that the Ord irrigation project was marked by a 'persistent unwillingness to appreciate the limits imposed by climate, ecology and economics', and on occasions, the scheme was adjudged a failure (see also Davidson, 1965, 1982; Graham-Taylor, 1982). Indeed, one could be forgiven for questioning why the Ord River scheme continues to be pursued, given the agronomic and ecological consequences. Part of the answer lies in the political history of Western Australia (Walker, 1992), and the short-term economic imperative of irrigation schemes generally (Walker *et al*., 1997).

Contemporary Australian water resource policy requires setting aside water for the ecological environment of regulated river systems (Arthington and Zalucki, 1998). Davies *et al*. (1998) aligned environmental water requirements to the natural flow variability and critical flow requirements of in-stream biota to define flow releases in southwestern Australian rivers. Two problems arise when these criteria are generalized to other river systems. First, those temperate rivers, unlike arid zone rivers, have highly seasonal and predictable hydrologies with generally low monthly variability (Pettit *et al*., 2001); and second, most studies of environmental water requirements concentrate on the in-stream fauna and ignore the broad riparian community (Kingsford, 2000).

The planned expansion of irrigation will place further demands on the water resources of the Ord River system. Planning now includes consideration of wider ecological and socio-economic water requirements (Water and Rivers Commission, 1999a). The challenge, then, is to understand the constraints of the scheme and prescribe the 'balancing act' required to optimize water allocations to reflect those values. Provisional estimates are that monthly flow volumes on the lower Ord River should be maintained at levels 'at least equal to the 20th percentile of their pre dam monthly values'; the 20th percentile value is the monthly flow volume not likely to be exceeded on 20% of occasions (Water and Rivers Commission, 1999a). Presumably the 20%

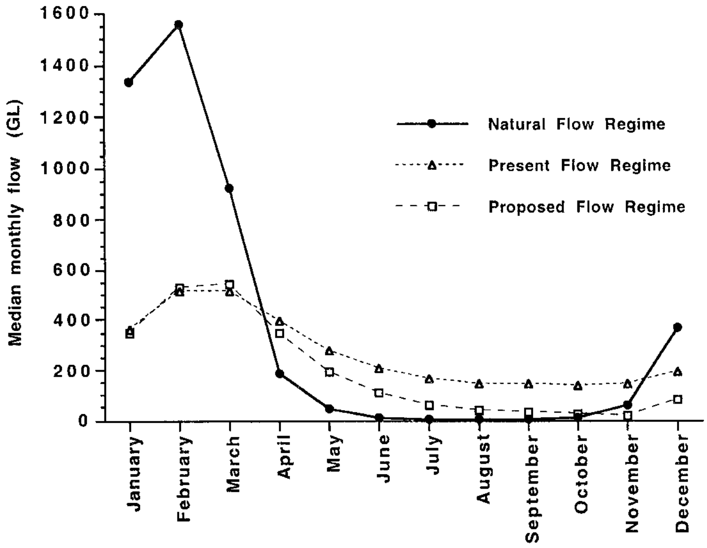

Figure 5. Median monthly river flow for the lower Ord River at Carlton Crossing. Natural flows are for the river prior to dam construction in 1963 and are calculated from catchment modelling. Present and proposed flows are based on respective 300 Gl and 1235 Gl irrigation allocations (Water and Rivers Commission, 1999b)

figure, or whatever is finally determined, is based on how much water is allocated for irrigation, rather than any clear ecological reason.

The hydrographs of past, present and proposed flow regimes at Carlton Crossing (for location see Figure 1) are shown in Figure 5. The proposed flow regime for the lower Ord River substantially reduces dry season flows to almost base level from August to October. We question the proposed regulation of in-stream flow patterns to mimic the natural seasonal hydrograph of the lower Ord River for two reasons. First, the river vegetation is clearly shaped by high disturbance floods (Figure 4). Therefore, the highly episodic nature of the unregulated Ord indicates that flows for any given month or year, are predictable only 67% of the time (Figure 2), whereas the proposed monthly water allocation would always be predictable. Second, a management dilemma ensues for reducing water flows late in the dry season because peak irrigation water demand results in agricultural effluent draining into the river during that time of year when, under the proposed conditions, periods of little or no flow are required for important ecological processes to occur.

Ecological water requirements

Succession theory is central to wetland and river restoration (Zedler, 2000). Therefore, understanding the vegetation dynamics and the mechanisms of recruitment under natural (unregulated) flow conditions is critical to understanding or anticipating the effects of river flow regulation on riparian vegetation (Nilsson *et al.*, 1997). Fluvial processes on the unregulated Ord River are dominated by frequent, large, high energy floods that are capable of scouring out the soil, destroying the existing riparian vegetation community and preventing the establishment of stable mature stands (see Figures 2 and 4). The natural disturbance regime results in long periods of stable states with short periods of transition (Westoby *et al.*, 1989; Hobbs, 1994). High frequency flooding can keep the vegetation in an early stage of succession (Naiman *et al.*, 1998), and consequently, a regime of intermittent but large disturbances prevents the establishment of climax communities and weed invasions. For example, Pettit (2000) observed that reduced frequency and magnitude of flooding has enabled the establishment of exotic lianes (e.g. *Passiflora foetida*, *Clitoria ternatea* and *Cardiospermum halicacabum*) along the lower Ord River. The vegetation is subjected to long periods of biotic processes (e.g. competition for resources) because of low frequency flooding disturbance, and short periods of physical (abiotic) processes.

Where flooding disturbances are chronic to frequent, riparian forests are young, as vegetation patch development is continually reset and remains in stand initiation and exclusion successional stages (Wissmar and Swanson, 1990).

Management of the riparian vegetation should take account of the frequency of change in the vegetation resulting from highly variable and large floods. Disturbed states and long periods of transition between them are part of the natural process, and have important implications for the long-term structure and functioning of these communities. To maintain their dynamic nature, something resembling the natural flow regime is required. That is, high wet season flows that resemble climatic variability in frequency and magnitude, and low to no flow later in the dry season. The management 'window' for such a flow regime appears limited, because effective dilution of agricultural effluent may be compromised, and such a flow regime may impact other ecological and socio-economic values (see next sub-section). Nevertheless, testing of occasional and large flows elsewhere, such as the Colorado River (see Stevens *et al.*, 1995), indicates that these types of management problems are resolvable to some extent.

Agricultural water requirements

Flow-through irrigation schemes, like the Ord River project, require 'dry season flows' to dilute and disperse agricultural effluent, and maintain acceptable water quality for other environmental values. In September 1997, Doupé *et al.* (1998) measured total phosphorus and chlorophyll *a* concentrations at Carlton Crossing (about 60 km downstream of the ORIA), when irrigation water demand was about 160 Gl per annum, or half capacity. Total phosphorus levels were 47 $\mu g\ L^{-1}$, about twice those of Lake Kununurra and considered 'moderate' for tropical water bodies (Salas and Martino, 1991), whereas chlorophyll *a* levels were low (0.8 $\mu g\ L^{-1}$), and similar to those of Lake Kununurra. Ruprecht and Rodgers (in Anon., 1997b) modelled the relationship between projected irrigation and environmental water allocation scenarios, and monthly total phosphorus concentrations at Carlton Crossing. At maximum irrigation water demand for the existing ORIA (i.e. 300 Gl or a 34% reduction in median annual flows; Water and Rivers Commission, 1999b), they predicted total phosphorus concentrations to be only 15–20 $\mu g\ L^{-1}$ during September.

The fourfold expansion of the irrigation area is predicted to increase irrigation water demand to at least 1235 Gl and further reduce the median annual flow of the lower Ord River by an additional 33% (Water and Rivers Commission, 1999b). At those levels, Ruprecht and Rodgers (in Water and Rivers Commission, 1999b) predict a September total phosphorus loading of about 35 $\mu g\ L^{-1}$. We note the caution that predicted values 'are critically dependent on the quality and quantity of water return flow' (Water and Rivers Commission, 1999a), but that is our point. The allocation of additional environmental flows for the dilution

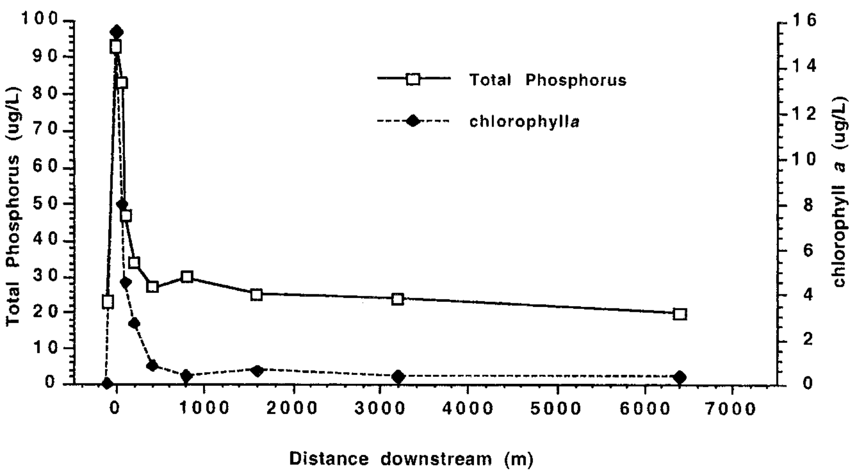

Figure 6. Dilution of total phosphorus and chlorophyll *a* concentrations with distance downstream from the wastewater treatment plant in the main irrigation supply channel

of total phosphorus concentrations at Carlton Crossing has been considered using the model of Ruprecht and Rodgers (Water and Rivers Commission, 1999a). At a 1235 Gl irrigation water allocation with an additional 5 m^3 s^{-1} dilution flow, September total phosphorus concentrations are predicted to approach 28 μg L^{-1}, and a 10 m^3 s^{-1} dilution flow is thought to reduce concentrations to about 25 μg L^{-1}. It was concluded that the need for additional dilution flows would not arise for some time (Water and Rivers Commission, 1999a).

In any of the proposed water allocation scenarios, the models appear to underestimate the quality of return water flow and overestimate the effects of dilution. Nevertheless, sufficient water will dilute nutrient and algal concentrations. For example, Doupé *et al*. (1998) investigated how water flows diluted sewage effluent in the main irrigation supply channel. They found that a 4000-fold dilution of total phosphorus and chlorophyll *a* concentrations occurred within 400 m of the outfall from the Kununurra wastewater treatment plant at peak growing season water flows of 1671 Ml d^{-1} (Figure 6), and demonstrated the requirement for sufficient water to dilute and disperse effluent in a flow-through irrigation scheme. There is a clear need for current land and water management practices within the existing ORIA to change, but equally, there are obvious implications for reducing downstream dilution flows whilst flow-through irrigation continues.

CONCLUSION

Extended time scales are necessary to understand the ecological consequences of any particular water allocation for the lower Ord River, but any choice now is compromised by the decisions of the past. Ideally, historic rainfall and flow data could guide the management regime. For the Ord River above Lake Argyle, we have about 20 years of data that demonstrate a strongly seasonal and highly variable flow regime across all months and years with intense flows of short duration (Pettit *et al*., 2001). Models based on median flows and their dispersion have very little relevance to the extreme events that skew the hydrograph of the Ord and other dryland rivers, and consequently, are less amenable to modelling and statistical analysis (Walker *et al*., 1995). To better understand the link between hydrology and ecology on the Ord River, a comparison of one or more rivers with little or no development is required. There are many rivers surrounding the Ord River region that have similar hydrologies, but they lack the magnitude of Ord River flow events (N.E. Pettit and R.G. Doupé, unpublished work). The nearby Fitzroy River is hydrologically, climatically and biogeographically similar, and is an ideal candidate river (see the papers in Storey and Beesley, 1998). An ecological understanding of that river may help to avoid the problems associated with investigating only post-regulation effects (e.g. Blanch *et al*., 1996) on the Ord River.

For rivers displaying highly variable hydrologies, Walker *et al*. (1995) asked if we should be determining flow allocations on a seasonal basis, rather than attempting to design a long-term flow regime. They argued that we should view the water requirements of the river *a priori* to demands for irrigation; irrigators would need to budget their water requirements based on the 'surplus water' not required by the river. One could predict a substantial political backlash to such a proposal; however, a better understanding of the total ecological and economic cost of irrigated agriculture is a prerequisite for any significant reform of the industry (see Agnew and Anderson, 1992).

Ideally, hydrologic models must predict flooding and drying patterns, and be linked to ecological processes and biotic life cycles (Kingsford, 2000). Where the juxtaposition of a flow-through irrigation scheme occurs, however, the best of management intentions become confounded because periods of low flow during the agricultural season would probably result in a marked deterioration of water quality. One obvious recommendation for management is seasonal desiccation to mimic natural flows, but because poor water quality, delivered by agricultural effluent, will always coincide with such periods, there is a dilemma for managers. The 'balancing act' between these two competing demands cannot be satisfactorily achieved concurrently because they require contrasting river flow regimes. The management dilemma would be resolved by deciding which value takes precedence in this section of a substantially regulated and altered river system. Managers should ask what primary value they are managing the water resource for. The water allocation scenarios for the Ord River (Water and Rivers Commission, 1999a,b) clearly indicate the precedence that irrigated agriculture holds over other water users. The present flow regime of the lower Ord River provides other significant socio-economic values including tourism and recreation, and a prosperous recreational barramundi fishery (West *et al*., 1996; Water and Rivers Commission, 1999a).

The expansion of the irrigation area appears inevitable, supposedly embracing the concept of ecological sustainability. The history of the Ord River irrigation scheme suggests this is unlikely. Part of the management challenge is to prescribe remedies for present land and water management practices within the existing irrigation area (Doupé *et al*., 1998). Another challenge is to protect the existing values of the regulated river environment. If socio-economic values have continued precedence in water management on the Ord River, some degree of risk assessment based on questions is needed. What is being sustained and for how long? And for whose benefit and at what cost? Answers will mostly involve factors other than science because we will never have all the information we might desire; however, a broad consensus in determining those values will help guide management decisions that are based on the best available information (see Calver *et al*., 1998). A quantitative framework for determining how and when to apply a precautionary approach to the protection of existing values is available (Deville and Harding, 1997), and these concepts together with appropriate measurements have been successfully applied to justify management decisions between competing resource uses (e.g. Kruger *et al*., 1997). Clearly, the time has come to make some similar decisions for the Ord River.

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